Engenharia Agrícola

ISSN: 1809-4430 (on-line)

www.engenhariaagricola.org.br

Special Issue: Energy in Agriculture

Scientific Paper

Doi: http://dx.doi.org/10.1590/1809-4430-Eng.Agric.v43nepe20220130/2023

THERMAL EXCHANGES IN A COVERED LAGOON BIODIGESTER TREATING PIG FARM EFFLUENT HEATED BY SOLAR ENERGY

Priscila da S. Maradini[1], André P. Rosa[1*], Juciara O. Lopes[1], Joyce C. Carlo[1], Alisson C. Borges[1]

[1*]Corresponding author. Universidade Federal de Viçosa/Viçosa - MG, Brasil.
E-mail: andrerosa@ufv.br | ORCID ID: https://orcid.org/0000-0001-5490-5698

KEYWORDS

effluent heating, biodigester, heat-transfer media, mathematical modeling, energy recovery.

ABSTRACT

Covered lagoon biodigesters are widely used in Brazil for treatment of agro-industrial effluents; however, under natural conditions, they operate at temperatures below the ideal. Thus, external sources for heating the effluent can enhance reactor performance and optimize thermal exchanges between the biodigester and the environment. This study aimed to evaluate the thermal exchanges in the internal and external environments of a covered lagoon biodigester from the influence of effluent heating through solar energy. Mathematical modeling (EnergyPlus software) was used as a tool to simulate thermal exchanges and obtain heat transfer rates. To do so, two scenarios were considered: with and without heated effluent. The results showed that solar radiation is the primary source of heating for anaerobic reactors and that the high thermal inertia of the soil contributes to a small variation in temperature of the resident biomass over the course of the day, even in the scenario with heated effluent. The temperature of the resident biomass reached and stabilized at 30°C, even after thermal exchanges with biogas and soil, in both hot and cold periods when heating was applied.

INTRODUCTION

In Brazil, covered lagoon biodigesters (CLB) have been increasingly used in treatment of agro-industrial effluents due to their low technological demand and because they fit within investment conditions of producers of different sizes (Sousa et al., 2022; Cheng et al., 2018). The stabilization of organic matter in these reactors occurs through anaerobic conditions, but process speed and efficiency can be influenced by different factors (Náthia-Neves et al., 2018). Temperature is considered the most critical variable from an operational point of view, as it has a direct effect on the microbial activity inside reactors (Adrover et al., 2020).

According to Deng et al. (2016), mesophilic anaerobic digestion (with internal temperatures between 30 and 35°C) affects the economic viability of biodigesters for organic matter degradation. However, most full-scale systems operate at ambient temperature, compromising treatment efficiency and biogas production (Sousa et al., 2022). Given this scenario, new alternatives have been proposed to optimize anaerobic reactors, such as effluent heating using internal and external sources. In this sense, solar energy presents itself as a viable alternative due to its sustainability and permanence.

Most research related to heating effluent takes place through bench studies (Cao et al., 2020; Chae et al., 2008; Deng et al., 2016) and mathematical modeling (Gunjo et al., 2017; Liu et al., 2017) for different configurations of anaerobic reactors. Using computational models for modeling and simulation of heating systems can benefit technical and economic feasibility studies and later large-scale implementation, reducing costs and achieving more effective results (Meister et al., 2017).

In Brazil, there are few studies on full-scale heating systems in covered lagoon biodigester models.

[1] Universidade Federal de Viçosa/Viçosa - MG, Brasil.

Area Editor: Gizele Ingrid Gadotti
Received in: 8-18-2022
Accepted in: 1-24-2023

Additionally, biodigester monitoring typically occurs only in terms of inlet and outlet temperatures, without considering heat exchanges between biodigesters and the external environment. CLBs are semi-submerged models with exposure to ultraviolet rays. Hence, the analysis of temperature behavior and heat exchanges between a reactor and its surrounding environment is of great relevance, as it allows for a more detailed study of interactions both inside and outside the system (Tápparo et al., 2021). This enables identifying operating conditions for systems that result in greater utilization of solar radiation, lower heat losses to the external environment, increased microbial activity rate, optimization of treatment, and selection of materials with more favorable thermal properties (Sousa et al., 2022).

The analysis of thermal exchanges with heated effluent in anaerobic reactors is a pioneering approach and can bring interesting discussions in the field of operational and construction aspects of covered lagoon-model biodigesters. Still, understanding the mechanisms and thermal exchanges of the biodigester with the interface environments is necessary (Mahmudul et al., 2021). Studies indicate that heating the effluent inside the biodigesters can increase biogas production, as well as reduce hydraulic retention time (HRT), eliminate pathogens, and ensure stability of biogas production throughout the year (Makamure et al., 2021). Therefore, studying heat transfers between internal and external components of biodigesters, considering the heated effluent, allows for assessment of whether the resident biomass is capable of maintaining temperature throughout the day, as well as quantifying rates of energy gain and loss between the heated effluent, biogas, soil, and external environment.

The objective of this work was to evaluate, through simulations, the thermal exchanges that occur in the internal and external environments of a covered lagoon biodigester, based on the influence of effluent heating through solar energy.

MATERIAL AND METHODS

Study site characterization

The study of thermal exchanges in covered lagoon biodigesters (CLBs) was conducted using data from a treatment system located in a pig farm in the municipality of Teixeiras, in the Zona da Mata of the state of Minas Gerais – Brazil. The location lies at 20° 34' 07.2" S latitude, 42° 52' 01.6" W longitude, 03:00 UTC window, 678-m altitude, and inclined 30° from the north-south direction. The wastewater treatment system consists of a distribution tank that receives incoming wastewater by gravity, which is directed to two CLBs operating in parallel. After treatment in the biodigesters, outgoing wastewater (digestate) is directed to a stabilization pond.

The biodigesters were constructed in an inverted pyramid trunk shape and lined with a flexible HDPE geocomposite of 1.25 mm thickness on the bottom and walls. They were covered with another blanket of the same material, creating a biogas reservoir of 1.0 mm thickness. Each biodigester had a volumetric capacity of 1,250 m³. Figure 1 shows the main dimensions of the biodigesters. The arrow indicates the flow of effluent inside the reactor. Biogas produced in the CLBs was converted to electrical energy using a generator with 120 kVA power, model GMWM120.

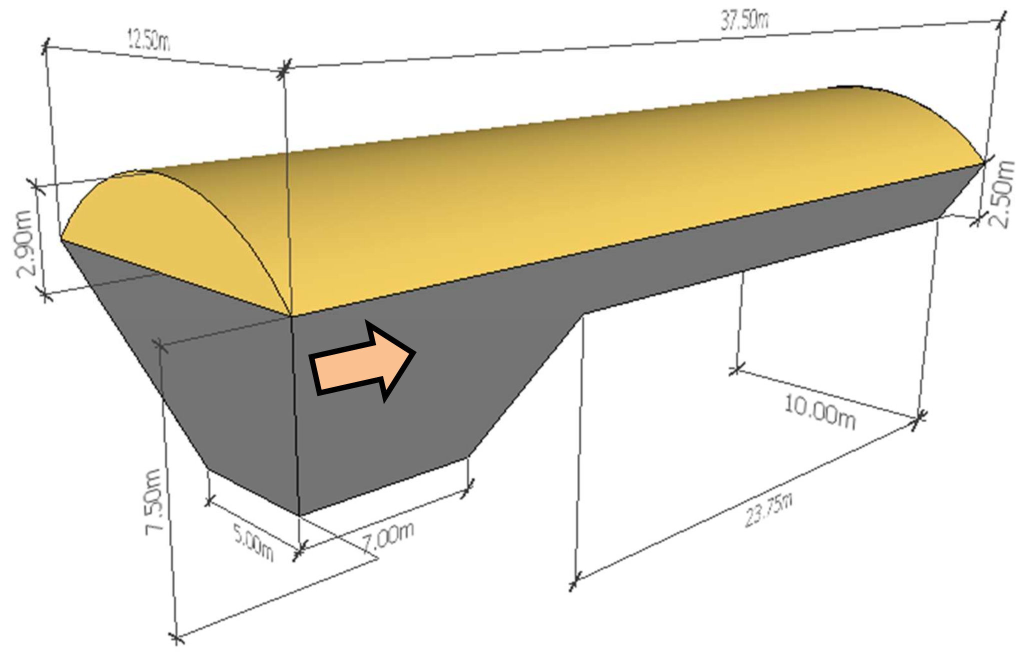

FIGURE 1**.** Details of the internal and external dimensions of the biodigesters.

Monitoring of effluent treatment system

The wastewater treatment station of the farm was also monitored in terms of temperature using 3-wire Pt100 sensors, with a PCA/S class B design. Sensor 1 (Figure 2) was located near the generator house and was used to monitor the external temperature. Sensor 2 was located 1 meter deep in the soil and near the first biodigester, monitoring soil temperature. Sensors 3 measured the temperature of the resident biomass and were located in the passage boxes next to the respective biodigesters. Sensor 4 was positioned between the two biodigesters to measure biogas temperature. Finally, sensors 5 were installed in the biodigester's exit boxes and measure the temperature of the effluent (digestate) at the exit. Figure 2 shows the representation of the wastewater treatment units in the farm and locations where temperature measurement sensors were installed.

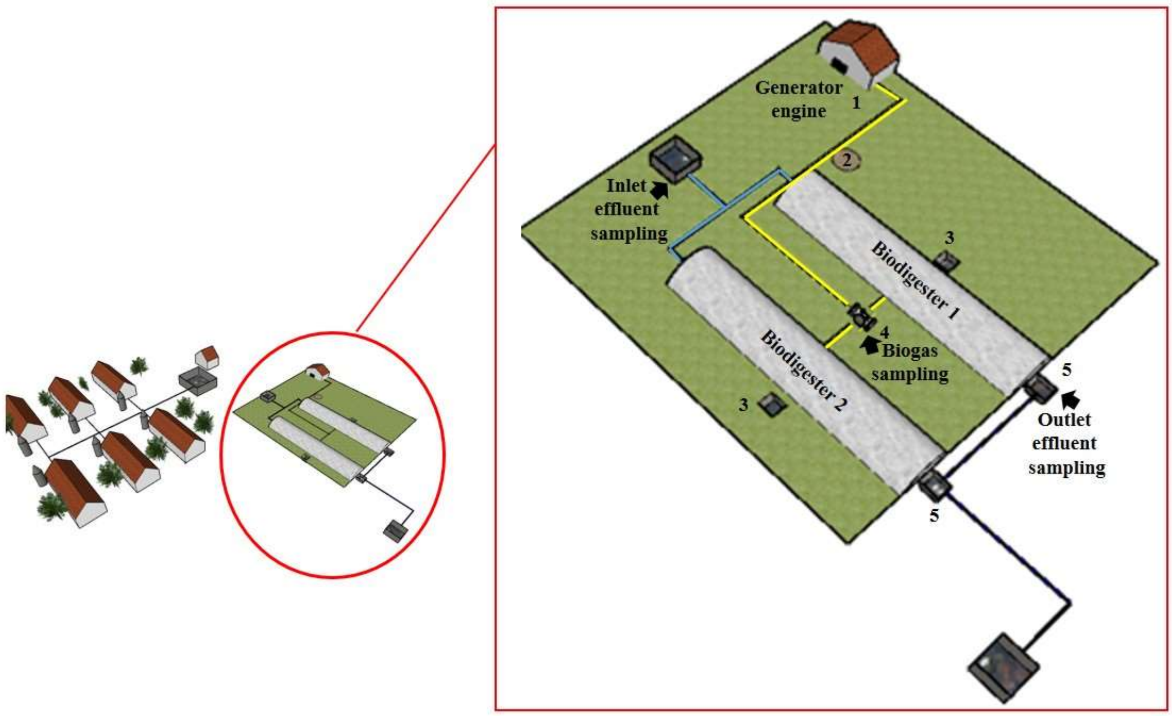

FIGURE 2. Schematic diagram of the effluent treatment station and location sites of the temperature sensors.
Source: Sousa et al. (2022). Temperature sensors: 1- Environment, 2- Soil, 3- Resident biomass, 4- Biogas, 5- Digestate
Line colors: effluent at the inlet/outlet biogas

Here, we monitored temperatures from January 2018 to December 2019. For this purpose, monthly average temperatures of the environment, soil, resident biomass, and biogas were considered to validate the biodigester simulation.

Biodigester modeling

Mathematical modeling was used to simulate thermal exchanges and heat transfer rates between the biodigester and internal and external environment, considering two scenarios: without heated effluent and with heated effluent. The proposal for heating the effluent considers the use of solar panels under optimized temperature conditions, as reported by Maradini (2021). Biodigester geometry was developed in the SketchUp software (version 17.2), while the modeling and simulation were performed simultaneously using the Energy Plus software (version 8.7) and the Legacy Open Studio plugin.

The input data for the biodigester simulation were: (i) climatic file and location of the study; (ii) soil temperature data; (iii) physical and thermal properties of soil, resident biomass, and biodigester building materials; and (iv) simulation run period. Hourly climatological data was extracted from the climatic file of Viçosa (Zona da Mata, Minas Gerais - Brazil), since a weather station is close to the rural area of Teixeiras, representing climate of the region.

Soil temperature data was obtained through sensors installed at the effluent treatment station on the farm. Measured values were tabulated and organized into monthly averages considering two simulation run periods: (i) hot period (Jan., Feb., and Mar./2018 and 2019) and (ii) cold period (Jun., Jul., and Aug./2018 and 2019). The numerical method described by Xing (2014) was selected to evaluate thermal exchanges between resident biomass and soil around biodigester.

Table 1 presents the thermal and physical properties of the biodigester building materials and internal and external components considering two scenarios: (i) saturated soil for the hot period; and (ii) dry soil for the cold period. In the Energy Plus software, each internal environment is considered a homogeneous thermal zone. This study considered two thermal zones, one for biogas and one for resident biomass, as this configuration provides a detailed and specific evaluation of temperatures and thermal exchanges of the two components separately. The same thermal physical properties were assigned to the surface separating the biogas zone and resident biomass zone.

TABLE 1. Physical and thermal properties of the biodigester building materials and internal and external components of the biodigester.

Physical properties	Components / Materials			
	Resident biomass	Saturated soil	Dry soil	Biodigester blanket
Thermal conductivity (W m^{-1} K^{-1})	0.58[1]	1.58[2]	0.25[2]	0.35[3]
Specific heat (J kg^{-1} K^{-1})	4186.80[1]	1550.00[2]	890.00[2]	1700.00[3]
Specific mass (kg m^{-3})	1040.00[1]	2000.00[2]	1600.00[2]	950.00[3]

References: [1](Almeida et al., 2017); [2](Oke, 2002); [3](DIN 52612 – 2).

The corresponding mass of biogas was not modeled in Energy Plus due to limitations of the software and due to having similar thermal-physical properties to air. The resident biomass inside the CLB was approximated as a uniform internal mass for the calculation of material's inertia effects. To model the internal heating of the effluent to reach the desired temperature of 30°C, considered an ideal value for the operation of biodigesters (Chae et al., 2008), a heating source was modeled inside the reactor with a power of 19900 W.

Energy budget

Thermal exchanges between the biodigester and its surrounding environment was assessed by analyzing heat flows between external environment, plastic cover (upper blanket), and biogas (q_1); between biogas and resident biomass (q_2); and between resident biomass and the soil (q_3) (Figure 3).

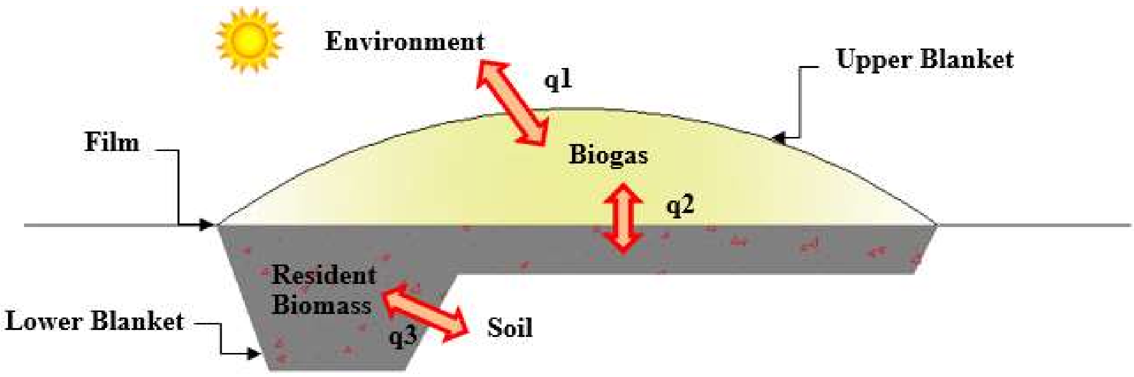

FIGURE 3. Schematic diagram of the thermal exchanges among biodigester, external environment, and soil.

Table 2 displays the main heat transfers between internal and external components of biodigesters, considering two scenarios: (i) reality and (ii) simulation. This is because certain assumptions were adopted in simulation, affecting the existing heat exchange. The main difference is that, in the model, resident biomass was regarded as a uniform internal mass without temperature gradient, whereas, in reality, it is a fluid in a liquid state.

TABLE 2. Thermal exchanges between internal and external components of biodigesters

Component	Heat exchange type	
	Reality	Simulation
Environment-Upper blanket	Radiation + Convection	Radiation + Convection **(q_1)**
Environment-Biogas	Radiation / Diffraction	Thermal radiation **(q_1)**
Upper blanket-Biogas	Radiation + Convection	Convection **(q_1)**
Biogas-Resident Biomass	Convection	Convection + Radiation **(q_2)**
Resident Biomass-Soil	Convection	Conduction + Radiation **(q_3)**

Main forms of heat transfer between external environment and biodigester are solar radiation and convection (q_1), while energy exchange between soil and resident biomass in reactor mainly occurs through convection (reality) or conduction (simulation) and thermal radiation (q_3). Finally, biogas and resident biomass exchange heat through convection and thermal radiation (q_2).

The upper blanket of the biodigester is primarily heated by incident solar radiation. However, heat exchange also occurs between the blanket and external air through convection, as air temperature varies temporally within the domain. Then, the blanket exchanges heat with the biogas inside the reactor through convection. Additionally, some of the solar radiation that strikes the dome undergoes diffraction and reaches the biogas, heating it. In this study, we admitted a direct heat exchange between the biogas and resident biomass through convection and thermal radiation. This is because the same thermal physical properties of the resident biomass were adopted for the separation surface between both zones. Heat exchange also occurs between the resident biomass and soil through conduction (simulation) and thermal radiation. The model allowed us analyzing the temperature behavior of the environment, biogas, resident biomass, and soil, as well as quantifying heat transfer rates between internal and external components of biodigester.

Simulation validation

For simulation validation, a statistical analysis was performed comparing the simulated data in the scenario without heating to the experimental data obtained through temperature monitoring in real scale. The validated values were the temperatures of the environment, biogas, resident biomass, and soil.

Root mean square error (RMSE) and root mean square relative error (RMSRE) were adopted as performance indicators (Equations 1 and 2). Results closer to zero indicate better performance of the models and better validation fit (Hallak & Pereira, 2011).

$$RMSE = \sqrt{\frac{\sum_{i}^{n}(Y_i - X_i)^2}{n}} \quad (1)$$

$$RMSRE = \sqrt{\frac{\sum_{i}^{n}(Y_i - X_i)^2}{n}} \times \frac{100}{\bar{X}} \quad (2)$$

Where:

Y: simulation value;

X: observed value;

n: number of analyzed values;

RMSE: root mean square error;

RMSRE: root mean square relative error;

$\bar{X}$: mean of observed values.

RESULTS AND DISCUSSION

Simulation validation

Table 3 shows the results of performance indicators for average hourly temperatures of the environment, biogas, resident biomass, and soil obtained by the model, considering the scenario without heating, and compared to temperatures measured by sensors installed in the effluent treatment unit of the farm. The temperature results obtained by the simulation are from the climate file used in the model. The evaluation was conducted for the hot and cold periods.

TABLE 3. Performance indicators for different temperature profiles and considering hot and cold periods.

Temperature / Period	**Environment**		**Biogas**		**Resident biomass**		**Soil**	
	Hot	Cold	Hot	Cold	Hot	Cold	Hot	Cold
RMSE (°C)	4.10	1.75	8.10	4.20	6.80	1.90	7.30	0.20
RMSRE (%)	16.20	10.10	29.00	24.60	25.70	9.00	26.00	1.10

RMSE: root mean square error; RMSRE: root mean square relative error.

Overall, simulated results were closer to monitored data in the cold period (Table 3). Soil temperature during the cold period was the most reliable (1.10%), while biogas temperature during the hot period was the furthest from actual values (29.00%). There was no homogeneity between hot and cold periods, and the results regarding resident biomass and soil showed the greatest discrepancies between the periods. In sum, the values were consistent with those reported in the literature (Leonzio, 2018; Liu et al., 2017).

In general, errors cannot be associated with the model since the simulated environmental temperature came from the climate file, hence independent of the geometry, and it did not show such large discrepancies compared to other parameters. Thus, discrepancies between simulated and monitored data are likely associated with difficulties inherent in real-scale studies, as there are external sources that can compromise data accuracy such as measurement failures, sensor irregularities, and model limitations (Meister et al., 2017).

Another aspect to consider is that the representative year that makes up the climate file is obtained through a statistical treatment of a time series of meteorological data, while the actual data used in this study were obtained by the average of the data measured in the years 2018 and 2019, making them more sensitive to climatic variations.

Energy budget

Figure 4 shows the variations in the average temperatures of the environment and biogas obtained from the simulation and the behavior of heat flow between the environment, the upper blanket of the biodigester, and the biogas, considering hourly averages for the warm (a) and cold (b) periods in the scenario without heating and warm (c) and cold (d) periods for the scenario with heating.

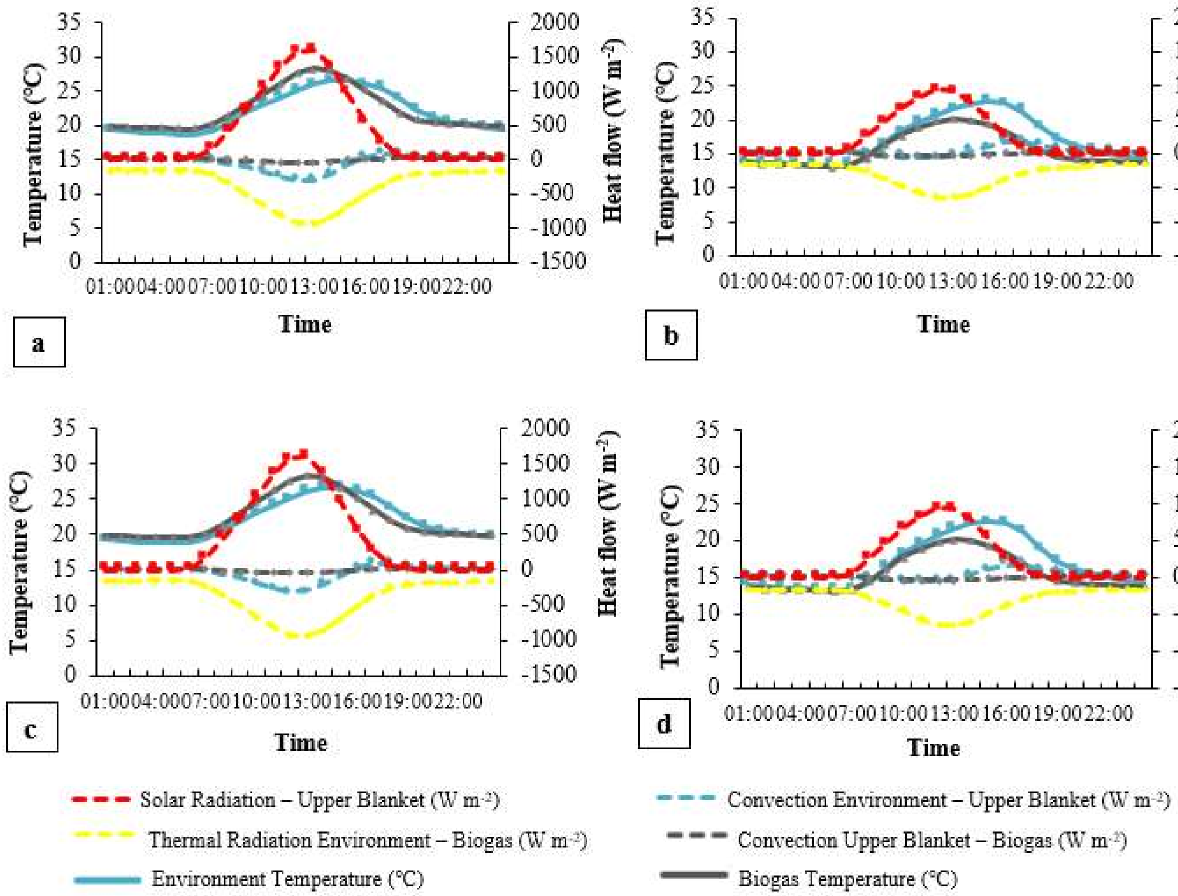

FIGURE 4. Variation in temperature of the environment and biogas, and heat flow (q_1) from hourly averages for hot (a) and cold (b) periods in the scenario without heating and for hot (c) and cold (d) periods in the scenario with heating.

Figure 4 demonstrates that the heat flow does not change when evaluating between the scenarios with and without heating in the respective hot and cold periods. The upper blanket is heated by direct solar radiation during the day, with a maximum heat transfer rate by direct solar radiation of 41% higher in the hot period (1593.6 W m^{-2}) than in the cold period (945.7 W m^{-2}) due to the higher incidence of solar radiation in the months related to the hot period. The results show that solar radiation is the primary source of heating for the covered lagoon biodigesters.

The environment also exchanges heat with the biodigester's upper cover through convection. During the day, the cover loses heat to the environment, while at night the heat exchange is reversed, since due to the low thermal inertia of the cover's construction material and the high incidence of solar radiation during the day, the cover has a temperature that is more pronounced in relation to the external environment, so as to give off heat to the environment and reach thermal equilibrium. In the hot period, the maximum heat transfer rate from the environment to the cover (-310.1 W m^{-2}) is about 71% greater than the heat transferred from the cover to the environment (90.1 W m^{-2}); while in the cold period, the maximum heat transfer rate from the cover to the environment (175.2 W m^{-2}) is 68% greater than the heat transferred from the environment to the cover (-56.1 W m^{-2}). Thus, the cover gains more heat in the hot period and loses more heat in the cold period, coinciding with the result of radiation.

The heat transfers between biogas and upper blanket and between biogas and the outside environment happen through both convection and thermal radiation, respectively. During the day, the blanket loses heat to biogas and, at night, it receives heat from biogas. In hot conditions, the maximum heat transfer rate from the upper blanket to biogas is 39% higher (-41.6 W m^{-2}) than that from biogas to the upper blanket (25.4 W m^{-2}). In cold conditions, the maximum heat transfer rate from the upper blanket to biogas is 24% higher (-31.4 W m^{-2}) than that from biogas to the blanket (23.8 W. m^{-2}). Biogas only receives heat from the sun that has been converted into thermal radiation by the blanket. The maximum values were -942.0 W m^{-2} and -648.8 W m^{-2} during the hot and cold periods, respectively.

The temperatures of the surrounding air in the scenarios with and without heating showed similar maximum values for the hot (26.6°C) and cold (22.6°C) periods. A similar behavior was noted for biogas temperatures in both scenarios, with maximum values of 28.3°C in the hot and 20.2°C in the cold periods. Both environment and biogas temperatures are strongly influenced by the weather conditions that biodigesters are susceptible to, leading to variations throughout the day (Mahmudul et al., 2021). Such a behavior of biogas temperature was also observed by Hreiz et al. (2017), who analyzed a temperature range of up to 10°C throughout the daily cycle.

Figure 5 exhibits the average temperature variation plots for resident biomass and soil obtained by simulation. The plots also display the heat flow pattern among biogas, resident biomass, and soil. They were plotted using hourly averages for the hot (a) and cold (b) periods in the scenario without heating, as well as hot (c) and cold (d) periods in the scenario with heating.

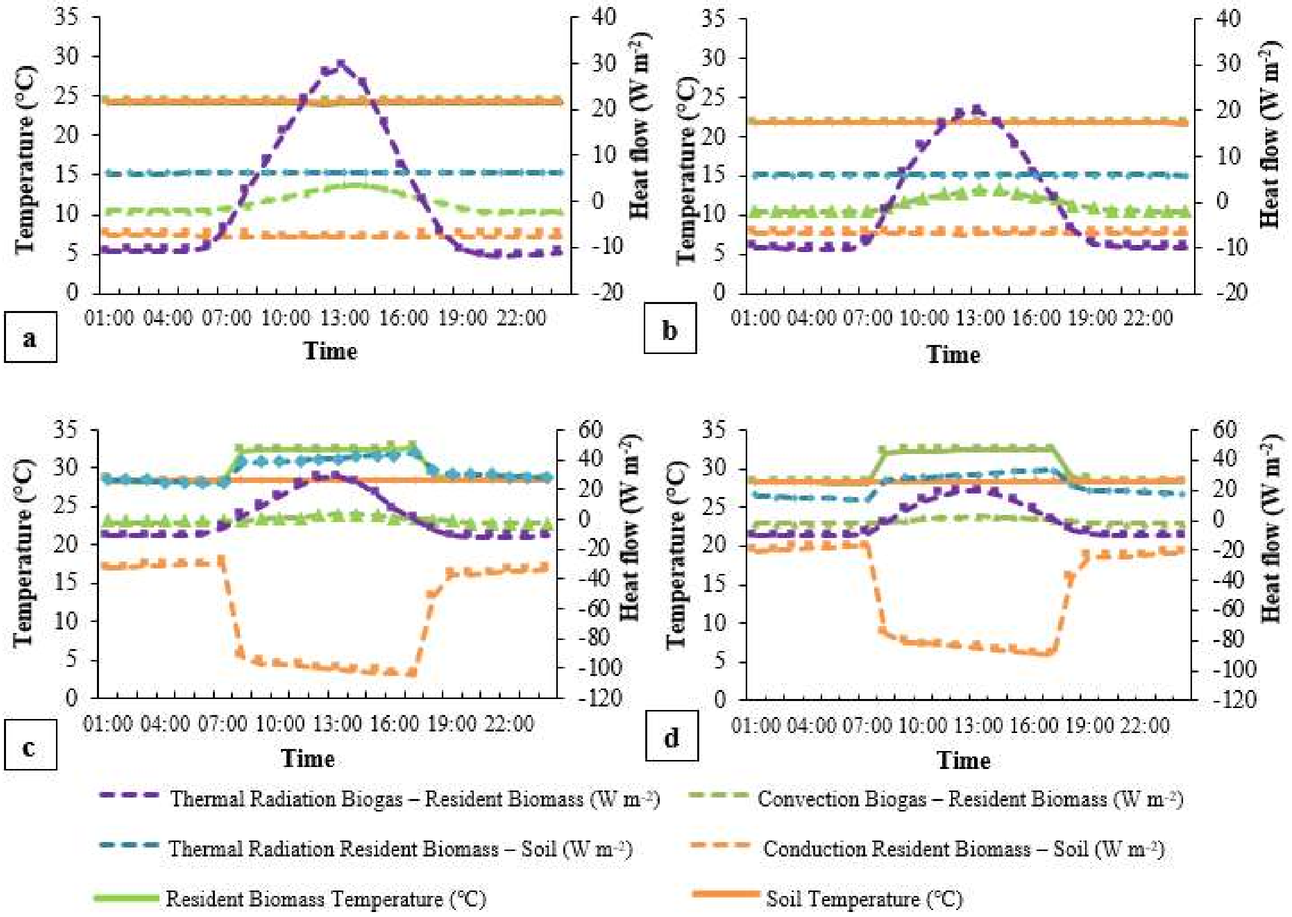

FIGURE 5. Temperature variation for resident biomass and soil, and heat flows (q_2 and q_3), from hourly averages for hot (a) and cold (b) periods in the scenario without heating, and hot (c) and cold (d) periods in the scenario with heating.

The items in Figure 5 display different behaviors between the scenarios with and without heating, with heat transfers being stronger under heating conditions. It should be noted that heat flow ranges have different maximum and minimum limits between both scenarios

Biogas exchanges heat with resident biomass through convection and thermal radiation. During the day, the biogas loses heat to the resident biomass through convection, with maximum values of 3.4 W m^{-2} and 2.4 W m^{-2} in the hot and cold periods, respectively. At other times of the day, the biogas receives heat from the resident biomass, with maximum values of -2.2 W m^{-2} and -2.1 W m^{-2} in the hot and cold periods. The values of heat losses and gains were similar, so a thermal balance between the two components can be assumed throughout the day, especially in the cold period. These relationships and values were equal for both the studied scenarios (with and without heating).

Heat is exchanged between biogas and resident biomass through radiation. During the day, biogas releases heat to the resident biomass and receives heat at night, with a maximum rate of 29.9 W m^{-2} between biogas and resident biomass, which is 60% greater than the heat transferred from resident biomass to biogas (-11.8 W m^{-2}) in the hot period. During the cold period, heat transfer rate was 48% greater between biogas and resident biomass (19.9 W m^{-2}) than from resident biomass to biogas (-10.4 W m^{-2}). These relationships and values were the same for both the heated and unheated scenarios.

Heat exchange between biogas and resident biomass was stronger through radiation than convection. Notably, heat transfer rates between the environment, upper blanket, and biogas were significantly higher than those between biogas and resident biomass. This result might be due to biogas forming a highly insulating layer for heat transfer, as well as the large thermal capacity of resident biomass and its high response time to changes in climatic conditions outside the biodigester (Amaral et al., 2022).

Resident biomass, in turn, exchanges heat with soil through conduction and thermal radiation. Regarding conduction, values were negative for the entire day, thus resident biomass loses heat to the soil, whether under heated and unheated conditions, and for both periods studied (hot and cold). In the scenario without heating, values showed small variations throughout the day, with maximum values of -7.9 W m^{-2} and -6.8 W m^{-2} in the hot and cold periods. In the heating scenario, results varied with the studied period when effluent was hotter, as heating source was programmed to run from 07:00 to 17:00. In the hot period, maximum heat flow was -104.6 W m^{-2}, while in the cold period it was -89.7 W m^{-2}. In both scenarios (with and without heating), heat transfer rates in the hot period were, on average, about 14% higher than in the cold period; therefore, soil saturation does not have a significant influence on heat exchanges with resident biomass.

Heat exchanges between resident biomass and soil by radiation showed positive values. Thus, resident biomass loses heat to soil both in the heating and non-heating scenarios and for both periods studied (hot and cold). Heat exchange by conduction has a similar behavior, as in the non-heating scenario, values showed lesser variations throughout the day, with maximum values of 6.43 W m^{-2} and 6.0 W m^{-2} in the hot and cold periods. In the heating scenario, results varied with periods when effluent was hotter. Therefore, maximum heat flow was 43.9 W m^{-2} in the hot period and 33.7 W m^{-2} in the cold period. Heat exchange by conduction between resident biomass and soil was more intense than heat exchange by radiation, especially in the heating scenario.

The soil temperature in both scenarios (with and without heating) for the hot and cold periods showed a linear behavior with small variations throughout the day. In the scenario without heating, average temperature was about 24.3°C for the hot period and 21.9°C for the cold period. On the other hand, in the scenario with heating, average temperature was about 28.4°C for both hot and cold periods, hence the soil receives heat from the heated resident biomass.

Biomass temperature showed a linear behavior in the scenario without heating. The results were very close to soil temperatures in the same scenario, with an average of 24.2°C during the hot period and 21.9°C in the cold period. In the heating scenario, however, temperatures were higher during the day, with averages of 32.5°C, and, at other times of the day, they averaged 28.4°C during both hot and cold periods. Vaz et al. (2020) evaluated the influence of automation on the same CLB using heating of the effluent and internal recirculation processes through Computational Fluid Dynamics (CFD). These authors observed an increase in velocity gradient in the CLB from 0.210 s^{-1} (without heating) to 1.747 s^{-1} (with heating), as well as a greater thermal amplitude for resident biomass in the scenario with heating, which was also reiterated in our study.

The relationship between heating and increased temperature in resident biomass was also reported by Hreiz et al. (2017) . This behavior is justified by the high thermal inertia of the material, which results in small and slow temperature variations over time. Such characteristic is essential for the proper functioning of biodigesters, as it prevents abrupt temperature fluctuations within reactors and allows maintaining metabolic activities of the anaerobic bacteria in degradation process (Amaral et al., 2022).

Resident biomass and soil temperatures were very similar, especially in the scenario without heating. This is because soil is responsible for maintaining temperature inside biogas reactors, due to its high thermal inertia (Souza et al., 2011). A similar behavior was observed in Vietnam (Pedersen et al., 2020) for unheated and insulated biogas reactors. The study showed that resident biomass temperature was driven by the temperature in the surrounding soil, but the main source of heat for maintaining internal temperature was solar radiation. Furthermore, the authors of that study identified that in heated biogas reactors, energy flow was predominantly from the horizontal movement of heat mass exchanges between heat exchanger and resident biomass.

Additionally, resident biomass temperature was able to reach and stabilize at 30°C, which is considered ideal for bioreactor operation, even after thermal exchanges with biogas and soil. Thus, an external source to increase resident biomass temperature, such as the sun, is an alternative to optimize operation of bioreactors and maintain their internal temperature in response to fluctuations in the environment and solar radiation (Wang et al., 2017).

CONCLUSIONS

The study of thermal exchanges in heated anaerobic reactors is still an incipient approach, particularly in Brazil, making our results of paramount importance for optimizing the operation of covered lagoon biodigesters. For instance, by selecting materials for construction and improvements in energy flow inside and outside the reactors.

Our findings showed that solar radiation is the primary heating source for the biodigesters, and the high thermal inertia of the soil contributes to the low variation in resident biomass temperature throughout the day, even in the scenario with heated effluent.

Biogas exchanges heat with the external environment through solar radiation, convection, and thermal radiation, thus exhibiting similar behavior to the ambient temperature with high daily amplitudes. It also exchanges heat with resident biomass through convection and thermal radiation, but heat transfers between these two components were much lower than those between it and the external environment. Moreover, thermal exchanges among biogas, resident biomass, and external environment were the same in scenarios with and without heating.

On the other hand, heat exchanges between resident biomass and soil were different in the scenarios with and without heating. Resident biomass and soil exchange heat through conduction and thermal radiation, with higher heat transfer rates in the scenario with heating, due to a larger thermal difference between them. Furthermore, conductive exchanges were more intense than radiative exchanges, especially in the scenario with heating.

Finally, in the scenario with heating, even after thermal exchanges with biogas and soil, resident biomass temperature is able to reach and stabilize at 30°C, which is considered an ideal temperature for biodigesters.

ACKNOWLEDGEMENTS

This work was supported by the Coordination for the Improvement of Higher Education Personnel of Brazil (CAPES) - Finance Code 001; the National Council for Scientific Technological Development of Brazil (CNPq) - process number 132402/2019-0 and Minas Gerais Research Foundation (FAPEMIG) grant number APQ-01576-22.

REFERENCES

Adrover ME, Cotabarren I, Madies E, Rayes M, Reartes SBR, Pedernera M (2020) Anaerobic co-digestion of rabbit manure and sorghum crops in a bench-scale biodigester. Bioresources and Bioprocessing 42(7):1-12.

Almeida C, Bariccatti RA, Frare LM, Nogueira CEC, Mondardo AA, Contini L, Gomes GJ, Rovaris SA, Santos KG, Marques F (2017) Analysis of the socio-economic feasibility of the implementation of an agro-energy condominium in western Paraná – Brazil. Renewable and Sustainable Energy Reviews 75:601–608.

Amaral AC, Steinmetz RLR, Kunz A (2022) Biodigesters. In: Kunz A, Steinmetz RLR, Amaral AC. Fundamentals of anaerobic digestion, biogás purification, use and treatment of digestate. Concordia, Sbera, Embrapa Suínos e Aves, p.41-68.

Cao L, Keener H, Huang Z, Liu Y, Ruan R, Xu F (2020) Effects of temperature and inoculation ratio on methane production and nutrient solubility of swine manure anaerobic digestion. Bioresource Technology 299:1-32.

Chae KJ, Jang AM, Yim SKE, Kim IS (2008) The effects of digestion temperature and temperature shock on the biogas yields from the mesophilic anaerobic digestion of swine manure. Bioresource Technology 99:1-6.

Cheng DL, Ngo HH, Guo WS, Chang SW, Nguyen DD, Kumar SM, Du B, Wei Q, Wei D (2018) Problematic effects of antibiotics on anaerobic treatment of swine wastewater. Bioresource Technology 263:642-653.

Deng L, Chen C, Zheng D, Yang H, Liu Y, Chen Z (2016) Effect of temperature on continuous dry fermentation of swine manure. Journal of Environmental Management 177:247-252.

DIN (1984) Tesing of thermal insulating materials; determination of thermal conductivity by means of the guarded hot plate apparatus; conversion of the measured values for building applications. In: DIN 52612-2. Available: https://standards.globalspec.com/std/171082/DIN%2052612-2. Accessed May 15, 2020.

Gunjo DG, Mahanta P, Robi PS (2017) CFD and experimental investigation of flat plate solar water heating system under steady state condition. Renewable Energy 106:24-36.

Hallak R, Pereira AJ (2011) Metodologia para análise de desempenho de simulações de sistemas convectivos na região metropolitana de São Paulo com o modelo ARPS: sensibilidade a variações com os esquemas de advecção e assimilação de dados. Revista Brasileira de Meteorologia 26(4):591–608.

Hreiz R, Adouani N, Jannot Y, Pons MN (2017) Modeling and simulation of heat transfer phenomena in a semi-buried anaerobic digester. Chemical Engineering Research and Design 119:101-116.

Leonzio G (2018) Study of mixing systems and geometric configurations for anaerobic digesters using CFD analysis. Renewable Energy 123:578-589.

Liu Y, Chen Y, Li T, Wang D, Wang D (2017) Investigation on the heat loss characteristic of underground household biogas digester using dynamic simulations and experiments. Biosystems Engineering 163:116-133.

Makamure F, Mukumba P, Makaka G (2021) An analysis of bio-digester substrate heating methods: A review. Renewable and Sustainable Energy Reviews 137:1-8.

Mahmudul HM, Rasul MG, Akbar D, Narayanan R, Mofijur M (2021) A comprehensive review of the recent development and challenges of a solar-assisted biodigester system. Science of the Total Environment 753:1-24.

Maradini PS (2021) Implicações do aquecimento de efluentes de suinocultura na eficiência energética e termodinâmica em biodigestores modelo lagoa coberta. Mestrado, Universidade Federal de Viçosa, Engenharia Agrícola.

Meister M, Rezavand M, Ebner C, Pümpel T, Rauch W (2017) Mixing non-Newtonian flows in anaerobic digesters by impellers and pumped recirculation. Advances in Engineering Software 115: 194-203.

Náthia-Neves G, Berni M, Dragone G, Mussato SI, Forster-Carneiro T (2018) Anaerobic digestion process: technological aspects and recent developments. International Journal of Environmental Science and Technology 15:2033-2046.

Oke TR (2002) Boundary layer climates. Oxfordshire, Taylor & Francis e-Library, v1:435p.

Pedersen SV, Martí-Herrero J, Singh AK, Sommer SG, Hafner SD (2020) Management and design of biogas digesters: A non-calibrated heat transfer model. Bioresource Technology 296:1-10.

Sousa IP, Rosa AP, Lopes JO, Magos BR, Cecon PR, Perez R, Borges AC (2022) Study of internal and external temperatures and their influence on covered lagoon digester performance. Biomass and Bioenergy 159:106380.

Souza HA, Amparo LR, Gomes P (2011) Influência da inércia térmica do solo e da ventilação natural no desempenho térmico: um estudo de caso de um projeto residencial em light steel framing. Ambiente Construído 11:113–128.

Tápparo DC, Cândido D, Steinmetz RLR, Etzkorn C, Amaral AC, Antes FG, Kunz A (2021) Swine manure biogas production improvement using pre-treatment strategies: Lab-scale studies and full-scale application. Bioresource Technology Reports 15:1-8.

Vaz PN, Oliveira DF, Martins MA, Carlo JC, Rosa AP, Mendes EMAM (2020) Computational fluid dynamics simulation of thermodynamic behaviour of tubular digester. IFAC PapersOnLine 53:15829-15834.

Wang C, Lu Y, Hong F, Li X, Zeng X, Lu H (2017) Two-phase anaerobic digester combined with solar thermal and phase change thermal storage system in winter. Energy Fuels 31:4003-4012.

Xing LU (2014) Estimations of undisturbed ground temperatures using numerical and analytical modeling. PhD Thesis, Oklahoma State University, Philosophy.