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Anaerobic co-digestion of rabbit manure and sorghum crops in a bench-scale biodigester

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Abstract

Any type of biomass can be used as substrate for biogas production, but the performance of the biodigestion depends on the composition of the feed, and no direct extrapolation of the yield of the process from one substrate to another can be made. In this work, the performance of a bench-scale anaerobic biodigester of 93 L installed at ambient conditions is studied. The biodigester was set up in a region where temperature varies significantly during the year, and was operated under semi-batch conditions with non-thermal control for 16 months with a feed of rabbit manure and ground sorghum grains. To our knowledge, this is the first time the co-digestion of rabbit manure with sorghum grains is considered. To evaluate the biodigestion performance, critical operational variables (pH, temperature, biogas flowrate) were monitored, and composition of substrate, digestate and produced biogas was determined. Moreover, the following variables were quantified: (a) the theoretical methane potential, (b) the specific methane yield and (c) the degree of degradation of the substrate. A 1-D non-stationary model was formulated and validated with experimental data in order to analyze, in a theoretical form, the impact of incorporating thermal insulation to the unit. The results show that is it possible to produce biogas in a bench-scale biodigester, with a novel feed of rabbit manure and ground sorghum grains, in a region with significant temperature changes along the year. Moreover, it is shown that the 1-D model constitutes a useful tool for the design or improvement of biodigesters regarding the insulation system and the warming policies.

Keywords: Anaerobic digestion, Rabbit manure, Sorghum crops, Heat transfer model, Theoretical methane potential, Specific methane yield

Introduction

Technologies around renewable resources are gaining more importance. Biogas constitutes a product derived from renewable resources and is defined as secondary energy source, which means that it is a product generated through transformation of primary energy carriers into higher quality products by applying a fermentation process (Deublein and Steinhauser 2008). Anaerobic conversion of organic matter such as animal manure and crop residues into biogas provides not only a clean and renewable source of energy but also a nutrient-rich digestate for land applications (Wellinger et al. 2013). The stable and efficient operation of biogas production units from an specific substrate requires the study of this complex process from a general perspective considering: the characterization of the substrate and its proper formulation, the determination of the energy potential of the produced biogas and the process performance, and the formulation of proper policies for the monitoring and the operation of the unit (Schnurer et al. 2016).

Regarding the substrate, it should be mentioned that all types of biomass can be used as substrates for biogas production as long as they contain carbohydrates, proteins, fats, cellulose, and hemicelluloses as main components. Historically, anaerobic digestion has mainly been associated with the treatment of animal manure and sewage sludge from aerobic wastewater treatment

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(Weiland 2010). However, it has been demonstrated that the anaerobic co-digestion of manure and various biomass substrates increases the biogas yield (Li et al. 2013b) and offers a number of advantages for the treatment of manure and organic wastes, improvement of fertilizer properties of the digestate and reduction of greenhouse gas emissions from manure and organic wastes (Holm-Nielsen et al. 2009).

Few authors have studied the biogas yield and digestate properties of rabbit manure alone (Mahadevaswamy and Venkataraman 1988; Trujillo et al. 1991; Li et al. 2015) or associated with other manures or wastes (rabbit and pig manure by Aubart and Bully (1984), and tomato waste and rabbit manure by Trujillo et al. (1993)), comprising all of their laboratory experiences (volume smaller than 6 L) at full controlled conditions, more specifically mesophilic conditions. Rabbit manure has been shown to be a suitable raw material for anaerobic digestion. In fact, the composition of rabbit manure is comparable from other manure (Li et al. 2015). Rabbit manure has four times more nutrients than cow or horse manure and is twice as rich as chicken manure (Groppelli and Giampaoli 2001). Then, to our knowledge, this is the first time that a study of the co-digestion of rabbit manure with ground sorghum grains in a bench-scale biodigester is performed. It is important to highlight that the conditions considered in the present study are ambient conditions and long-term operation in a region where temperature changes significantly during the year.

Regarding biogas production and process performance, it should be noticed that the planning and operation of biogas production units requires the evaluation of process performance. This can be assessed through comparison of expected methane production and that obtained in practice (Schnurer et al. 2016). The biogas potential of the substrate used can be calculated from elemental analysis composition (Chae et al. 2008; Li et al. 2013a, 2015) based on Buswell formula (Buswell and Mueller 1952) while the specific methane yield can be obtained from measurements of the produced gas volume in the biodigester and their methane content (Schnurer et al. 2016). The determination of the volatile solid´s degree of degradation is also a typical parameter to assess the efficiency of biological processes (Koch 2015).

There are several operational parameters that impact on the biodigester performance, i.e., organic loading rates, biodigester mixing, temperature control, pH, nutrient and trace elements, and C/N ratios should be taken into account (Schnurer et al. 2016). Among them, temperature is the most critical variable as it affects two key attributes of biogas production: (1) the microbial activity and (2) the viscosity of the slurry (digestate) (Surendra et al. 2013). In this context, heat transfer mathematical models constitute a key tool in order to predict temperature variations of the slurry, adopt operational policies and guide the proper design of the unit especially when the biodigester must be installed in cold regions.

There are several theoretical studies in the literature about heat transfer in large-scale anaerobic digestion systems, i.e., with more than 30 m^3 working volume (Axaopoulos et al. 2001; Gebremedhin et al. 2005; Merlin et al. 2012; Curry and Pillay 2015; Hreiz et al. 2017). These modeled digesters present large thermal capacitances that soften fluctuation of surrounding temperature. Pilot and bench-scale biodigesters present less thermal inertia, then a mathematical model specifically developed for such scales is necessary to correctly predict temperature changes and consequently, to avoid unwanted effects at lower scales. Valle-Guadarrama et al. (2011) developed a model, based on fundamental thermodynamic laws, to predict the temperature changes in a thermophilic biodigester of a 27.43 m^3 working volume with a heating system allowing digestate temperature control within a very low predefined span. The heat transport parameters of their model were fitted with plant experimental data. The digestate temperature was predicted through this model with a 5% of error.

Perrigault et al. (2012) proposed a one-dimensional time-dependent model for a low-cost plug-flow pilot-scale PVC biodigester. The biodigester of 2.5-m^3 volume was daily fed with a mixture of cow manure and water and operated with a hydraulic retention time of 60 days located in a greenhouse. The model accounts for solar gains as well as heat transfer with the ground, the greenhouse air, the plastic greenhouse cover, the greenhouse walls, the ambient air, and mass transfer via the influent and effluent flows. The proposed model was calibrated to fit the mean experimental slurry temperature by adjusting the straw insulation thickness. Then, a high correlation between the modeled and experimental slurry temperature was obtained (2% of standard error), while a higher standard error was found for the biodigester walls and greenhouse temperatures predictions (14.6% and 11.1%, respectively). This model was used to predict the influence of geometry and materials on the performance of the digester (Perrigault et al. 2012).

Weatherford and Zhai (2015) studied experimentally the thermal performance of four full-scale solar-assisted plug-flow test biodigesters, with a capacity of 2.5 m^3 each, located in a site with a cold climate (i.e., Cusco, Perú). They posed a one-dimensional thermal model, based on Perrigault's model (Perrigault 2010), which was calibrated and validated with site-specific field data of one of the studied biodigesters; then the model renders just applicable for this unit. The model predicted diurnal slurry temperatures fluctuations and overall slurry temperatures with reasonable deviations error (Weatherford and Zhai 2015). Moreover, some recommendations to improve the design and construction of small-scale solar-assisted plug-flow biodigesters were made based on the model parametrizations.

Hreiz et al. (2017) studied heat transfer phenomena in a farm-scale semi-buried agricultural digester constructed of reinforced concrete and fed with livestock waste. The digester processed 430 m^3 of liquid digestate. They proposed a model that assumes a uniform digestate temperature and that accounts for heat losses to the ground and rain events. Through their model, they simulated the temporal variations of the digestate and biogas temperatures as a function of climatic conditions, and their numerical results are in reasonable agreement with available experimental data. They also proposed technical solutions to reduce heat losses in anaerobic digesters.

In the previously described works, heat transfer in medium and small-scale biodigesters was described in detailed, by means of models of different complexity which make use of a high number of fitting parameters. Hence, none of them can be directly applied to the biodigester studied in this work since they were not developed for the particular characteristics and volume (bench-scale) of the unit here used.

Thus, the goal of this work is to study the performance of a bench-scale anaerobic biodigester installed at ambient conditions. The unit was set up in Bahía Blanca, Argentina (a region where temperature varies significantly throughout the year), and was operated under semi-batch conditions for a period of 16 months with a feed of rabbit manure and ground sorghum grains, combination that has not yet been tested in the literature. The feed stream, produced biogas and liquid digestate were completely characterized. The anaerobic process performance was evaluated by means of the determination of the theoretical methane potential, the specific methane yield, and the degree of degradation of the substrate. Additionally, a one-dimensional non-steady-state mathematical model was developed and validated with experimental data obtained from a bench-scale biodigester in order to evaluate the impact of incorporating thermal insulation to the unit. The developed model is based on fundamental thermodynamic laws and well-established correlations to estimate heat transfer coefficients. As it does not require fitting parameters, it is for general application.

Materials and methods

Experimental setup

An anaerobic biodigester of 93 L was constructed and installed in Bahía Blanca (Argentina), a city located in a region where temperature varies significantly during the year (average maximum temperature of 30.8 °C, average minimum temperature of 2.6 °C (Servicio Meteorológico Nacional 2016).

The biodigester was operated in semi-batch mode and fed with 1.7 L of substrate per week. The physicochemical analyses of each substrate used (CHN628 Series and TruSpec Micro Oxygen Add-On Module Elemental Determinators. LECO) are shown in Table 1. Based on these analyses, the biodigester feed composition was set as 12.3% w/w of rabbit manure, 1.3% w/w of sorghum crops and 86.4% w/w of water. The biodigester was installed in a closed room without any heating or cooling system. Figure 1 presents a schematic representation of the unit with its main components.

This unit was constructed with the aim of assessing the performance of a biodigester under the posed fed and ambient conditions. Based on the obtained experimental data, a pilot-scale biodigester will be designed and installed in the previously mentioned region. In other words, further studies foresee the scaling up of the bench-scale biodigester studied in this contribution.

In order to test the biodigester performance, several variables were measured during the operation by the procedures described in Sect. "Experimental procedures". On overall, these variables were: temperature inside the biodigester and ambient temperature; pH, elemental composition (C, H, N and O), total solids and volatile solids of liquid substrate and liquid digestate; nitrogen and potassium content of liquid digestate; biogas flowrate and composition.

Experimental procedures

The performance of the biodigester was evaluated over a period of 16 months. During this period, the ambient temperatures as well as the temperature inside the biodigester were weekly measured using thermocouples. The biogas volumetric total flowrate as well as the pH of the feed stream and the liquid inside the biodigester were measured over the mentioned period of time.

Samples of the liquid digestate were taken monthly for a period of 4 months and properly stored (cooled) for further characterizations, starting 10 months after the biodigester start-up in order to allow stabilization of the

Table 1 Physicochemical analysis of the substrate used

Property	Value	
	Sorghum crops	Rabbit manure
C (% w/w)	39.90 ± 0.28	40.45 ± 0.35
N (% w/w)	1.51 ± 0.11	2.79 ± 0.03
H (% w/w)	7.25 ± 0.01	7.51 ± 0.01
O (% w/w)	47.55 ± 1.63	42.8 ± 0.14

References	
1	Digestion chamber
2	Biogas chamber
3	Charge tube
4	Discharge tube
5	Stirrer
6	U-tube manometer
7	H_2S filter
8	Thermocuple
9	Sampling point
10	Flowmeter

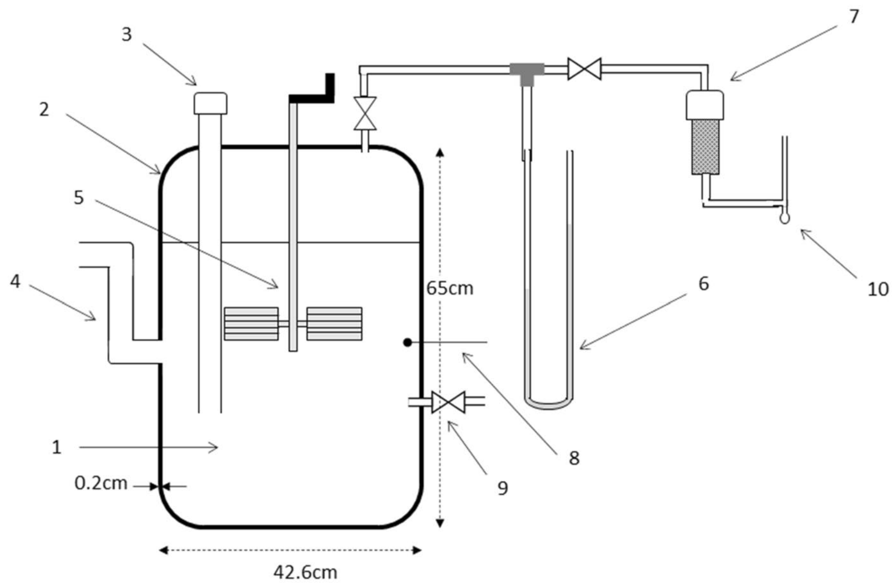

Fig. 1 Biodigester schematic representation

system. The samples (0.5 L each) were collected in polyethylene sampling containers and stored cool (1–5 °C) up to performing its analysis, following the procedure proposed by Vaneeckhaute et al. (2013b). Biogas samples were collected in 1-L Tedlar sample bags (Icon Argentina IyE) and immediately analyzed by gas chromatography.

Analytical methods

Liquid substrate and liquid digestate sample analysis

Liquid substrate and liquid digestate samples were characterized as follows. For both type of samples, total solids (TS) content was determined according to Mekki et al. (2013) and Smith et al. (2007) standard method. Indeed, a known weight of each liquid sample was introduced into a porcelain crucible followed by drying at 105 °C until constant weight. Volatile solids (VS) were determined by incineration of the dry samples in a furnace (SIMCIC Hornos, Argentina) at 550 °C during 4 h (Vaneeckhaute et al. 2013a). The content of total nitrogen, carbon and hydrogen were measured for the digestate samples obtained after the total solids analysis in an elemental analyzer CHNS/O 2400 Series II Perkin Elmer (USA) (Zirkler et al. 2014). Regarding the liquid substrate, elemental oxygen was also determined.

Furthermore, all fresh liquid digestate fractions were wet digested and then total phosphorus and potassium content were determined. The acid digestion was performed under the standard method EPA 3050B (10 mL of liquid sample + HNO_3 + H_2O_2 (EPA 1996)). Total phosphorus was determined using the colorimetric method of Scheel (Scheel 1934; Vaneeckhaute et al. 2013a). The absorbance at 700 nm of samples and standards was determined using a PG Instruments spectrophotometer (T60 UV–visible, Lutterworth, UK). Potassium of the digested liquid samples (see above) was analyzed using a flame photometer (Perkin Elmer AAnalyst 700, USA) (Vaneeckhaute et al. 2013a; Zirkler et al. 2014).

Biogas analysis

Biogas composition was determined by means of gas chromatography. A gas chromatograph (HP 4890D) equipped with Porapak Q and Carbosieve S-II columns and a TCD detector was used to measure gas concentrations. Previously, the presence of hydrogen sulphide was analyzed by bubbling the biogas stream through a solution of silver nitrate to yield silver sulphide (black precipitate) (Group 2006).

Theoretical methane potential, specific methane yield and methane productivity

The theoretical methane potential (TMP) of the substrate was estimated using Buswell formula (Buswell and Mueller 1952) based on elemental composition of the organic substrates, as shown in Eqs. 1 and 2 (Chae et al. 2008; Li et al. 2013a, 2015). In this study, all the TMP data were converted assuming biogas at standard temperature and pressure.

$$C_nH_aO_bN_c + \left(n - \frac{a}{4} - \frac{b}{2} + \frac{3c}{4}\right)H_2O \rightarrow \left(\frac{n}{2} + \frac{a}{8} - \frac{b}{4} - \frac{3c}{8}\right)CH_4 + \left(\frac{n}{2} - \frac{a}{8} + \frac{b}{4} + \frac{3c}{8}\right)CO_2 + cNH_3 \quad (1)$$

$$\text{TMP}\left(\frac{\text{mlCH}_4}{g\text{VS}}\right) = \frac{22.4 \times 1000 \times \left(\frac{n}{2} + \frac{a}{8} - \frac{b}{4} - \frac{3c}{8}\right)}{12n + a + 16b + 14c} \quad (2)$$

The specific methane yield can be calculated from measurements of the produced gas volume and the methane concentration in the biogas according to the following equation (Schnurer et al. 2016):

$$\frac{\text{ml CH}_4}{g\text{VS}} = \frac{Q_g \times \%\text{CH}_4}{Q_s \times \text{TS}_{\text{in}} \times \text{VS}_{\text{in}}}, \quad (3)$$

where Q_g is the flow rate of produced gas (ml/day), % CH_4 is the methane percentage of the produced gas, Q_s is the inflow rate at the reactor (g/day), TS_{in} is the total solids content in the incoming substrate and VS_{in} is the volatile solids present in the total solids.

Finally, methane productivity was calculated as the volume of methane produced per unit volume of digester per day (CH_4L/L-day) (Karim et al. 2005).

Degree of degradation

The degree of degradation ($VS_{removed}$) represents the proportion of fed organic matter that was transformed to biogas through digestion. Based on the assumption that the mass of inorganic solids is constant during degradation, Eq. 4 has been developed for $VS_{removed}$ calculation (Koch 2015):

$$\text{VS}_{\text{removed}} = \left(1 - \frac{\text{VS}_{\text{out}}(1 - \text{VS}_{\text{in}})}{\text{VS}_{\text{in}}(1 - \text{VS}_{\text{out}})}\right)100\%, \quad (4)$$

where VS_{in} is the volatile solids content in the influent, VS_{out} is the volatile solids content in the effluent, and $VS_{removed}$ is the volatile solid´s degree of degradation (%).

Mathematical model

In order to describe the thermal behavior of the biodigester under non-steady conditions, a 1-D model was formulated under the following hypothesis:

1. Only natural convection was considered as the biodigester is located ia closed room.
2. Net radiation transfer was neglected as the surface presents low emissivity and temperatures are low.
3. Thermal conductivity of the biogas inside the biodigester was neglected.
4. The biodigester walls were considered planar plates as $\frac{D}{L} \geq \frac{35}{Gr^{0.25}}$ is satisfied (Bergman et al. 2011), where Gr is the Grashof number defined as:

$$\frac{g\beta(T_\infty - T_s(t))x^3}{\nu^2}$$

being g the acceleration of gravity, β the coefficient of volumetric expansion, T_s the surface temperature, T_∞ the ambient temperature, x the characteristic length and ν the kinematic viscosity.
5. The reaction heat associated with the biochemical reactions occurring, i.e., the biodigester was considered negligible (Kishore 1989).
6. Heat losses from evaporation inside the biodigester and exit biogas flowrate were neglected (Kishore 1989).
7. Thermophysical properties of the digestate were considered to be similar to thermophysical properties of water (Bergman et al. 2011).
8. Lumped parameter model was considered, i.e., temperature is not dependent on the position, as low values of Biot number were estimated. The digestate temperature is equal to the temperature measured in the liquid inside the biodigester.
9. Heat losses associated with the bottom surface area were neglected due to low thermal conductivity of the wood table that supports the biodigester.

Under the stated hypothesis, the lumped parameter model obtained is:

$$\rho_d V_d C_p \frac{\partial T_d}{\partial t} = Q_T, \quad (5)$$

where V_d is the volume occupied by the digestate (65 L), ρ_d and C_p are the density and calorific capacity of the digestate, respectively. All the estimated thermophysical properties of the digestate are temperature dependent. T_d is the temperature in the biodigester and Q_T the total heat exchanged.

The total heat (Q_T) taking into account the heat losses associated with lateral and top surfaces areas is defined as:

$$Q_T = \left(\frac{1}{\frac{1}{h_L A_L} + \frac{t}{kA_L}} + \frac{1}{\frac{1}{h_T A_T} + \frac{t}{kA_T}}\right)A_t(T_\infty - T_d(t)) \quad (6)$$

where
A_L is the lateral surface area (πDL),
A_T is the top surface area ($\frac{\pi D^2}{4}$)
A_t is the total area,
h_L is the heat transfer coefficient associated with free convection at the lateral surface,
h_T is the heat transfer coefficient associated with free convection at the top surface and
k is the thermal conductivity (0.43 W/m K, polyethylene).

With the aim of estimating the heat transfer coefficient associated to free convection, the Rayleigh number was estimated (Eq. 7) for both surfaces perpendicular to the heat transfer based on their characteristic lengths (x). The biodigester length (L) is the characteristic length associated to the lateral surface and A_s/P is the characteristic length associated to the top surface, i.e., $D/4$. Therefore:

$$Ra_x = Gr_x \Pr = \frac{g\beta(T_\infty - T_s(t))x^3}{\alpha\nu} \tag{7}$$

where α is the thermal diffusivity defined as $\alpha = k\rho/C_p$, β is the volumetric thermal expansion coefficient defined as $\beta = 1/(T_S(t) + T_\infty)$ and $T_s(t)$ is the outer surface temperature:

$$T_s(t) = Q_T \frac{t}{kA_t} + T_d(t) \tag{8}$$

For turbulent flow, the heat transfer coefficient for a vertical plate (can be estimated from Eq. 9, while the heat transfer coefficient for a horizontal plate $\left(\bar{h}_T\right)$ can be estimated by means of Eq. 10 (Bergman et al. 2011):

$$\bar{N}u_x = \frac{\bar{h}_L x}{k} = 0.1 Ra_x^{\frac{1}{3}} \tag{9}$$

$$\bar{N}u_x = \frac{\bar{h}_T L}{k} = 0.15 Ra_x^{\frac{1}{3}} \tag{10}$$

The set of differential and algebraic equations (Eqs. 5 to 10) were implemented under the gPROMS Model Builder environment (Process System Enterprise, gPROMS 2019). This is a multipurpose software mainly used to build and validate process models, including steady-state and dynamic optimizations among several other functions (2019). Its flexibility and robustness have been widely proved by many other workers (Di Maggio et al. 2010; Ierapetritou et al. 2016; Rehrl et al. 2017). By solving the set of equations simultaneously, it was possible to predict the digestate temperature (T_d) of each $n+1$-day based on the average ambient temperature (T_∞) and the digestate temperature corresponding to the n-day.

Results and discussion

Substrate physicochemical analysis

The physicochemical analysis of the substrate used is shown in Table 2. The substrate was composed by rabbit manure, ground sorghum grains and water in the proportions previously mentioned.

The co-digestion of manure and crops has been demonstrated to produce a synergistic effect since it promotes the adequate balance of the carbon-to-nitrogen (C/N) ratio (Li et al. 2013b; Mata-Alvarez et al. 2014; Schnurer et al. 2016). The proper C/N ratio should range from 15 to 25 for an optimal anaerobic digestion (Mata-Alvarez et al. 2014; Schnurer et al. 2016). In this study, the substrate presents a C/N ratio of 15.1 (see Table 2). It is worth noting that, according to our determinations, the C/N ratio for rabbit manure alone is 14.5 (see Table 1), which is less suitable for anaerobic processes and requires the addition of a carbon source (i.e., sorghum crops). Besides, a VS (% w/w of TS) value of 89.7 was determined, indicating a high organic content, which is desirable for biogas and methane production (Li et al. 2013b). Additionally, water content was adjusted to achieve the desired 8% of TS, accordingly to literature (Huerga et al. 2014; Schnurer et al. 2016) (see Table 2).

Table 2 Substrate physicochemical analysis

Property	Value
TS (% w/w of FW)	7.2 ± 0.6
VS (% w/w of FW)	6.5 ± 0.6
VS (% w/w of TS)	89.7 ± 0.7
C (% w/w of TS)	40.40
H (% w/w of TS)	7.49
O (% w/w of TS)	43.26
N (% w/w of TS)	2.67
C/N	15.1

FW, fresh weight

Study of the main operational variables

Figure 2 shows the measured pH values of the feed mixture and digestate as a function of time. The substrate mixture was blended and water was added before feeding it to the biodigester. The pH of the aqueous mixture was measured. Additionally, before feeding the biodigester an aliquot of the digestate was taken from a sampling point located in the biodigester (see Ref. 9 Figure 1). Although the pH of the feed mixture remains approximately constant, the pH of the digestate increases during the start-up of the biodigester and afterwards, reaches a value that fluctuates between 7 and 7.5. The fatty acids and acetic acids released at the start of the process lead to pH values lower than 6.7. This is in agreement with previous results (Mudhoo 2012) that attributed this phenomenon to the hydrolysis and acidogenesis reactions that take place during the start-up. The pH between 7 and 7.5 values indicates that the methane production was stabilized due to acid consumption in the acetogenesis and methanogenesis stages by means of the methanogenic bacteria. This is verified by high CH_4 composition values (66.5% ± 2.6%) obtained by gas chromatography which were similar to that reported by Mahadevaswamy and Venkataraman (1988) and Trujillo et al. (1991) for rabbit droppings digestion. The error bars are low, especially for the pH

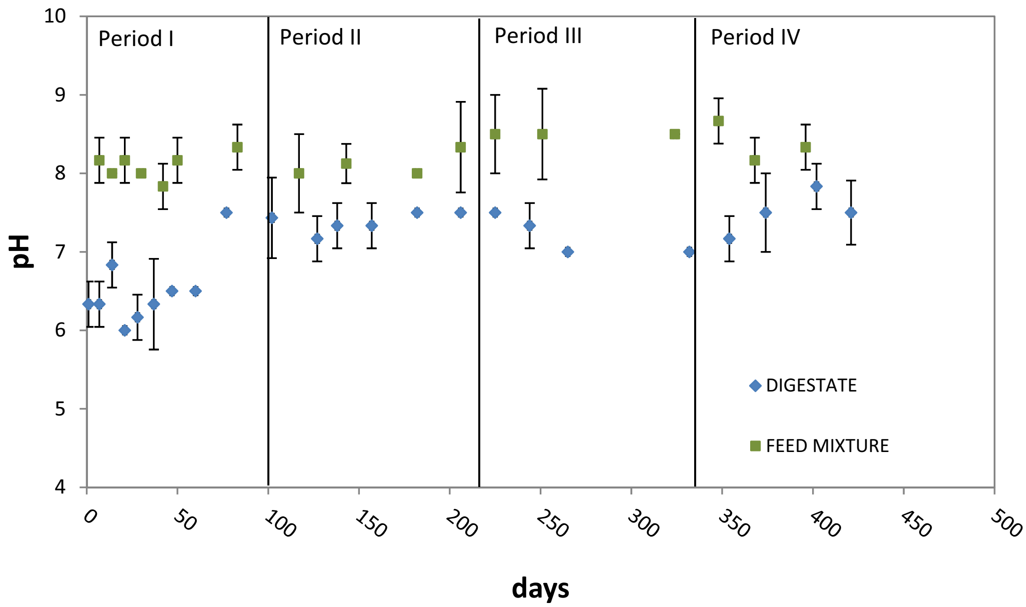

Fig. 2 Digestate pH and feed mixture pH

values corresponding to the digestate. The mean deviations for pH are 0.3, with a maximum of 0.6.

Figure 3 presents the ambient and inside biodigester temperatures measured as a function of time. It should be noticed that although the biodigester was located in a closed environment, it had no insulation and consequently, the digestate temperature follows the fluctuations of the biodigester surroundings, with a maximum thermal amplitude of 22.5 °C during the period under study. Figure 3 evidences that the maximum difference between the ambient and digestate temperature was 5 °C. This difference can be mainly attributed to the absence of insulation or temperature control in the unit.

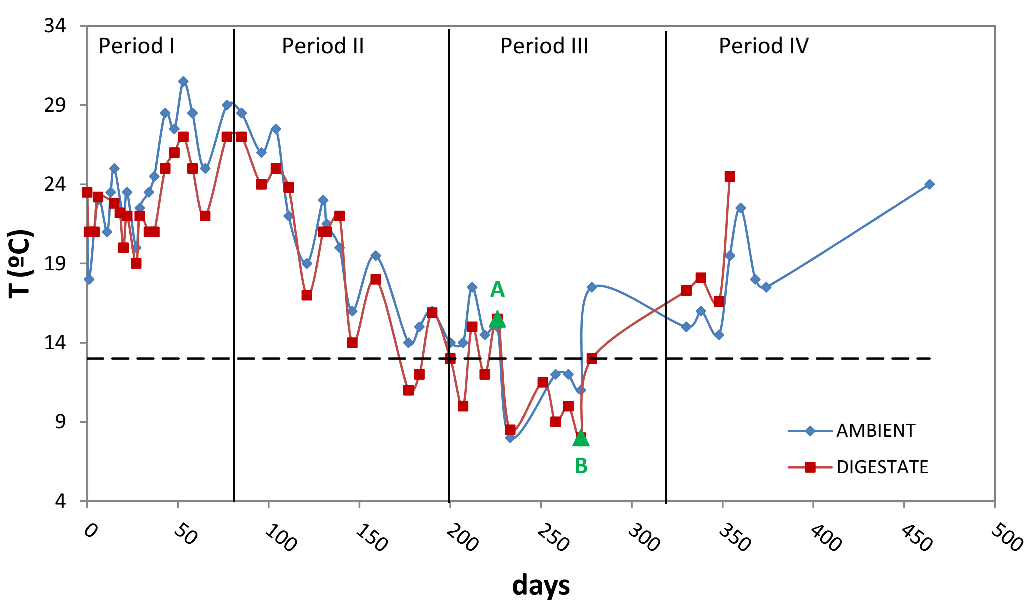

Fig. 3 Ambient and digestate measured temperatures as a function of time

Figures 2 and 3 consider the temperature and pH measurements for the whole period of study (i.e., 16 months), respectively. From the experimental measurements, it is possible to determine four different periods for the analysis. The first period, (Period I), encompass the start-up of the biodigester, and a low digestate pH was observed with respect to the one determined during other periods, as was previously discussed (see Fig. 2). During the second period, (Period II), a proper temperature for biodigestion (> 14 °C, spring and summer months) and a stable pH were observed. The third period (Period III) includes autumn and winter months, when measured temperatures were low (some of them < 13 °C), and a drop in biogas flow was experimentally observed, corresponding to bacteria inhibition. The last period (Period IV) considers warmer months, when proper conditions and stable operation were observed again. For the periods of stable operation (Period II and IV) an average biogas flow rate of 2.4 ± 0.7 ml/min was measured. The liquid digestate composition was assessed during the fourth period of operation (see Sect. "Liquid digestate sample analysis").

Effluents and biogas characterization

Liquid digestate sample analysis

Table 3 presents the total solids (TS) content of the different analyzed samples. All samples were tested by triplicate. As it can be seen, the measurements present quite small standard deviation, proving that the biodigester is operating under stable conditions.

The total phosphorus and potassium content of the liquid digestate are shown in Table 3 as well. All bacteria, including the ones responsible of anaerobic biological treatment processes, present nutrient needs that have to be fulfilled in order to properly function. Macronutrients, for example, nitrogen, phosphorus and potassium, are nutrients that are required in relatively large quantities by all bacteria. Micronutrients, for example, cobalt and nickel, are nutrients that are required in relatively small quantities by most bacteria. The amount of macronutrients needed to satisfy anaerobic bacterial activity and maintain acceptable biodigester performance may be determined by one of two methods. The first method consists of calculating the amount of nutrients that must be present in the biodigester feed and, if necessary, adding the nutrient. In the second method, adequate residual concentrations of soluble nutrients must be found in the biodigester effluent. If these residual concentrations are not found, the nutrients must be added (Gerardi 2003). In this contribution, macronutrients are assessed by the second method.

Table 3 Average value and deviation of main analyzed parameters for digestate

Variable	Average	Deviation
TS (% w/w of TS)	1.1	0.1
P (% w/w)	0.015	0.002
K (% w/w)	0.239	0.015
VS (% w/w of TS)	56.3	1.0
H (% w/w of TS)	3.60	0.10
C (% w/w of TS)	26.90	0.30
N (% w/w of TS)	3.33	0.06

Regarding the phosphorus content, each sample was tested by duplicate. The low deviation values show the high reproducibility of the colorimetric technique and the stability between samples. For testing the potassium content, each sample was analyzed by triplicate. In this case, the standard deviation value is a little higher, nonetheless is still proving that the digestate is stabilized. Furthermore, it is verified that the macronutrients needs of the anaerobic bacteria are properly met, since residual concentrations are found.

As previously mentioned, no reports on rabbit and sorghum digestate quality have been reported in the open literature constituting this a novel information. Nonetheless, the average values of total solids, K and P for the digestate under study are within the range reported by Vaneeckhaute et al. (2013b) and Mekki et al. (2013) for digestates of pig manure with energy maize and agriculture wastes, respectively.

Table 3 also presents the average value and deviation of all the other analyzed parameters (C, N and H content). Taking into account the value of total C and N determined by elemental analysis, the digestate presents a C/N ratio of 8.1, similar to that reported by Mekki et al. (2013), and less than the encountered for the feed stream. Table 3 shows a reduction in the VS content and the carbon content of the digestate with respect to the VS and C in the substrate (see Table 2). This is an evidence of the organic matter breakdown and the loss of carbon for the production of methane and carbon dioxide.

Biodigestion performance

According to the elemental analysis of the substrate (see Table 1), the chemical composition of the feed used in this study was determined as $C_{17.74}H_{39.39}O_{14.23}N$. This allowed to calculate the theoretical methane potential of the feed at standard conditions through Eq. 1, resulting in 447 ml CH_4/g VS.

A specific methane yield of 134 ml CH_4/g VS was obtained through equation 3, by considering the operational policies and the produced biogas properties already mentioned (inlet substrate flow of 1.7 L/week, 60% CH_4 -mean between experimental measurements-, and 2.4 ml gas produced/min). This yield value could be considered as low when compared with the theoretical methane potential results. However, it should be taken into account that the operating conditions of the bench-scale biodigester under study are not fully controlled, i.e., the unit was operated under environmental conditions and the temperature was not the optimal for anaerobic digestion during the whole period of operation. Moreover, it should be also considered that theoretical methane calculations, as the one obtained through Eq. 2, usually give an overestimate of the methane potential since part of the organic matter is used for biomass formation and some carbon compounds are recalcitrant (Schnurer et al. 2016).

By means of Eq. 4, an 85.2% for the VS reduction was obtained, which corresponds to fiber-rich materials such as rabbit manure and sorghum crops (Schnurer et al. 2016).

The methane productivity in this study is 0.04 CH_4L/L-day. Methane productivity was reported to be within 0.05 CH_4L/L-day and 0.45 CH_4L/L-day for a biodigester of similar scale fed with bovine waste (Borole et al. 2006). However, it is important to highlight that the mentioned biodigester was operated at 35 °C under temperature-controlled conditions.

Modeling results

Model predictions

By considering the average ambient temperatures and the digestate initial temperatures of points A (T_∞ = 11.5 °C, $T_d(t=0)$ = 15.5 °C) and B in Fig. 3 (T_∞ = 14.3 °C, $T_d(t=0)$ = 8 °C), together with the parameters of Fig. 1, the digestate temperature (T_d) was calculated by means of the proposed mathematical model. Figure 4a and 4b present the temperature profiles over the time corresponding to points A and B of Fig. 3, respectively. It is possible to observe in Fig. 4a that the temperature inside the biodigester decreases as the ambient temperature is lower than the initial temperature, acting as a coolant. On the other hand, in Fig. 4b it can be seen that heat is transferred from the surroundings, as its temperature is higher than the initial temperature. It is also worth noting that the model properly predicts the observed temperature. In case A, the difference between the experimental digestate and predicted temperatures is 3.3 °C while in case B, the difference between both temperatures is 0.5 °C.

In order to assess the adequacy of the heat transfer model to all the measured conditions, its predictions were compared with the recorded experimental temperatures inside the biodigester. Figure 5 presents a parity plot of the estimated vs. the measured digestate temperatures. Particularly, temperatures predicted by means of the mathematical model presented in Fig. 4a and 4b (corresponding to points A and B of Fig. 3) are indicated as A´ and B´, respectively, in Fig. 5. The predicted results do not show any systematic deviations since the points reasonably spread around the tendency line. The determination coefficient (R^2) of 0.92 reveals that the heat transfer model predicts with reasonable accuracy the performance of the biodigester under the operating conditions of practical interest. Then, the agreement between predicted and observed data shows the validity of the proposed heat transfer model.

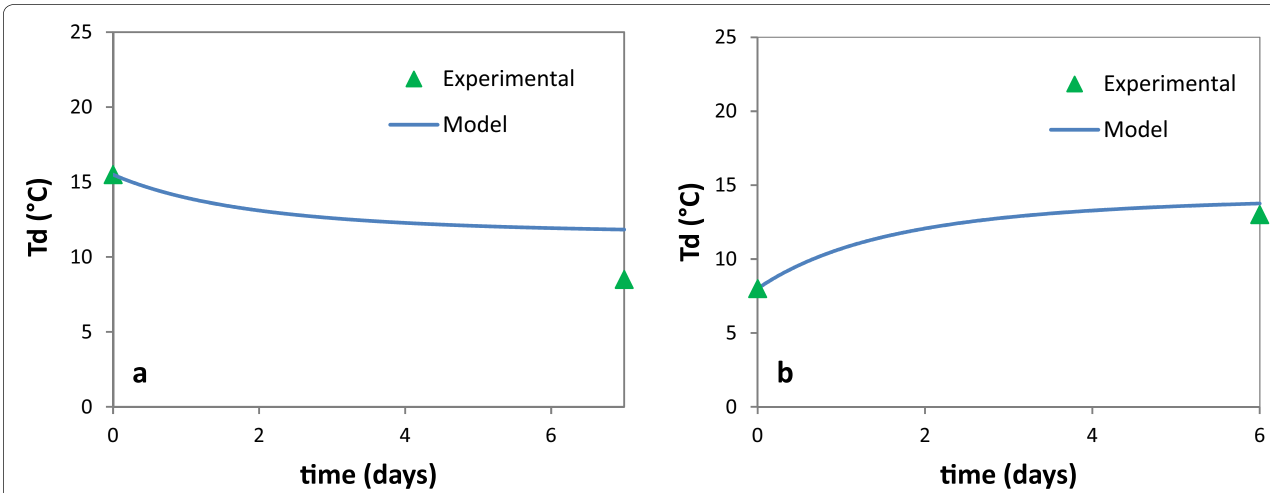

Fig. 4 **a** Temperature axial profile inside the biodigester corresponding to point A of Fig. 3. **b** Temperature axial profile inside the biodigester corresponding to point B of Fig. 3

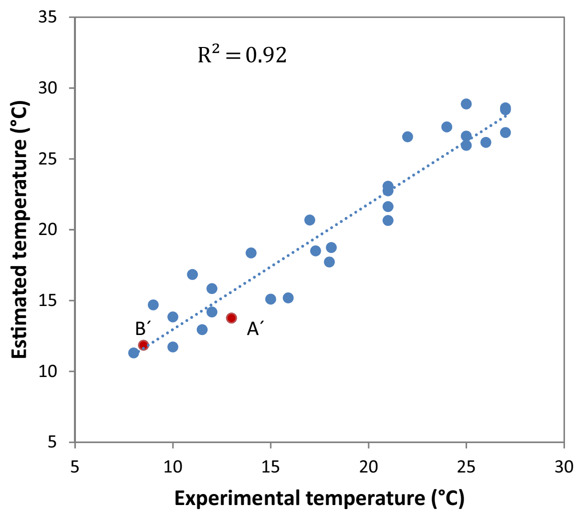

Fig. 5 Parity plot of experimental and calculated temperatures inside the reactor. Red points (stated here as A′ and B′) correspond to conditions with temperature axial profiles shown in Fig. 4

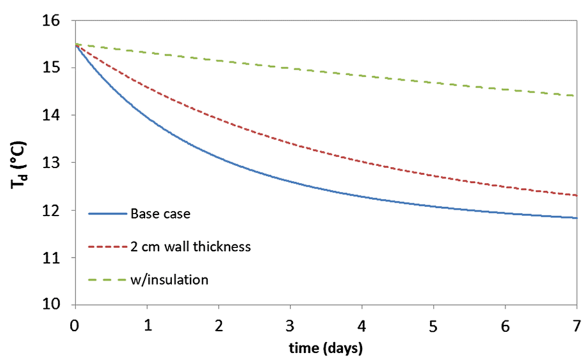

Fig. 6 Temperature profiles corresponding to the base case, a higher wall thickness biodigester and a biodigester with insulation

Study of the influence of the design variables over the heat transfer in the bioreactor

According to our field data, bacterial inhibition was detected during wintertime, with a drop in biogas production (see Sect. "Study of the main operational variables"). This behavior is attributed to thermal effects and directly affects the biodigester performance. In this section, by means of the proposed validated model, a theoretical study of the effect of the main design variables over the temperature inside the unit is made.

For comparison purposes, the point B corresponding to Fig. 3 ($T_\infty = 11.5$ °C, $T_d(t = 0) = 15.5$ °C) was considered as the base case. Figure 6 shows temperature profiles corresponding to: a) the base case; b) a biodigester with wall thickness of 2 cm (one magnitude higher than the one presented in Fig. 1) in order to increase the thermal resistance associated with conduction and temperature profiles; c) a biodigester with full insulation (*glass fiber conductivity*, $k = 0.043$ W/mK).

It is possible to observe in Fig. 6 that varying the biodigester wall thickness does not lead to significant temperature changes inside the biodigester. However, insulation of the biodigester would reduce thermal effects inside the biodigester leading to an almost isothermal profile. This means, that the mathematical model constitutes a useful tool to design improvements of the existing unit. In this sense, the model can contribute to reach a stable operation of the biodigester for the whole period of production, i.e., during the whole year.

Conclusions

In this work, biogas was produced in a bench-scale biodigester installed in a region with significant temperature changes during the year and fed with rabbit manure and ground sorghum grains. In fact, a specific methane yield of 134 ml CH_4/g VS and a degree of degradation of 85.2% of the substrate were obtained. Under an inlet substrate flow of 1.7 L/week, the biodigester produced 2.4 ml/min of biogas with a mean methane inlet composition of 60% CH_4 under stable neutral pH. Through these results, the process performance was evaluated as satisfactory considering that the biodigester was operated under non-controlled temperature conditions in a region with significant ambient temperature variation. In fact, it was possible to verify the ability of the system to operate properly under quite variable ambient conditions, observing a decrease in biogas production during the coldest months.

Regarding the liquid digestate, it presents a composition similar to values reported in the literature. Furthermore, small standard deviations for all the assessed variables were obtained over the total sampling time, demonstrating that the biodigester had reached a stable operation.

In this work, the proposed heat transfer model was validated with experimental data without parameter fittings and consequently, constitutes a useful tool for the design of new equipment or the improvement of the existing unit regarding the insulation system and the warming policies adopted. In this sense, the model can contribute to reach a stable operation of the biodigester for the whole period of production, i.e., during the whole year.

Abbreviations

1-D: One-dimensional; *L*: Biodigester height,; *D*: Biodigester diameter; *t*: Wall thickness; *k*: Thermal conductivity; TMP: Theoretical methane potential; Q_g: Flow rate of produced gas (ml/day); % CH_4: Methane percentage of the produced gas; Q_s: Inflow rate at the reactor (g/day); TS_{in}: Total solids content in the incoming substrate; VS_{in}: Volatile solids content in the influent; VS_{out}:

Volatile solids content in the effluent; $VS_{removed}$: Volatile solid´s degree of degradation; *Gr*: Grashof number; *g*: Gravity acceleration; T_s: Surface temperature; T_∞ : Ambient temperature; *x*: Characteristic length; ν: Kinematic viscosity; Q_T: Total heat exchanged; V_d: Volume occupied by the digestate; ρ_d: Density of the digestate; C_p: Calorific capacity of the digestate; T_d: Temperature in the biodigester; A_L: Lateral surface area (πDL); A_T: Top surface area $\left(\frac{\pi D^2}{4}\right)$; A_t: Total area; h_L: Heat transfer coefficient associated with free convection at the lateral surface; h_T: Heat transfer coefficient associated with free convection at the top surface; Ra_x: Rayleigh number; *Pr*: Prandtl number; $\bar{N}u_x$: Nusselt number; $\bar{h}_L$: Heat transfer coefficient for a vertical plate; $\bar{h}_T$: Heat transfer coefficient for a horizontal plate; $\frac{A_s}{P}$: Characteristic length associated to the top surface; α: Thermal diffusivity; β: Volumetric thermal expansion coefficient; $T_s(t)$: Outer surface temperature; $\bar{T}_\infty$: Average ambient temperature; VS: Volatile solids; TS: Total solids; C/N: Carbon-to-nitrogen ratio; FW: Fresh weight.

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Authors' contributions
EM and MR had fed and monitored the biodigester. IC performed sample collection and digestate characterization. EA formulated and ran the heat transfer model in collaboration with MP. SBRR carried out the calculations to evaluate the biodigestion performance. EA wrote the manuscript in collaboration with IC and SBRR. MP and all authors edited the manuscript and gave their consent to the final version. MP supervised the project; and EA, IC, SBRR and MP conceived the original idea of this work. All authors read and approved the final manuscript.

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Not applicable.

Consent for publication
All the contributing authors had seen and approved the submission to ***Bioresources and Bioprocessing*** as an original work.

Competing interests
The authors declare that they have no competing interests.

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