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Effect of Heating Strategy on Power Consumption and Performance of a Pilot Plant Anaerobic Digester

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Abstract The effect of heating strategy on power consumption and performance of a pilot plant anaerobic digester treating chicken litter, under thermophilic conditions, has been studied. Heating strategy was evaluated using three different spans (0.2 °C, 0.6 °C, and 1.0 °C) for triggering the temperature control system from target temperature (56.7 °C). The hydraulic retention time in the pilot plant digester was in the range of 32 to 37 days, varying the total solids concentration fed from 5% to 6%. The results showed that under the experimental conditions, heating was the most energy-demanding process with 95.5% of the energy used. Increments up to 7.5% and 3.8%, respectively, on mechanical and heating power consumption, were observed as the span, for triggering the temperature control system from target temperature, was increased. Under the experimental conditions studied here, an increment of 30.6% on the global biodigester performance index was observed when a span of 1.0 °C was compared to the one of 0.2 °C.

Keywords Temperature control · Chicken litter · Pneumatic agitation · Biogas mixing · Heat transfer coefficient

Introduction

The performance of anaerobic digestion process depends on several factors, such as feed chemical composition, microbial population present in the reactor and also in the feed, organic loading rate, feed frequency, temperature, digester geometry, and hydraulic

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retention time, among others. In the case of thermophilic anaerobic digestion, one of the key parameters that have to be considered to account for process stability is temperature. Several research groups have reported that changes in temperature could affect the biogas production [1–3]. Any increment or reduction from optimal temperature implies a reduction in the biogas production. For a pilot plant anaerobic digester, under thermophilic conditions, our research team [4] reported that bioreactor temperatures between 56.7 °C and 60 °C produced a similar biogas yield. In that work, it was also reported that in the range from 52.2 °C to 56.7 °C, a temperature reduction diminishes methane production at a rate of 11.1%/°C. A similar trend was reported by Lübken et al. [5]. These authors used the Anaerobic Digestion Model # 1, in order to evaluate the changes in biogas production, using sludge as a substrate; they reported that in the range from 50 °C to 55 °C, the reduction of yield as temperature diminished occurred at a rate of 6%/°C.

In order to accomplish a constant temperature in anaerobic digesters, heat transfer is achieved by configurations such as internal loops, jacketed tanks, and external heat exchangers. In that context, mixing plays an important role, enabling homogeneity of the medium in terms of chemical composition and temperature; thus, steady-state conditions for biogas production could be achieved. Consequently, a poor mixing could lead to a reduction in the biogas production and the introduction of process instabilities. Several strategies have been used in order to satisfy the homogeneity inside a bioreactor, which include stirring and pumping of the digestate, as well as biogas recycling.

In the pilot plant used by our research team [6], mixing was achieved by pumping digestate and recycling biogas. In that particular case, temperature control had a narrow span (0.1 °C) between the target and the tank temperatures. Under that heating strategy, pumping digestate and biogas recycling took place in around 11 and 3.5 h, respectively, in a 24-h period. As a result, in a day, the material inside the tank was recycled almost six times and, consequently, the digestate was exposed to mechanical stress due to pumping. It is believed that this period of time was so long and could lead to a detriment in the performance of the process due to consortia aggregates could be exposed to intermittent mechanical stress. Thus, the hydrodynamics imposed in the process could have an important influence on biodigester performance. In fact, it has been reported that an excessive mixing by pumping could compromise the bioreactor performance for methane production [7]. Thus, the overall objective of this study was to evaluate whether heating strategy in a thermophilic anaerobic pilot plant, using chicken litter as a feed, can modify power consumption and whether these changes are reflected in the biogas production of the biodigester.

Materials and Methods

The feedstock for the experiments was poultry litter (manure, feathers, and wood chips) from wood chip based bedding, delivered to the site from a commercial broiler producer in Moorefield, WV, USA. The litter as delivered contained 70% totals solids (TS). It was diluted with freshwater to achieve a TS concentration of 5.5% to prepare feed slurry for the biodigester. That particular TS concentration was selected in order to avoid possible obstruction in the heat exchanger. Feed and effluent samples were taken once per day. Volatile solids (VS) and TS were determined with the standard methods for the examination of water and wastewater [8]. The chemical oxygen demand (COD) was analyzed with Method 8000 reported in the Hach Water Analysis Handbook [9]. Table 1 shows the characteristics of the feed used in the experiments; each deadband (interval between heating

Table 1 Characteristics of diluted manure used in experiments.

Device or source	Treatment (deadband used)		
	0.2 °C	0.6 °C	1.0 °C
Feed (L)	752.4 a	801.8 a	872.4 a
TS (%)	6.0 a	5.2 a	5.0 a
VS of TS (%)	76.1 a	73.1 a	72.1 a
COD (mg L^{-1})	57,933 a	45,967 a	46,544 a

Treatments with letters in the same row showed significant statistical difference (α=0.05)

TS total solids, *VS* volatile solids, *COD* carbon oxygen demand

event cessation and initialization) represents a treatment. During the experiments, a total of 752.4–872.4 L was loaded per day, resulting in hydraulic retention times of 32 to 37 days. The TS ranged from 5.0% to 6.0%, while the percentage of VS varied from 72.1% to 76.1%. As a result, the average COD in the feed was 50,148 mg L^{-1}. That indicates that all the treatments were fed with similar diluted manure. Consequently, differences among treatments could be attributed to the changes in heating strategy.

Experiments were conducted in the summer of 2006 on a 40-m^3 anaerobic biodigester located on the campus of West Virginia State University, in Institute, WV, USA. Figure 1

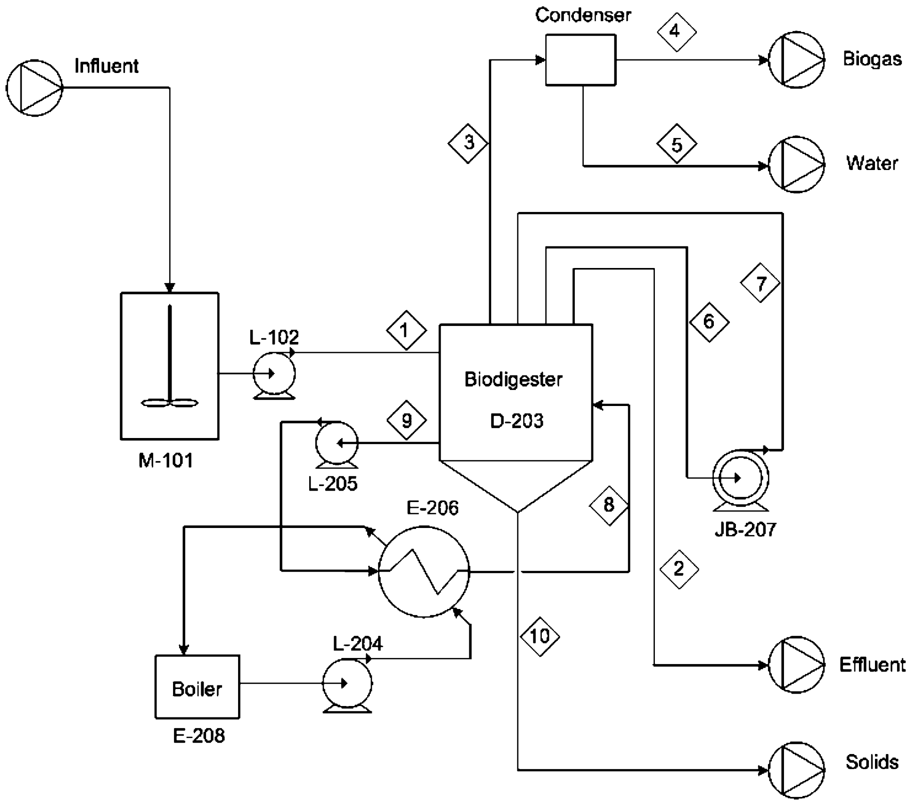

Fig. 1 Process diagram of the thermophilic anaerobic pilot plant

shows the experimental setup of the pilot plant used. The target of the digester temperature was selected based on a previous report of our research group [4], where 56.7 °C was considered the optimal value for the pilot plant used in this research. The numbers displayed in flags, in Fig. 1, represent the main paths, known as currents, of the process. The material that flows through each current is as follows: (1) feed, (2) effluent, (3) mixture of biogas and water, (4) biogas, (5) water, (6) and (7) recycled biogas, (8) and (9) recycled digestate, and (10) solids.

A computer-controlled submersible Flygt chopper pump automatically loaded feed slurry into the biodigester once every hour. The cylindrical biodigester (D-203) has a 4.2 m in diameter and 3.5 m in high, with a conical form at the bottom of the tank (0.90 m high and angle of 70° respects to the horizontal reference). It was kept at a working volume of 27.43 m^3. The digestate was heated by an external shell and tube heat exchanger (E-206) and a Gorman Rupp T-Series recirculation pump (L-205). The biodigester liquid was pumped through the tubes of E-206 and back into the tank, while a heated glycol/water mixture (70 °C), used as heating medium, was pumped through the shell of E-206 by L-204, the boiler loop recirculation pump. Both the boiler and digester recirculation pumps were computer controlled. Heating occurred when the biodigester internal temperature, measured by an internal thermocouple, dropped to preset intervals below target temperature. Biogas from the headspace was pulled by a blower (JB-207) through a mixing ring located at the base of the tank for 5 min each hour.

Biogas was discharged from the biodigester by differential pressure when internal pressure exceeded 10 in. water column. Biogas was then cooled to remove water prior to flow and composition measurement. A Coriolis (Emerson, #CMF025M319NABAEZZZ) mass flowmeter measured biogas discharge from the tank. Biogas composition was measured with an online Hewlett-Packard Gas Chromatograph (Model 5890) once per hour. Online pH, temperature, and biogas flow were recorded into a computer database every 5 min. The digester pH was monitored with an online Omega pH probe. Motor power consumption of each device was evaluated at a sampling rate of 0.5 s, using Watt transducers (Omega, OM10 series). Signals were acquired and processed using a data acquisition system (National Instruments, NI-DAQ7, NI 4351, and NI 4350) and a data logger (National Instruments, NI VI Logger).

Overall heat transfer coefficients of heat exchanger (U_{he}) and tank (U_t) were evaluated using the Eq. 1, which is the result of applying an energy balance [10] to the system reported in Fig. 1. In this equation, the subscript numbers refer to the corresponding currents as presented in Fig. 1. The subscript letters *d*, ref, he, lm, *t*, and env refer, respectively, to the digestate, reference, heat exchanger, logarithmic mean, tank, and environment.

$$m_d \mathrm{Cp}_d \frac{\mathrm{d}T_d}{\mathrm{d}t} = \dot{m}_1 \mathrm{Cp}_1 (T_1 - T_{\mathrm{ref}}) - \dot{m}_2 \mathrm{Cp}_2 (T_2 - T_{\mathrm{ref}}) - \dot{m}_4 \mathrm{Cp}_4 (T_4 - T_{\mathrm{ref}}) - \dot{m}_5 h_5^{\mathrm{sat}} - \dot{m}_{10} \mathrm{Cp}_{10} (T_{10} - T_{\mathrm{ref}}) + U_{\mathrm{he}} A_{\mathrm{he}} \Delta T_{\mathrm{lm}} + \dot{m}_8 \left(\frac{P_9 - P_8}{\rho_d} \right) + \dot{m}_6 \left(\frac{P_7}{\rho_7} - \frac{P_6}{\rho_6} \right) - U_t A_t (T_d - T_{\mathrm{env}}) \quad (1)$$

Specific heat capacity (Cp) of the liquids, expressed in J kg^{-1} °C^{-1}, was determined by Eq. 2 [11]; the prediction was based on the solids mass fraction (X_s).

$$\mathrm{Cp} = 0.837 + 3.349(1 - X_s) \quad (2)$$

The Cp for biogas was calculated considering the pondered contribution of its CH_4, CO_2, and H_2O mass fractions. The corresponding individual Cp of the mentioned components for the operation temperature (329.75 K) were 2,340.6, 873.9 and 4,186, respectively; all of them were expressed in J kg^{-1} $°C^{-1}$ [12].

The pilot plant had been running at steady-state conditions for 6 months prior to the experiment. Thus, it is possible to attribute the changes in performance exclusivity to the control temperature strategy applied. Between treatments, a period of 8 days was taken to reach a new steady-state condition. The experiment measured the effect of the heating initialization deadband on biodigester power consumption and specific methanogenic activity. The final 3 days of each experiment were used as replicates. It means that for statistical analysis, an experimental unit was considered to be one 24-h period of continuous operation. Analysis of variance was performed using SAS© (version 9.1). When the analysis of variance showed differences among treatments, a Tukey test (α=0.05) was performed to compare means.

Results and Discussion

In all the treatments, methane percentage and pH were around 61% and 7.7, respectively (Table 2), which is an indicator that experimental conditions of the thermophilic anaerobic digestion process were practically stable along the experiments. Under such conditions, the overall heat transfer coefficient of the heat exchanger varied from 1,636.8 to 2,042.0 W m^{-2} $°C^{-1}$. In the case of the overall heat transfer coefficient from the digester to the surroundings varied from 1.4 to 2.4 W m^{-2} $°C^{-1}$ (Table 2); these results indicate that the insulation of the tank is adequate for the evaluated environmental conditions. In Table 2, it could be observed that operation times of the pump L-205 and the blower JB-207 have the trend to increase as the deadband expands.

Figure 2 shows temperature changes inside the bioreactor during the experiments, including the inferior and superior limits of the deadband and the mean temperature in each treatment. A positive slope of the temperature curve indicates that heating is taking place, while a negative one is related to cooling. Thus, an inferior peak indicates the beginning of heating and a consecutive superior one, the cessation of that. It is important to point out that

Table 2 Operation conditions under different temperature control strategies.

Parameter	Treatment (deadband used)		
	0.2 °C	0.6 °C	1.0 °C
Hydraulic retention time (days)	36.7 a	34.2 a	31.6 a
Methane in biogas (%)	61.2 a	61.3 a	60.5 a
pH (−)	7.70 a	7.73 b	7.76 c
Tank temperature (°C)	56.7 a	56.5 b	56.4 c
Temperature of the environment (°C)	26.7 a	26.5 ab	24.3 b
Operation time L-205 (min)	279.5 a	284.3 a	301.2 a
Operation time JB-207 (min)	69.6 a	72.2 ab	73.2 b
U_{he} (W m^{-2} $°C^{-1}$)	1,636.8 b	2,042.0 a	1,730.2 ab
U_t (W m^{-2} $°C^{-1}$)	2.4 a	2.3 a	1.4 b

Treatments with different letters in the same row showed significant statistical difference (α=0.05)

U overall heat transfer coefficient

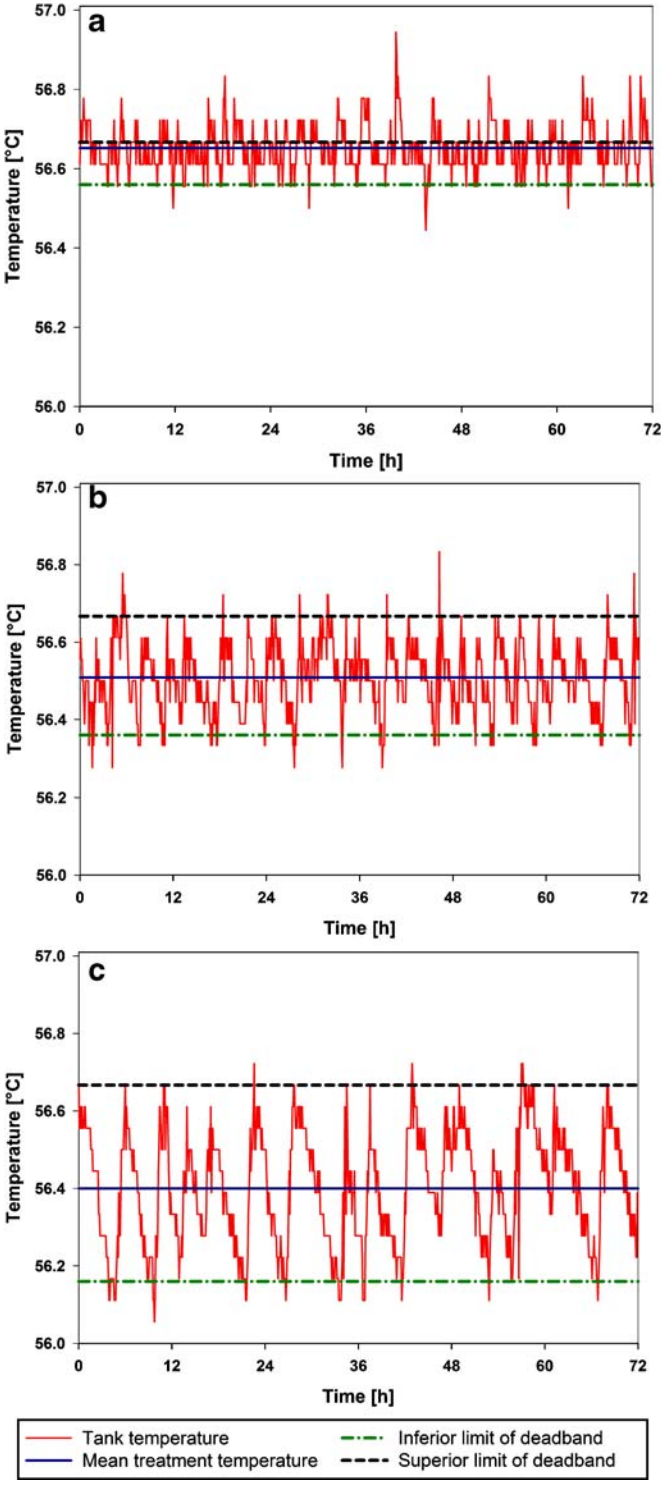

Fig. 2 Temperature fluctuation for different deadbands: **a** 0.2 °C, **b** 0.6 °C, and **c** 1.0 °C

in the pilot plant studied here, the heating process is associated to mixing by pumping; each individual temperature curve of Fig. 2 is related also to the operation of the pump L-205. In the temperature curve, as far two consecutive superior and inferior peaks are, higher is the time that the fluid is not exposed to mechanical stress.

As expected, the difference between the target and mean tank temperatures increased as the deadband increased. It was noteworthy that for the deadband of 0.2 °C (Fig. 2a), the tank temperature exceeded the target temperature several times along the experiment, being less frequent for the 0.6 °C (Fig. 2b) and 1.0 °C (Fig. 2c) deadbands. This resulted in the statistical differences in average tank temperature of the treatments (Table 2), which could be attributed to the changes in flow patterns inside the tank, and consequently the degree of mixing achieved into the tank. The nonhomogeneity into the tanks led to the activation of heating system. Figure 2 shows that the smaller the deadband, the higher the frequency of activation of the pumps. At the same time, the smallest deadband has shorter periods of working time than in the other experiments with wider deadbands, as it is shown in Table 2. Thus, as temperature control system activates with a smaller deadband, shorter is the temperature variation, and at the same time, the period of time that the liquid remains without exposition to mechanical stress is smaller. These facts had an effect on the power consumption and the performance of the bioreactor as explained in the following sections.

Table 3 shows the mechanical energy used for recycling the digestate (L-205) and biogas (JB-207), as well as the thermal requirements to keep the digester under thermophilic conditions (E-208) and the energy content of the biogas produced, considering in all the cases a 24-h period of time. Taking into account the amount of energy used for mixing (L-205 and JB-207) and for heating the digestate (E-208), the average energy used for heating represents 95.6% of the total energy consumed, which is similar to the 94.8% previously reported for the same pilot plant [6]. These facts have important technological implications, considering that heat requirements represent more than 95% of the energy needs for the system and taking into account that the global heat transfer coefficient of the tank is small, it is clear that energy is used mainly to heat the input feed slurry and that losses to the environment are marginal. Thus, in order to increase the energy efficiency of the pilot plant, the incorporation of a heat economizer would be useful to recover the thermal energy of the currents that leave the digester. A sensitivity analysis based on Eq. 1 (data not shown) established that the most important causes of the cooling of the mass inside the tank were the heating of the feed (current 1) and the exit of current 2 (Fig. 1). Thus, the energy exchange between currents 1 and 2 inside the heat economizer could contribute to increase the thermal efficiency of the process.

Table 3 Energy used in a 24 h of continuous operation under different temperature control strategies.

Device or source	Treatment (deadband used)		
	0.2 °C (kJ)	0.6 °C (kJ)	1.0 °C (kJ)
L-205	13,639 a	13,804 a	14,657 a
JB-207	5,491 a	5,698 a	5,692 a
E-208[a]	409,795 a	416,577 a	447,040 a
Total energy used in 24 h	428,931 a	436,036 a	467,404 a
Biogas produced[b]	348,367 b	362,593 b	422,896 a

Treatments with different letters in the same row showed significant statistical difference (α=0.05)

[a] The energy was calculated based on a heat of combustion of 35,881 kJ/m^3

[b] The energy was calculated based on a heat of combustion of 33,943 kJ/m^3

The average mechanical and thermal energies used each treatment kept practically the percentage into each treatment, being respectively 4.4% and 95.6%. Even no statistical differences were observed in the energy used in each treatment, the trend in Table 3 shows that for a wider deadband treatment, the power input increases. It is important to notice that since there were no statistical difference in the amount of solids used in each treatment (Table 1), the differences observed could be attributed to the effect of the heating strategy. Thus, taking the deadband treatment of 0.2 °C as reference, the mechanical energy used for mixing by pump L-205 increased 1.2% and 7.5% for the deadbands of 0.6 °C and 1.0 °C, respectively. In the case of the energy used by the blower, the corresponding increments were 3.8% and 3.7%. It indicates that the main component in the increment of mechanical energy, with wider span for triggering the temperature control system from target temperature, is due to pumping which is in agreement with the time that the pump L-205 is operated (Table 2). Base on these results, it is possible to speculate that short times of activation of pumping L-205 could be related to large particles settling and therefore to create segregated zones into the tank. Thus, longer periods of pumping could lead to improve digester mixing and consequently a better digester performance.

In the present study, the amount of energy from the biogas represents between 85.0% and 95.4% of the total energy required to keep the digester working at the target temperature (Table 3). For the same pilot plant, results presented by Espinosa-Solares et al. [6] showed that the amount of energy from the produced biogas represented just 75.8% of the heat requirements of the system. The improvement could be attributed to the longer hydraulic retention time used in the present research (31.6 to 36.7 days) than in the one (9.9 days) used by Espinosa-Solares et al. [6], which implies that the percentage of the daily feed, taking as reference the total volume of digestate inside the tank, in the present work was lower than 3.2% while in the previous work [6] was 10.1%.

Table 4 presents the performance of the digester using as indicator the methane yield with respect to the amount of VS and COD fed, as well as a global index that involves the energy used for mixing and heating the system. The methane yield ranged from 0.330 to 0.451 $m^3\ kg_{VS}^{-1}\ day^{-1}$ (0.252 to 0.311 $m^3\ kg_{COD}^{-1}\ day^{-1}$), which is in the same order of magnitude as reported in the literature [13–16]. If the digestate volume contained in the tank is taken as a reference, it was recycled daily in the range of 2.53 to 2.72 times during experiments, while volume biogas was recycled between 3.72 and 3.91 times (Table 4). In both cases, the amount is less than those used in the previous pilot plant configuration [6].

Table 4 shows that the 0.2 °C deadband treatment had the smallest methane yield 0.330 $m^3\ kg_{VS}^{-1}\ day^{-1}$ (0.252 $m^3\ kg_{COD}^{-1}\ day^{-1}$). Increments of 17.9% and 36.5% on digester performance were observed for the 0.6 °C and 1.0 °C deadband treatments, respectively. When the amount of energy used is considered in the performance, it is

Table 4 Biodigester performance under different temperature control strategies.

Parameter	Treatment (deadband used)		
	0.2 °C	0.6 °C	1.0 °C
Methane yield ($m^{-3}\ kg_{VS}^{-1}\ day^{-1}$)	0.330 a	0.389 a	0.451 a
Methane yield ($m^3\ kg_{COD}^{-1}\ day^{-1}$)	0.252 a	0.301 a	0.311 a
Global biodigester performance index ($m^3\ kg_{VS}^{-1}\ kJ^{-1}\ day^{-1}$)	7.61×10^{-7} a	8.76×10^{-7} a	9.94×10^{-7} a
Digestate recycled/digestate in tank volume ($m^3\ m^{-3}\ day^{-1}$)	2.53 a	2.57 a	2.72 a
Biogas recycled/digestate in tank volume ($m^3\ m^{-3}\ day^{-1}$)	3.72 a	3.86 ab	3.91 b

Treatments with different letters in the same row showed significant statistical difference (α=0.05) possible to define a global biodigester performance index, expressed as the ratio of methane yield to total energy used. In that case, the global biodigester performance ranged from 7.61×10^{-7} to 9.94×10^{-7} m^3 kg_{VS}^{-1} kJ^{-1} day^{-1} and, with the use of this index, it was clear that the best performance was achieved by the largest deadband evaluated here (30.6% higher than the smallest deadband). These results indicate that heating strategy has an important effect on digester performance. The observed enhancement strengthens the idea that a wide deadband improves digester mixing, while a narrow one permits the formation of segregated zones into the digester.

Conclusions

In the range of deadbands studied here for temperature control (0.2 °C to 1.0 °C), the results showed that heating was the most energy-demanding process with 95.5% of the energy used. Increments up to 7.5% and 3.8%, respectively, on mechanical and heating power consumption were observed as the span for triggering the temperature control system from target temperature was increased. This indicates that for scaling up, it is necessary to address this issue mainly in terms of bioreactor design and energy recovery equipment inclusion. Thus, it is suitable to design the bioreactor with the highest possible volume/transfer area ratio. The process design, particularly for thermophilic conditions, must consider a manner to recover the thermal energy of the effluent. Additionally, in the range of deadbands studied here, important increments on digester performance were observed; when a span of 1.0 °C was compared to the one of 0.2 °C the performance, evaluated as methane produced per volatile solids fed, an enhanced of 36.5% was observed. When the global performance index was used in the same comparison, the increment in performance was 30.6%. The enhancement was explained considering that a wide deadband improves digester mixing, while a narrow one permits the formation of segregated zones into the digester. Additional research is needed to elucidate the role of pumping and gassing on mixing performance of digesters, which is left for future communications.

Nomenclature

$\dot{m}$	mass flow (kg h^{-1})
m	mass (kg)
Cp	specific heat capacity (J kg^{-1} °C^{-1})
T	temperature (°C)
h^{sat}	specific enthalpy of saturated liquid (kJ kg^{-1})
P	pressure (kPa)
ρ	density (kg m^{-3})
ΔT	temperature difference (°C)
U	overall heat transfer coefficient (W m^{-2} °C^{-1})
X_s	solids mass fraction (dimensionless)

Subscripts

d	digestate
t	tank
he	heat exchanger

ref reference
lm logarithmic mean
env environment

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