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Short Communication

Comparison of the mesophilic and thermophilic anaerobic digestion of spent cow bedding in leach-bed reactors

S. Riggio, M.A. Hernández-Shek, M. Torrijos, G. Vives, G. Esposito, E.D. van Hullebusch, J.P. Steyer, R. Escudíé

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Comparison of the mesophilic and thermophilic anaerobic digestion of spent cow bedding in leach-bed reactors

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Abstract

Anaerobic digestion of spent cow bedding in batch leach-bed reactors was compared in mesophilic and thermophilic conditions for the first time. Results show that the use of thermophilic conditions enhanced only the degradation kinetics of easily-degradable matter during the first days of the digestion, whereas similar methane yields (80% of the Biomethane Potential) were reached after 42 days at both temperatures. Therefore, thermophilic conditions did not improve the overall process performance when spent cow bedding, a substrate rich in slowly-degradable compounds, was digested. Moreover, the high initial biogas production rate in thermophilic reactors was found to significantly reduce the energetic performance of the cogeneration unit at industrial scale, leading to a 5.9 % decrease in the annual electricity production when compared to a mesophilic one.

Keywords

Dry anaerobic digestion; leach-bed reactor (LBR); thermophilic temperature; discontinuous biogas production; electric energy production

1 INTRODUCTION

Anaerobic digestion (AD) is a very widespread biological process aiming at the treatment of organic waste and the production of green energy. Spent animal bedding, the accumulating mixture of animal faeces with a bedding material (e.g. straw, wood chips) onto the soil of a stable, has been proved to be efficiently treated in discontinuous dry anaerobic digesters such as leach-bed reactors (LBRs) (Riggio et al., 2017). Spent animal bedding constitutes a slowly-degradable substrate mainly because of its high content in lignocellulosic material (Buffiere et al., 2006). For this reason digestion times ranging from 40 to 60 days are generally used in discontinuous LBRs at industrial scale. In order to improve the economic performance of the entire process, there is a real interest in increasing the substrate degradation kinetics, thus reducing the overall digestion time. In this regard the use of thermophilic conditions in LBRs treating spent cow bedding could represent an effective solution to enhance the process performance. Indeed, when comparing the influence of mesophilic and thermophilic temperatures, several authors agreed on the faster degradation kinetics when using thermophilic conditions to treat different substrates such as: spent horse bedding (Böske et al., 2015), the organic fraction of municipal solid waste (Fernández-Rodríguez et al., 2013), spent cow bedding (Gómez et al., 2011), wood chips (Hegde and Pullammanappallil, 2007) and cow dung (Jha et al., 2013).

In the literature, few data comparing mesophilic and thermophilic treatment are available on spent animal bedding consisting of faeces and straw. Böske et al. (2015) used a continuous upflow anaerobic solid-state (UASS) reactor to treat spent horse bedding, whereas Gómez et al. (2011) used a dry unmixed batch system to digest spent cow bedding. In thermophilic conditions, the first authors observed higher kinetics and methane yield than at mesophilic temperature, while the second reported higher kinetics and a lower methane yield. In addition to the discrepancy between their results, these latter hardly seem applicable to a different system such as a LBR.

The use of a LBR in thermophilic condition has not been frequently reported in the scientific

literature except for very few cases: Koppar and Pullammanappallil (2013) used it to treat citrus peel waste, Liang et al. (2014) to treat smooth cordgrass and Rico et al. (2015) to treat raw dairy manure (among other types). Moreover, no direct comparison has been made between LBRs run in mesophilic and thermophilic temperatures and nor has research ever involved two specific challenges connected with this discontinuous process: the start-up conditions (i.e. the inoculation) and the discontinuous biogas production. Inoculation, repeated at every digester loading, affects the methane production rates if it is not well managed, while the discontinuous gas production causes problems during combustion in a Combined Heat and Power (CHP) unit. Of note, the latter issue is particularly important when dealing with LBR plants in rural areas, since a reduced number of reactors, the main cause of a fluctuation in the biogas production, is often chosen to make this process economically feasible.

The efficiency of thermophilic treatment of spent cow bedding in LBRs remains an open question. Therefore, the aim of this work was to investigate if the operation of thermophilic mode when treating spent cow bedding in LBRs could be an effective measure for reducing the digestion time and increasing methane yield. In order to reach this objective, specific problems related to inoculation and the challenge connected to the combustion of biogas in a CHP unit were analyzed in detail.

2 MATERIALS AND METHODS

2.1 Experimental set-up

The three leach-bed reactors used in the present study were made of stainless steel; the internal diameter and total height were 40 cm and 80 cm, respectively, for a total volume of about 100 L. A mesh (3 mm holes) placed at 20 cm from the bottom separated the solid and the leachate volumes: 75 L and 25 L, respectively. To maintain the temperature, each reactor was connected to a dedicated thermo-regulated water bath. A centrifugal pump (Rover Pompe BE-M 20) was used to sprinkle the

leachate, stored at the bottom of the reactor, over the top of the bulk. A valve in the leachate circuit enabled samples to be taken for analysis while a port on the biogas circuit permitted the same for gas. The operating principle of the LBRs involved has been further detailed by Riggio et al. (2017).

2.2 Substrate collection and experimental conditions

Three conditions were tested: two reactors were inoculated with a mixture of digestate and leachate and were operated under mesophilic (37°C) or thermophilic (55°C) conditions (reactors named M_inoc and T_inoc, respectively); a third reactor was started up in thermophilic conditions but without specific inoculation (T_no inoc). Two successive runs were carried out in order to establish the process's stability and repeatability. The spent cow bedding used in each run was collected at the same farm during two different stable cleanings. The substrates sampled were stored for 2-3 days in plastic bags at ambient temperature before being used. The solid digestates and leachates used in run 1 were sampled from two previous batches adapted to thermophilic and mesophilic conditions for over three months (with two consecutive loadings). For run 2, the digestates and leachates collected at the end of run 1 were used instead. Total solids (TS), volatile solids (VS) and biomethane potential (BMP) tests (on raw matter) of digestate and spent cow bedding used in both run are reported in Table 1a. The protocols used have been described by Riggio et al. (2017).

The operating conditions for each run are described in Table 1b. In each reactor, about 1.5 kg of total solids (TS) of spent bedding was added. For the reactors inoculated, solid digestate was mixed to the spent bedding to reach a digestate TS/(substrate TS + digestate TS) of 13 %. The leachate was diluted before being added to the reactor in order to keep a N-NH_4^+ concentration in the leachate below 0.9 g L^{-1} at the start-up and to avoid any risk of nitrogen inhibition (Angelidaki and Ahring, 1993). The total amount of leachate to be added was chosen to keep the initial TS of the mix (manure + digestate + leachate) at 11.5 %, close to the one reported by Riggio et al. (2017) in similar systems. Before starting the digestion process, leachate was recirculated continuously for 10 min in order to achieve water saturation of the waste bed. Finally, the reactors were closed and the

internal recirculation of the leachate was scheduled twice a day for a total volume of $1 \text{ L kg}^{-1} \text{ TS d}^{-1}$. During digestion, volatile fatty acids (VFAs), pH, alkalinity and biogas volume and its composition were monitored. The frequency of analysis and the protocols used have been described by Riggio et al. (2017).

2.3 Hypothesis for electrical production

Based on the experimental results obtained in run 1, the electrical production of an industrial site running in thermophilic and mesophilic temperatures was simulated, and the overall amount of electrical energy produced was compared. The simulation considered the following hypothesis: treatment of 9,400 tons/year of spent cow bedding and 4 LBRs working in parallel, staggered over time with a batch duration of 44 days: every 11 days a LBR was emptied and reloaded. 4 LBRs were chosen as a representative number of digesters in this kind of farm plant. In fact, more digesters would affect the economic feasibility of the project and then this choice would not be realistic. A batch length of 44 days was chosen, not only because it is a representative digestion time for this kind of substrate, but also because the methane yields of the two conditions tested were the same after this time slot, cancelling the influence due to this factor on the comparison made. Finally, a staggering time of 11 days between the start-up of the digesters was indirectly set after the previous choices (4 digesters and 44 days of batch duration).

Biogas storage was not considered. A CHP unit with an electrical nominal power (P_{nom}) of 250 kW_{elec} (Schnell, 2016) was chosen, based on the average annual energy production of the site (considering the annual amount of substrate and the duration time evoked above). A minimum methane content of 45% was set for injection into the CHP unit and an electrical efficiency (η_{elec}) of 45.5 % was considered at P_{nom} on manufacturer recommendation. The electrical efficiency was considered to vary linearly (Bianchi et al., 2014) between electrical nominal power ($\text{max}_{\eta_{\text{elec}}}$ 45.5 %) and the electrical minimal power P_{min} ($\text{min}_{\eta_{\text{elec}}}$ 41.0 %) with the equation $\text{min}_{\eta_{\text{elec}}} = \text{max}_{\eta_{\text{elec}}} \times 0.9$. It is important to note that the electrical minimal power P_{min} (50% of P_{nom})

corresponds to the power under which the CHP shuts down.

3 RESULTS AND DISCUSSION

3.1 Effect of inoculation in thermophilic conditions

Figure 1a permits a comparison to be made between the specific methane production (SMP) rates in thermophilic conditions with and without the addition of solid digestate as inoculum. SMP rates between the two conditions were different: for the first 12 days in run 1 and 24 days in run 2.

Moreover, in both runs a lower SMP rate was measured during the first 5 days when the LBR was not inoculated with solid digestate. This result indicates that an inoculation with solid digestate mostly influenced the start-up phase of the process, leading to higher SMP peaks. Figure 1b shows that the VFAs which accumulated during this period were rapidly consumed after 5 days in both conditions and runs. Small differences were observed when adding solid inoculum, while different VFA concentration peaks between runs were due to the use of different samples of spent cow bedding. All along the digestion process, the pH remained in a suitable range for an optimized anaerobic digestion (i.e., 7.6 – 8.2).

In addition to the results of Chachkhiani et al. (2004) showing that thermophilic microbial community in cattle manure is present even if at a subdominant level compared to mesophilic communities, these results show that these microorganisms were sufficiently active to permit spent cow bedding to be digested without a specific addition of solid inoculum. The slightly faster start-up was not found significant enough to justify the use of solid inoculum when using spent cow bedding, a substrate which, in any case, needs a long time to be degraded.

3.2 Comparison of thermophilic and mesophilic conditions

3.2.1 Reactor performance

Figure 2a compares the SMP rates in LBRs inoculated with solid digestate and run under thermophilic (T_inoc) or mesophilic (M_inoc) temperatures. Operating under thermophilic

temperature increased the initial degradation kinetics as suggested by the higher SMP in thermophilic conditions during the first 7-8 days. The difference in the peaks reached was related to the use of two different spent bedding samples between runs. After 15 days, the SMP rates for both runs and conditions were similar.

Figure 2b presents the methane yield (MY) for both temperature conditions and runs. Run 2 was carried out to confirm SMP rates and MYs, but a technical problem required the interruption of the experiment after 37 days. However, MYs measured in runs 1 and 2 were very similar, thus indicating that the inoculum had already adapted in run 1 and that the results were repeatable. More precisely, after 37 days the errors on the MYs between the two runs (calculated as $|x_1 - x_2|/M(x_1, x_2)$ with x_1 and x_2 the measures and M the mean value of the measures) were 3.5% and 2.1% for the thermophilic and mesophilic reactors, respectively. Because of the higher initial SMP rates, the MY in thermophilic conditions were higher and only after about 42 days of operation the same MY was reached in thermophilic and mesophilic reactors. The additional amount of methane produced in thermophilic, in comparison to mesophilic conditions, is depicted in Figure 2c. Initially, the surplus was significant in both runs but it rapidly decreased to reach an average value of 27% at 13 days and 0% at 42 days. Methane yield at 42 days corresponded to 80% of the BMP (run 1). This means that if 80% of the potential energy were recovered, then thermophilic temperatures would not offer any advantage over mesophilic temperatures. However, for lower BMP value, the interest in using thermophilic conditions by reducing batch duration should be assessed economically.

In batch digesters fed with corn stover and operated at 20% TS, Shi et al. (2013) also reported similar MY in thermophilic and mesophilic conditions after 38-45 days of operation. However, when treating easily-degradable substrates such as vegetable waste, Hegde and Pullammanappallil (2007) reported better performance under thermophilic conditions with a significant reduction of the time (10 days) to reach the 95% of the BMP. The particular behaviour observed when treating spent

cow bedding suggests that a thermophilic temperature had an impact mainly on its easily-degradable fraction (higher methane production rates over the first 7-8 days) and not on the slowly-degradable one (similar SMP rates after 12 days). Since the easily-degradable compounds represent only a small fraction of spent cow bedding which is known to be rich in lignocellulosic material (Riggio et al., 2017), the advantage of operating under thermophilic conditions was thus extremely limited. It is interesting to note that the degradation kinetics recorded were not influenced by nitrogen inhibition (N-NH_4^+ kept below 0.9 g L^{-1}) and only the effect of temperature on kinetics was observed. Nitrogen inhibition should be considered as a further problem requiring a solution in thermophilic conditions.

Higher VFA concentrations were observed in thermophilic conditions as a consequence of faster hydrolysis (Figure 3a). However, after 5 days, very low VFA concentrations were measured in thermophilic conditions while 12 days were needed in mesophilic conditions to degrade completely the accumulated VFAs. The delay observed was due to an accumulation of propionic acid in mesophilic conditions (Figure 3b). In fact, thermophilic temperatures favour the consumption of propionic acid because the Gibbs free energy of the reaction (Amani et al., 2010) is lower in these conditions. The high alkalinity in the system (higher than $5 \text{ g CaCO}_3 \text{ L}^{-1}$ at start-up) hampered a big drop in the pH which remained between 7.3 and 8.2, considering both runs and temperature ranges.

3.2.2 Electricity production

Methane production rates have a significant impact on methane conversion into electricity through CHP units, mainly on account of their technical constraints (i.e. minimum methane content and maximum combustion power). Figure 4a depicts the combustion power (P_{biogas}) associated to the cumulated biogas of the four digesters at the inlet of the CHP. First, to prevent dropping below the minimum methane content (i.e. 45%), the use of biogas produced from a new batch can start only when the methane content is high enough and, hence, a part of the initial biogas produced is not exploited. For both temperatures, the amount of methane lost is quite similar: the difference is a

mere 1.4%. In addition, in thermophilic conditions, high SMP rates during the first days of each batch cause important fluctuations of the total methane flow at the entrance of the CHP unit (Figure 4a). When P_{biogas} overtakes the maximum power accepted by the CHP (i.e. 550 kW_{comb} or 250 kW_{elec}), the surplus biogas is burned in a torch and then lost if no storage is provided. As a consequence, about 7.9% of the methane is not converted into electrical power in thermophilic conditions compared to the 2.3% in a mesophilic environment.

Another interesting aspect is showed by Figure 4b which illustrates the electrical power (P_{elec}) produced by the CHP from biogas collected in mesophilic and thermophilic conditions. In mesophilic conditions, the CHP is operated at its P_{nom} for a longer than in thermophilic conditions (i.e. 54 % and 36 % of the time, respectively). As a consequence, a better exploitation of the biogas energy can be achieved in mesophilic conditions, since η_{elec} is the highest at P_{nom} whereas it decreases for lower powers.

To sum up, higher methane production rates in thermophilic conditions during the first days of the batch process are proved to induce, on one hand, the loss of a part of the biogas produced because the CHP power limits are overtaken, and, on the other hand, a poorer exploitation of the biogas's combustion power due to variable electrical efficiency. Based on this simulation, 5.9% less electrical energy can be produced for an annual period in thermophilic conditions (1.84×10^6 kW·h_{elec}) as opposed to mesophilic conditions (1.95×10^6 kW·h_{elec}). Thus, a reduced electric energy production represents a further drawback when using thermophilic temperatures in a discontinuous process, in addition to the higher energy consumption, the higher investment costs due to the use of thermo-resistant materials and to other biological issues such as nitrogen inhibition.

4 CONCLUSIONS

The digestion of spent cow bedding, a slowly-degradable substrate, was compared at mesophilic and thermophilic conditions. Thermophilic temperature increased methane production but this effect was restricted to the start-up period (degradation of the easily-degradable fraction), with a

reduced advantage for the cumulated methane recovered over the long term. Furthermore, higher kinetics during the first days caused higher fluctuation of the methane flow at the inlet of a CHP unit, with consequent lower electrical energy production. These issues should be considered when assessing advisability of implementing thermophilic conditions for the digestion of spent cow bedding in LBRs.

5 ACKNOWLEDGEMENTS

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7 FIGURE CAPTION

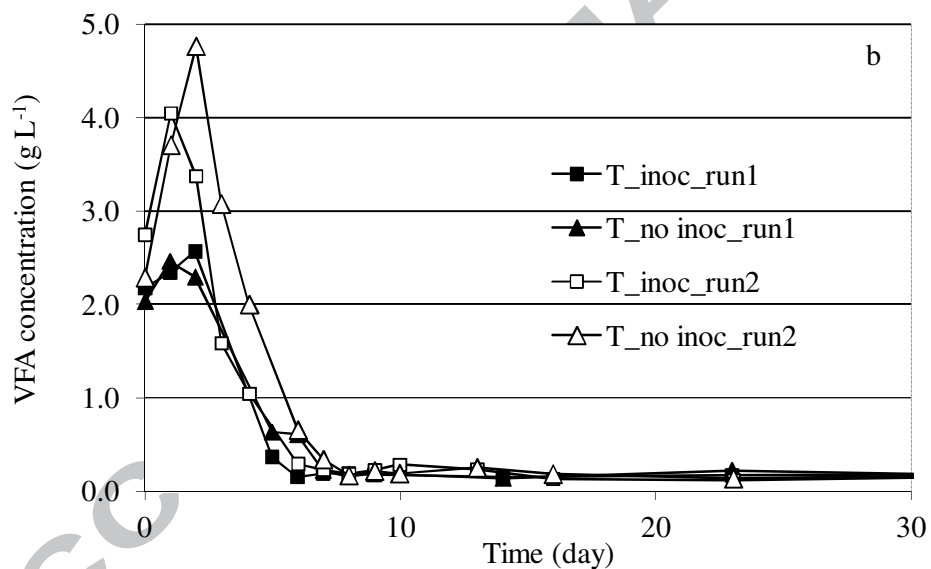
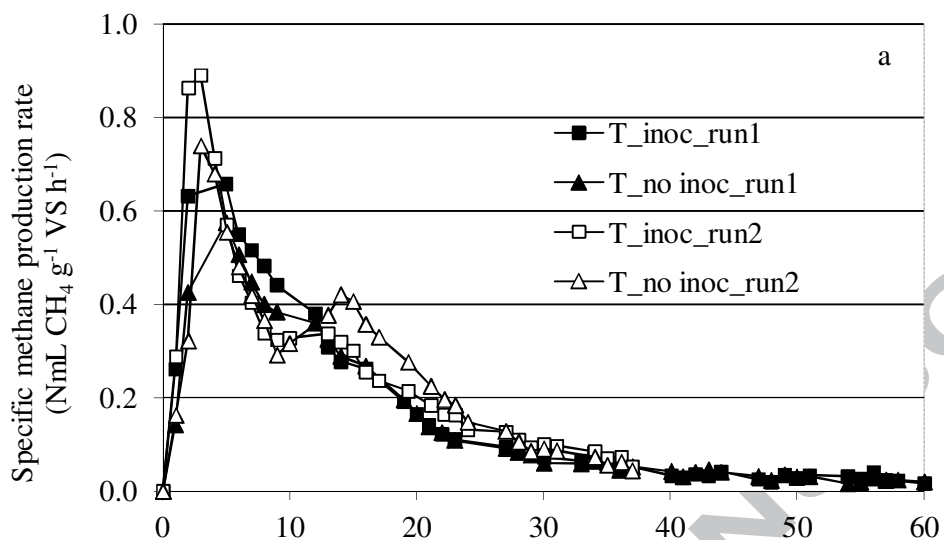
Table 1: (a) Characterization of the substrates loaded in the reactors in run 1 and run 2: total solids (TS), volatile solids (VS), ratio of VS to TS (VS/TS) and the BioMethane potential (BMP). (b) Loading set-up of run1 and run 2

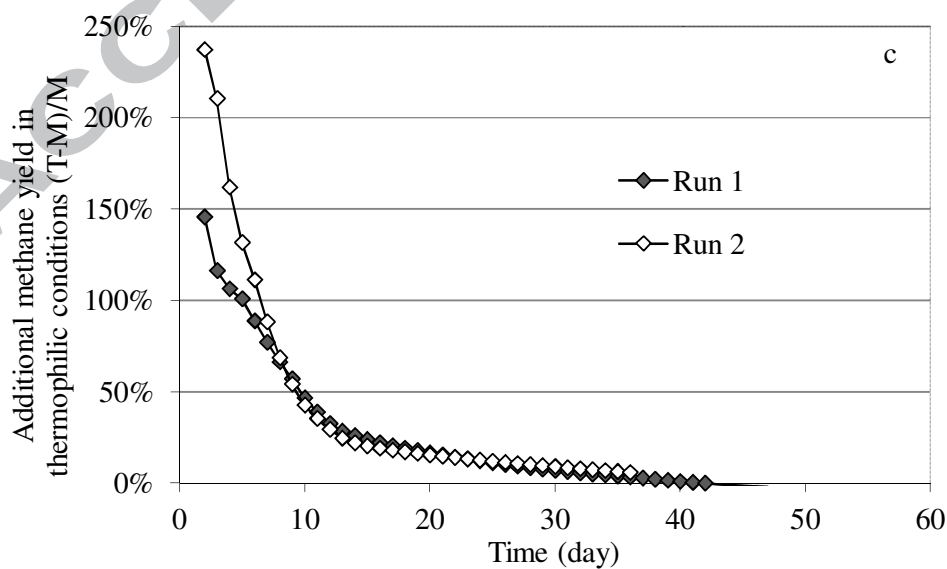
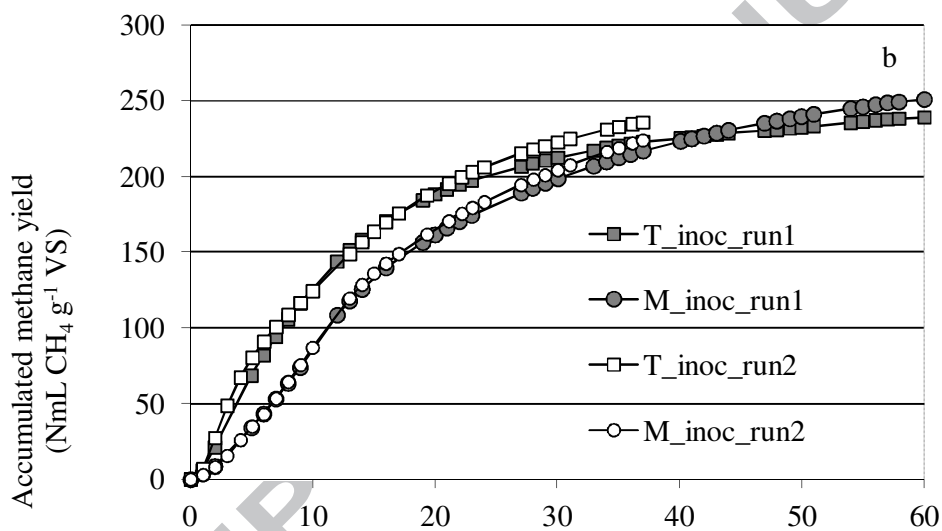
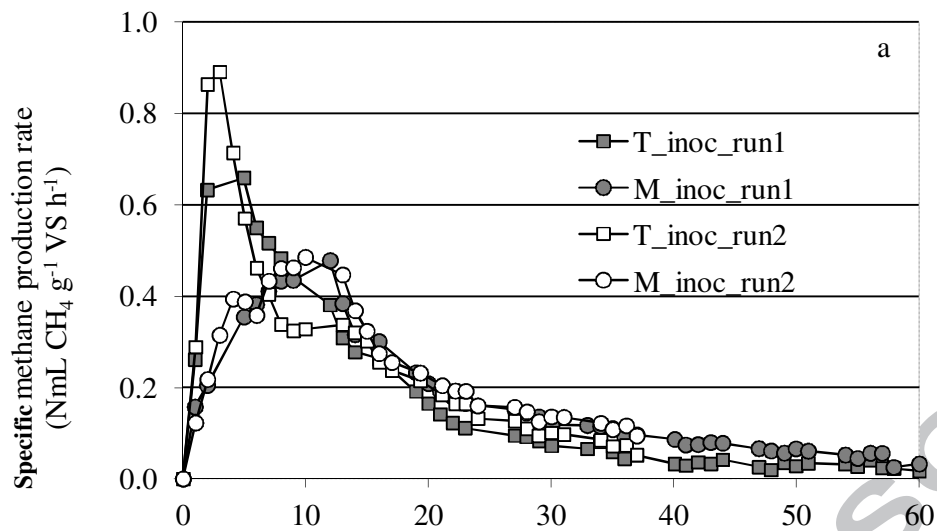
Figure 1: Comparison of thermophilic conditions with (T_inoc) and without (T_no inoc) solid digestate, in run 1 and run 2: (a) specific methane production rate; (b) VFA concentration

Figure 2: Comparison of mesophilic (M_inoc) and thermophilic (T_inoc) conditions, in run 1 and run 2: (a) specific methane production rate; (b) methane yield; (c) additional methane yield in thermophilic conditions

Figure 3: Comparison of mesophilic (M_inoc) and thermophilic (T_inoc) conditions: (a) VFA concentration in run 1 and run 2; (b) acetate and propionate concentrations in run 1

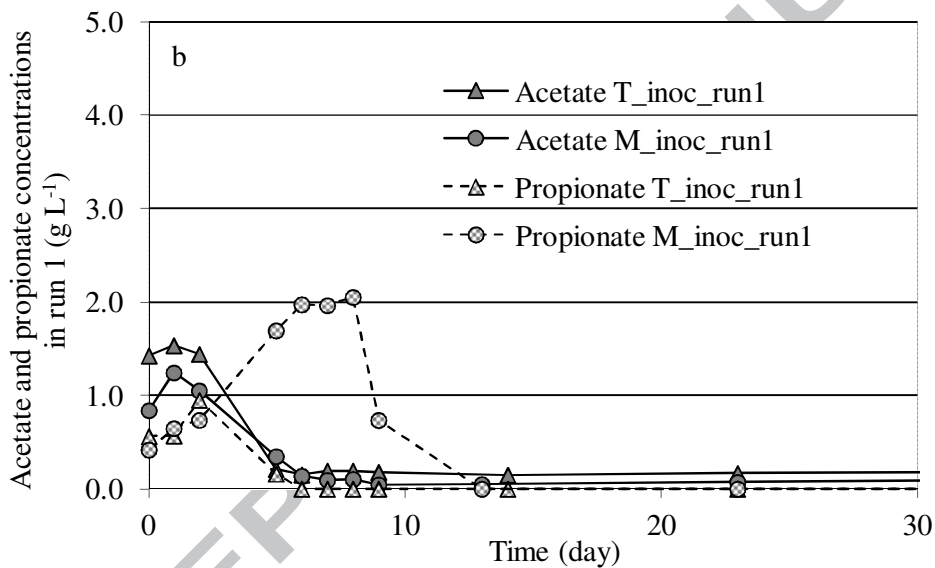
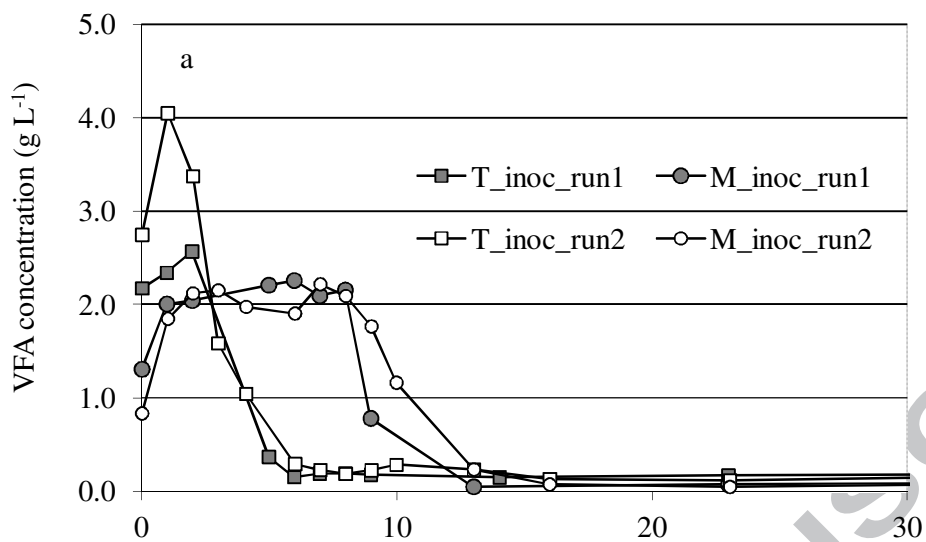
Figure 4: Comparison of a simulated industrial plant operated in mesophilic and thermophilic conditions. The simulation, based on the data from run1, consider the treatment of 9,400 tons/year of spent cow bedding, the installation of a combined heat and power (CHP) unit of 250 kW_{elec} and the use of 4 digesters staggered in time with a batch duration of 44 days. (a) Heat power contained in the cumulated biogas at the inlet of the CHP unit; (b) electrical power produced considering the CHP power working range: the maximum (P_{max_CHP}) and the minimum (P_{min_CHP})

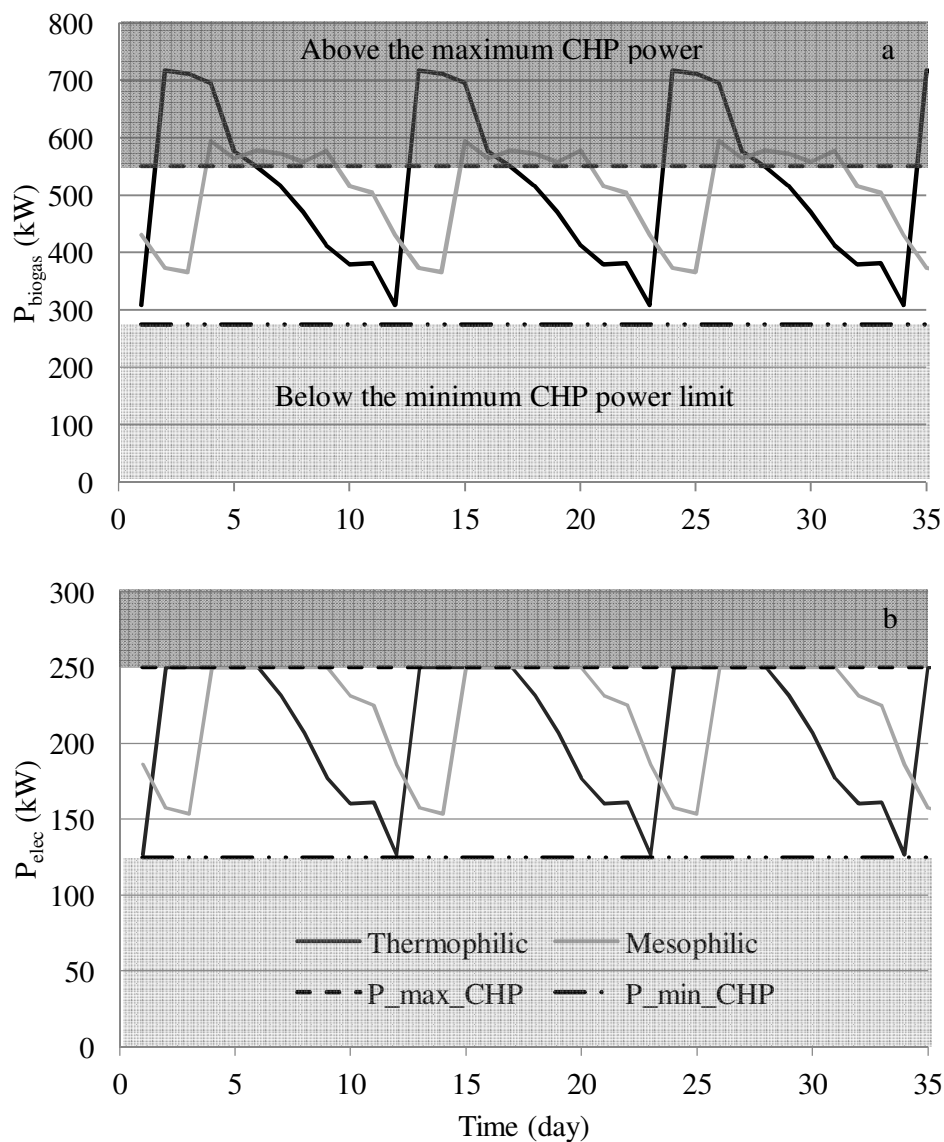




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a		Digestate T	Digestate M	Spent cow bedding
Run 1				
TS	kg TS kg ⁻¹ RM	(14.9 ± 0.5) %	(15.5 ± 0.0) %	(25.5 ± 0.1) %
VS	kg VS kg ⁻¹ RM	(11.3 ± 0.4) %	(11.6 ± 0.0) %	(22.8 ± 0.1) %
VS/TS	kg VS kg ⁻¹ TS	76.2 %	75.0 %	89.4 %
BMP	NmL CH ₄ g ⁻¹ VS	-	-	282 ± 25
Run 2				
TS	kg TS kg ⁻¹ RM	(14.3 ± 0.6) %	(15.7 ± 2.6) %	(28.1 ± 1.9) %
VS	kg VS kg ⁻¹ RM	(11.1 ± 0.3) %	(12.7 ± 1.9) %	(23.7 ± 2.2) %
VS/TS	kg VS kg ⁻¹ TS	78.1 %	81.0 %	84.5 %
BMP	NmL CH ₄ g ⁻¹ VS	-	-	-

Average values of the triplicate and standard deviation

b		Spent cow bedding	Digestate	Leachate	Water
		kg	kg	L	L
Run 1	T_inoc	5.35	1.51	4.0	4.0
	T_no inoc	5.35	-	4.0	4.0
	M_inoc	5.35	1.36	4.0	4.0
Run 2	T_inoc	5.90	1.56	3.0	4.4
	T_no inoc	5.90	-	3.0	4.4
	M_inoc	5.90	1.60	5.0	2.4

HIGHLIGHTS

1. Spent cow bedding digestion was compared in mesophilic and thermophilic conditions
2. Thermophilic temperature (TT) enhanced mainly easily-degradable matter digestion
3. Mesophilic and thermophilic reactors reached the same methane yield after 42 days
4. Higher biogas fluctuation at TT induced a decrease in the electricity production
5. The digestion of spent cow bedding at TT started easily without digestate addition