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Research Article

Insights to improve covered lagoon biodigesters through by-products recovery in pig farms

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ABSTRACT

Pig farming activity has an important role in the Brazilian economy and generates effluents with a high polluting potential. The covered lagoon biodigester is a simple and suitable alternative for the treatment of swine manure. This work aimed to propose improvements to the pig effluent treatment system composed by covered lagoon biodigesters. Therefore, a survey of a typical plant configuration of pig effluent treatment was accomplished and alternatives were suggested in order to get a greater energy sustainability in farms through resource recovery. The proposed interventions were based on studies of scientific papers, technical equipment manuals, technical research and consultation with professionals of the field. The optimization of the systems operation considers some criteria, such as: (i) need for solids removal; (ii) organic loading; (iii) operation temperature; (iv) effluent recirculation; and (v) biogas energy recovery. Firstly, a typical scenario was identified without any improvements, in which the biogas is sent to flares without energy recovery. Subsequently, systems improvement insights were proposed, mainly regarding effluent heating through a solar heating system or by recovering the thermal energy from biogas and biogas recovering. The treatment optimization would increase the efficiency of organic matter removal and biogas production, as well as electric energy production and reduction in greenhouse gases emissions. The use of tools such as Life Cycle Analysis (LCA) can favor decision making and comparing proposed alternatives.

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INTRODUCTION

Pig farming is among the main agribusiness activities in Brazil. In 2019, the country produced approximately four million tons and exported 861 thousand tons of pig meat, being the fourth largest producer and exporter in the world, and the fifth consumer. Brazil's Southern region is responsible for 66.0% of the national production, followed by the Southeastern region, responsible for about 18.0% [1]. The intense swine activity generates large amounts of manure rich in organic matter and nutrients such as nitrogen, phosphorus, and eventually antibiotics and steroid hormones with high polluting potential, thus requiring treatment and

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an adequate final disposal in order to minimize impacts to the environment [2, 3]. Anaerobic digesters stand out as a great treatment alternative because of their low costs of implementation and operation, low energy demand, reduced sludge yield and the biogas generation, a by-product with high energy potential [4].

Anaerobic digesters are available in the market in different models and configurations. Their selection must take into account local climate conditions, effluent characteristics, and financial resources available for their construction, operation and maintenance. The covered lagoon biodigester (CLB) is a simple technology, easy to build and operate, being among the main swine manure treatment alternatives in Brazil [5, 6]. Despite the advantages, there are some inherent limitations that can compromise treatment efficiency and biogas recovery. For instance, the absence of automated features to control and optimize the operational temperature and a full understanding of the hydraulic regime, which influences the distribution of microorganisms in the reactor and the accumulation of inhibitory metabolites by the microorganisms [7].

Anaerobic processes are carried out by various Bacteria and Archaea. The biological activity of these microorganisms is strongly affected by operational and environmental factors [4, 8], such as hydraulic retention time, temperature, and pH. Therefore, monitoring those factors is important to guarantee a stable and efficient treatment process and increase the biogas production, which can be used to generate thermal and electric energy.

According to Oliveira et al. [8] and Santos et al. [10], anaerobic digestion of swine manure in Brazil can generate energy in an order of 1,750 $TWh.year^{-1}$, contributing, for instance, to the generation of electricity from biomass, which in 2019 was 52,111TWh [11]. However, such potential isn't utilized. Regarding the state of Minas Gerais, only 34.8% of its pig farms have a CLB installed. From those with biodigesters, few of them generate decentralized energy from biogas recovery. Besides the energy potential, biogas recovery would avoid an average emission of 0.535 Mt $CO_2.year^{-1}$, making pig farming more sustainable [10]. In addition, the biogas recovery in Brazil may collaborate to achieve the following goals signed in the Paris Agreement: (i) reduce greenhouse gases by 37.0% below emission levels in 2005 until 2025 and 43.0% below emission levels in 2005 until 2030; (ii) increase the share of sustainable bioenergy in its energy matrix by 18.0% until 2030; and (iii) achieve a 45.0% share of renewable energy in the composition of the energy matrix until 2030 [12].

The low use of the biogas energy potential is associated with the lack of regulation and policies to encourage the development of accessible and appropriate technologies for the Brazilian context [13]. There are some studies regarding the optimization of CLBs treatment efficiency and biogas recovery in order to improve pig farms sustainability [8, 14–20]. Thereby, the implementation of constructive and operational improvements in covered lagoon biodigesters enables increasing the treatment efficiency and biogas recovery. This work aimed to present scenarios and alternatives associated with constructive and operational improvements of covered lagoon biodigesters, as well as integrating their by-products recovery in order to improve pig farms sustainability.

MATERIAL AND METHODS

The base layout scenario of treatment plants in pig farms, as well as the constructive and operational parameters improvements and by-products recovery alternatives were assessed based on technical literature review, manufacturer's manuals, and benchmarking of operational practices, experiences reported by pig farm facilities and technical reports from government agencies related to pig farming and biogas energetic recovery. CLBs optimization strategies contemplated technological alternatives and by-products recovery. The following aspects were considered: (i) solids removal; (ii) organic loading; (iii) operational temperature; (iv) effluent recirculation, and (v) biogas energy recovery. The possible alternatives to improve the system efficiency were described and compared with each other, presenting their advantages and disadvantages.

RESULTS AND DISCUSSION

Base Scenario for Pig Farms Using Covered Lagoon Biodigesters

The effluent treated by biodigesters requires a certain level of post treatment before being discharged into water bodies [6]. A stabilization pond is an interesting choice considering its advantages such as low constructive and management investments, as well as treatment efficiency, however this alternative requires a large construction area [21]. In addition, there are studies regarding the use of a stabilization pond to remove hormones present in swine manure such as progestogen, which poses potential risk to aquatic organisms [22]. Regarding the methane present in the biogas, its global warming potential is 25 times higher than that of CO_2 in a time span of 100 years [23]. Given that, it is environmentally more interesting to transform CH_4 into CO_2 through combustion, which can be done in flares, a mandatory equipment for safety purposes [8].

The flowchart in Figure 1 suggests a base layout scenario of treatment plants in pig farms in Brazil, featuring a covered lagoon biodigester and a post-treatment unit, with final disposal alternatives for the main by-products (Fig. 1). Initially, swine manure passes through a screen in order to retain small rocks, pieces of plastic and other unwanted coarse materials to get stuck inside the biodigester (Fig. 1, 2). The pass-

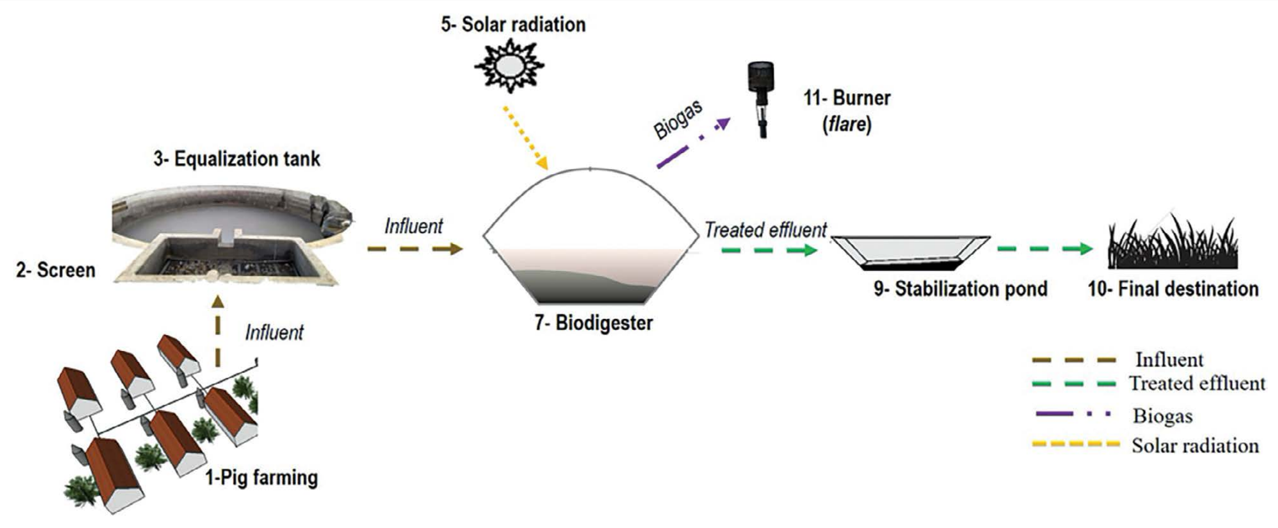

Figure 1. Base scenario for pig farms with covered lagoon biodigester treatment system.

ing liquid effluent is then stored in an equalization tank (Fig. 1–3). Afterwards, the swine manure is pumped to feed the biodigester (Fig. 1–7). The main by-products of anaerobic digestion are the effluent and the biogas. The first goes to a post-treatment, usually a stabilization pond (Fig. 1–9), being subsequently applied in the soil or used for crop fertigation (Fig. 1–10). The biogas generated is burned in flares (Fig. 1–11) [24]. Finally, the CLB's main source of heat is the incident solar radiation on the top of the biodigester (Fig. 1–5).

Improved Pig Farm Base Scenario Flowcharts

Two different layouts containing constructive and operational improvements and biogas destinations are shown in Figure 2 and Figure 3. In Figure 2 the heating system is based on solar energy, while in Figure 3 it is based on the thermal energy released from biogas combustion.

Figure 2 presents the treatment system indicated in the base scenario (Fig. 1), with a proposal of a pre-treatment by a solid-liquid separator, in order to reduce the total solids content to a range suitable for CLB operation (Fig. 2–4); a swine effluent heater ran by solar panels (Fig. 2–6); and a biogas purification system that will be designed according to the quality required for its use (Fig. 2–12). Finally, the biogas energy recovery in three ways: (i) burning in boilers to generate thermal energy (Fig. 2–13); (ii) burning in a motor generator to produce electricity (Fig. 2–14); and (iii) fuel generation (Fig. 2–15).

Figure 3 presents the treatment system indicated in the base scenario of Figure 1 with the proposal of a pre-treatment by a solid-liquid separator, in order to reduce the total solids content to a range suitable to the CLB operation (Fig. 3, 4); a swine effluent heater run by thermal energy released by biogas burning (Fig. 3–6); and a biogas purification system that will be designed according to the quality required for its use (Fig. 3–12). Finally, the biogas energy recovery in three ways: (i) burning in boilers to generate thermal energy (Fig. 3–13); (ii) burning in a motor generator to generate electricity (Fig. 3–14); and (iii) fuel generation (Fig. 3–15).

Improvement Alternatives

The aspects related to some treatment stages and their operational conditions, as well as improvement alternatives for these, are detailed below.

Solids Removal

Solids removal objectives the removal of coarse solids, in order to avoid abrasion and obstructions in equipment and pipes [21]. Pre-treatment alternatives are a function of pig farm management, biodigester set up, and effluent characteristics in terms of solids content, which is considered a limiting factor. In general, CLB's operate with low levels of total solids, up to 3.0%, and the pre-treatment is recommended for higher levels [8]. The phase separation reduces the swine effluent solids contribution, reducing the entry of recalcitrant material in the biodigester, allowing it to be more conducive to microbial action and, consequently, improving biogas production. There are several pre-treatment methods, such as decanting, centrifugation, sieving and/or pressing, dehydration by wind, forced air or heated air. The most used are decanting and sieving [17, 18, 25]. Decanting pros are the low costs of implementation and maintenance. However, it requires greater manpower. The sieves are classified as static, vibrating and rotating. Regarding the static sieve, maintenance and cleaning are major issues, as the formation of a thin layer of solids on the sieve surface can cause operational problems. The rotating and vibrating sieves allows continuous operation with little or no obstruction of the screens, enabling it to remove coarse and fine particles. However, they have a high initial investment cost and rely on power to operate [25].

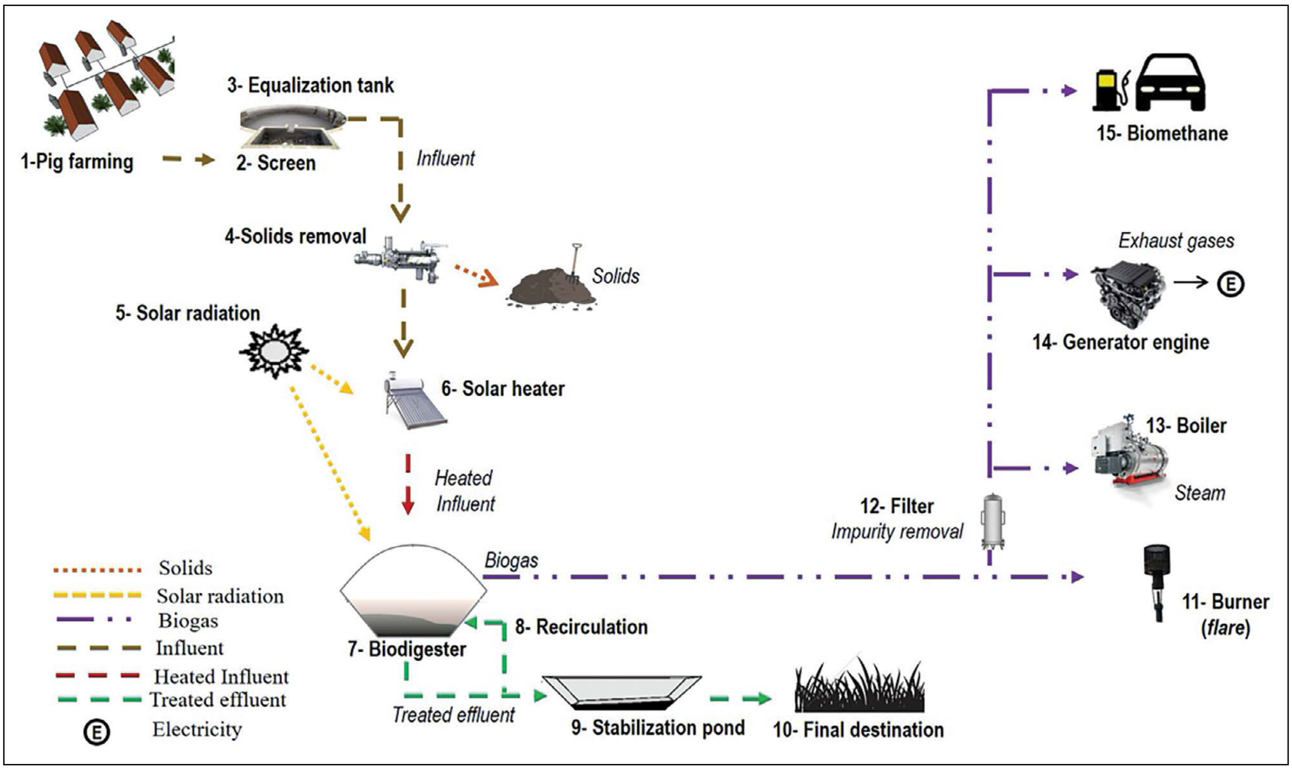

Figure 2. Improvements for the anaerobic process considering pre-treatment, swine effluent heating via solar energy and alternatives for the use of biogas.

The best pre-treatment alternative depends on the effluent characteristics, number of animals, land area and economic resources availability. Considering that rotating sieves are available in the market in different sizes and capacities, that way attending pig farms from different sizes, this alternative was selected and presented in Figure 2–4 and Figure 3, 4. The solid fraction retained by the sieve can be composted and used as a solid biofertilizer [25].

Biodigester Feeding - Organic Load in Terms of Volatile Solids

The volumetric organic load (VOL) influences anaerobic process dynamics, since it directly impacts the optimal conditions for microbial growth. CLBs usually treat effluents with a volumetric organic load of 0.3 to 0.5 $kgSV.m^{-3}$ $reactor.d^{-1}$ [8]. Feeding the biodigester with VOLs above the designed capacity can lead to system failure; while feeding it below the VOLs designed capacity leads to a low food/microorganism ratio, resulting in low biological activity, thus reducing the treatment efficiency [6].

Many studies have shown an increase in the methane yield for the co-digestion (AcoD) of swine manure with other substrates such as microalgae, agricultural and food residues. Astals et al. [24] reported an increase in the methane yield of microalgae from 0.163 to 0.245 m^3_{CH4} kg^{-1VS} (volatile solids) by applying the co-digestion with swine manure [27] reached 0.187 m^3_{CH4} kg^{-1}_{VS} in pig manure digestion, compared to 0.388m^3_{CH4} kg^{-1}_{VS} in pig manure and food waste co-digestion, in the ratio 17:83, respectively. This increase is due to overcoming ammonia inhibition which is sometimes a feature in digestion of pure manure and optimizing the carbon to nitrogen (C/N) ratio in the feedstock for the AD [28]. Although the C/N ratio is widely used to explain the synergies that occur during anaerobic co-digestion, specific microbes from pig manure, macro and micronutrients, and alkalinity can be also linked [29]. However, the co-digestion of lipid rich co-substrates may present operating problems, which are usually associated with foaming, clogging, and biomass flotation inside the reactor; and inhibition of the microorganisms due to the accumulation of long chain fatty acids [30].

Operational Temperature

Temperature is a parameter of great importance in anaerobic treatment, impacting microorganism's metabolism and biochemical reactions rates [8, 25]. Anaerobic reactors work under thermophilic (50.0 to 65.0°C) or mesophilic (20.0 to 45.0°C) conditions, being the optimal temperature for microorganism development the range between 35.0°C and 37.0°C [7, 26, 33]. Considering that Brazil is a tropical country, most anaerobic reactors operate at temperatures close to the lower limit of the mesophilic range. According to Sousa [18], the internal temperature of a covered lagoon biodigester without temperature control, in the city of Teixeiras, Minas Gerais (20°34'07,2" W, 42°52'01,6" S), varied

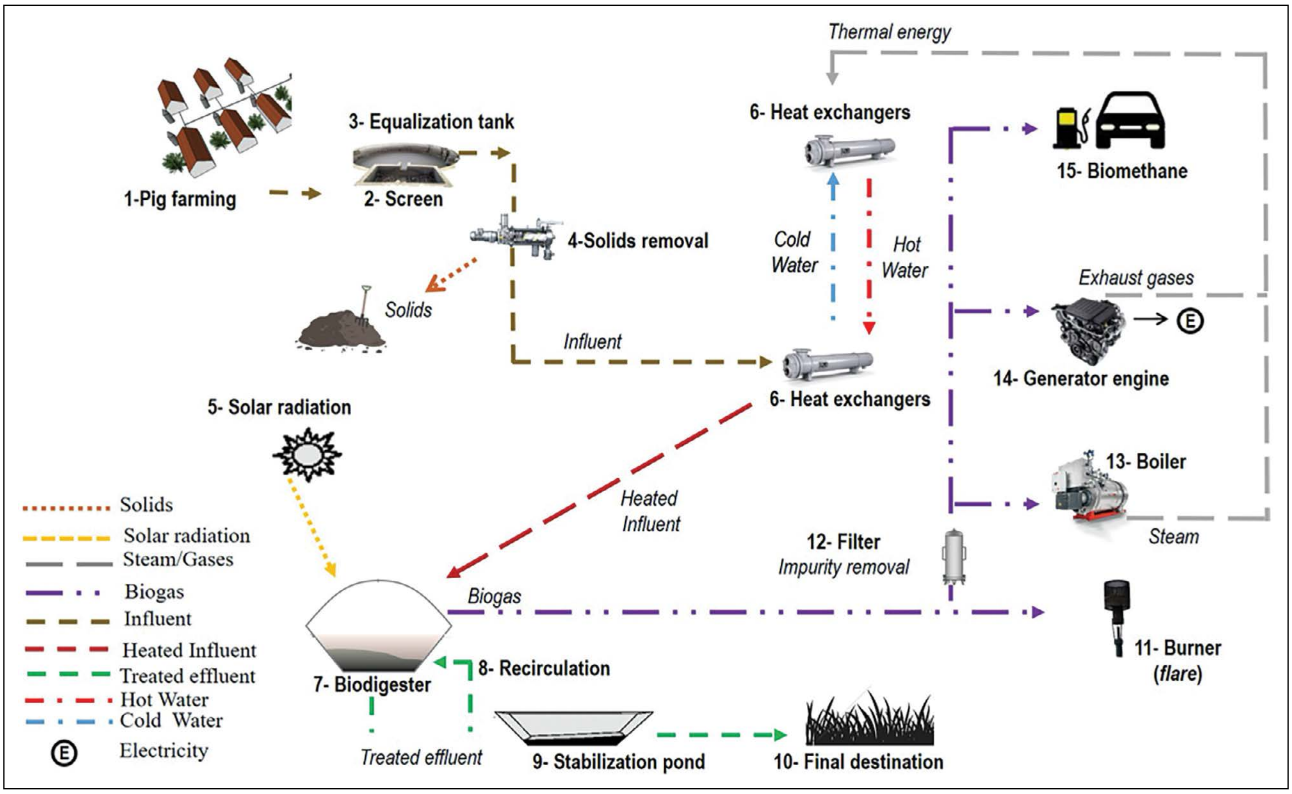

Figure 3. Improvements for the anaerobic process considering pre-treatment, heating the swine effluent via thermal energy from burning biogas and alternatives for the use of biogas.

from 20.5 to 26.8 °C, well below the optimum temperature, which may have contributed to decrease the system efficiency in terms of organic matter removal and biogas yield. Furthermore, anaerobic microorganisms are particularly sensitive to temperature variation; even small changes up to 2ºC may cause inhibition [8]. Thus, a temperature control system will ensure proper conditions for microbial activity, increasing treatment efficiency and biogas yield. Some alternatives are shown in Figure 2–5, Figure 2–6, Figure 3–5 and Figure 3–6 and described below.

The heat required for anaerobic reactions in the CLB comes from the effluent itself, from the heat released by microbial activity and, mainly, from the solar radiation on the top of the biodigester. The heat released by microbial metabolism does not affect the effluent temperature substantially, whereas solar incidence is responsible for up to 84.0% of the heat transfer rate to the interior of the biodigesters in the summer [17, 34].

Solar radiation plays an important role in CLB temperature control. It varies seasonally and along longitude and latitudes. The rate of solar radiation absorption by biodigesters varies according to local landscape aspects such as trees, buildings and other objects that may block the sunlight, as well as the reactor's layout, and the gasometer dome color and material properties. According to a study by [33], solar reflectance of a digester dome, external ambient temperature and solar irradiance are the factors that mostly influence the biodigester internal temperature. The same study showed that a black color dome with a reflectance of 4.8% lead the biodigester internal temperature close to 46.0 ºC in periods of intense solar radiation like summer, while a white color dome with a reflectance of 77.6% lead to an internal temperature of 38.0ºC during the same time of the year. The study clarifies that the heat provided by the solar incidence on the gasometer dome is inconveniently affected by different factors, making it difficult to control the temperature inside the biodigester. Given that, choosing a gasometer dome with a low reflectance is helpful to avoid the system overheating during periods of higher solar incidence, as well as adopting other mechanisms of temperature control are necessary to ensure the system operational stability throughout the year.

Han et al. [35] proposes a heating system by installing an external tank containing a heat exchanger with continuous flow of hot water (Fig. 3–6), which heats the swine effluent before it enters the biodigester. The exhaust gases from the internal combustion engine (Fig. 3–14) or the steam emitted by a boiler (Fig. 3–13) could also be used as a heating source in the heat exchangers. In addition, the heat exchanger could be installed inside the biodigester [32, 34].

Solar heaters are also an alternative to increase the swine effluent temperature (Fig. 2–6). Dong and Lu [15] developed and integrated a large-scale solar-powered water-heating system (SPWHS) to a biogas plant installed in a pig farm in China, which increased the biogas yield. Results showed an increase of 11.2% in biogas yields generated by the integrated system compared to the biogas plant without the SPWHS, as well as an increase of 14.3% in the swine manure biomass energy transformation ratio of SPWHS [15]. Duan et al. [36] compared, via modeling, three different heating systems alternatives for an anaerobic reactor in China powered by pig slurry at different organic rates: solar energy, biogas boiler and cogeneration system. The solar energy heating system obtained a better result when the treatment system was fed with higher organic loads, reducing solar panel area and, consequently, the cost [36]. Zhang et al. [37], in turn, simulated a hybrid heating system for an anaerobic reactor in China combining solar energy and a biogas boiler in order to provide thermal energy for buildings. The proposed system features advantages in energy savings (94.9%) and reduction of carbon emissions (2,961.85-ton year^{-1}) compared to the traditional fuel sources in the country (coal) [37]. However, the results also showed that the energy contributions are very small during the winter, due to the lower incidence of solar radiation and higher volumes of rain and snow, making this kind of system a good fit for tropical countries [15, 36, 37].

Internal Effluent Recirculation

The absence of a mixing system may lead to an accumulation of sludge in the bottom of the reactor and less contact is provided between microorganisms and substrate. Moreover, the sedimentation reduces the reactor useful volume and, consequently, the hydraulic retention time, leading to a loss of solids in the effluent [8]. Effluent recirculation (Fig. 2–8 and 3–8) is an insight that has been shown to be advantageous in anaerobic digestion, favoring substrate degradation, once it reintroduces methanogenic bacteria in the reactor. This process increases cell residence time by allowing a better contact between substrate and microorganisms, contributing to keep the effluent in an even temperature inside the biodigester [38].

In addition, this feature is theoretically simpler than a mixing structure with a certain number of agitators to maintain the effluent suspended, not to mention the energy costs associated and the complicated maintenance. Furthermore, the effluent can be recirculated back into the biodigester in different points, helping to keep the system homogene in terms of microorganisms and ensure a better contact between them and the substrate. In a study developed by PROSAB [39], regarding the treatment of landfill leachate in anaerobic reactors, the recirculation attenuated the effluent organic load and promoted an endogenous inoculation of biomass, since it reintroduces microorganisms more adapted to the substrate [39]. However, despite the advantages of the recirculation process, the studies still do not focus on covered lagoon biodigesters. Thereby, this is a promising research field as an alternative to improve the CLB configuration.

Biogas Energy Recovery

There are several alternatives for biogas energy recovery, such as: (i) thermal energy generation through biogas burn in boilers and ovens (Fig. 2–13 and 3–13); (ii) electricity generation in motor generators (Fig. 2–14 and 3–14); (iii) biogas processing for use as vehicular fuel (biomethane) (Fig. 2–15 and 3–15); (iv) and injection into the natural gas line. Each biogas recovery alternative requires a level of purity, which means a higher concentration of methane and lower concentration of other components, such as hydrogen sulfide (H_2S), carbon dioxide (CO_2) and humidity. In some cases, it is necessary to remove these components to prevent damage in equipment and structures such as engines and pipes [40].

Moreover, the economic viability of biogas energy recovery depends on local factors, such as the property's energy consumption and the concessionaire's electricity tariff. In this way, it is necessary to carry out specific economic studies for each location involving, for example, the net present value and the payback time [41]. The machinery needed for energy production can be very expensive for small producers [42]. In addition, the biogas flow may be insufficient for some generator engines available on the market. For instance, the smallest commercial motor generator of the ER-BR brand requires a minimum biogas flow with 65% methane concentration equal to 14 $Nm^3\ h^{-1}$. However, this issue may be solved by storing the biogas in a reservoir to be fed to the generator when the flow rate is convenient. Furthermore, for the engine to function efficiently, biogas must have a minimum content of 55% methane [43].

The use of tools such as Life Cycle Analysis (LCA) supports decision making on sustainability aspects at environmental levels. The LCA allows to evaluate and compare the environmental performance of the effluent treatment system, quantifying the impacts by categories, such as carbon footprint, eutrophication, acidification, among others, in addition to enabling proportions of improvements to the system in order to reduce the impacts [44, 45].

CONCLUSIONS

Covered lagoon biodigester is a simple and suitable alternative for pig waste treatment. The optimization of this system requires evaluations of some constructive and operational aspects, such as: (i) analyzing the need to implement a phase separation step to retain solids; (ii) developing strategies to increase the reactor operational temperature for mesophilic or thermophilic ranges, as well as maintaining it stable; and (iii) promoting the recirculation of the treated effluent in the system in order to promote a better contact between substrate and microorganisms and ensuring an even temperature of the effluent under treatment.

The use of strategies to improve the anaerobic digestion process in biodigesters promotes an increase in the treatment efficiency and in the biogas production. The biogas energy recovery depends on some factors such as local and economic issues and the amount and composition of biogas produced. The main possible biogas uses from the typical scenario correspond to: (i) thermal energy generation through burning in boilers and ovens; (ii) electricity generation in motor generators; (iii) processing for use as vehicular fuel (biomethane); and (iv) injection into the natural gas line.

However, the biogas energy recovery is still not very widespread, which highlights the need to disseminate techniques and studies in order to improve the economic viability of biogas energy processes. Furthermore, new regulations and policies may encourage the development of accessible and appropriate technologies for the Brazilian context. The use of tools such as the Life Cycle Analysis (LCA) can favor decision making and comparing proposed alternatives.

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DATA AVAILABILITY STATEMENT

The authors confirm that the data that supports the findings of this study are available within the article. Raw data that support the finding of this study are available from the corresponding author, upon reasonable request.

CONFLICT OF INTEREST

The author declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

ETHICS

There are no ethical issues with the publication of this manuscript.

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