Enhancement of Thermophilic Anaerobic Sludge Digestion by 70ºC Pre-Treatment: Energy Considerations

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ABSTRACT: The objective of this work was to investigate the effect of a low temperature pre-treatment (70°C) on the thermophilic anaerobic digestion of sewage sludge. Experimental results were used for the calculation of theoretical energy balances of full-scale digesters with and without pre-treatment step. The 70°C sludge pre-treatment increased sludge solubilization by 10 times and enhanced volatile fatty acids generation. Biogas production increased up to 30–40% and methane content in biogas from 64 to 68–70%. Theoretical calculations showed that additional surplus energy production would be expected by incorporating a 70°C pre-treatment step to a thermophilic reactor.

INTRODUCTION AND OBJECTIVES

THERMOPHILIC ANAEROBIC DIGESTION is more efficient than mesophilic anaerobic digestion in terms of biogas production, volatile solids removal and pathogens destruction [1]. Heat requirements in thermophilic sludge digestion are about twice those of mesophilic digestion, but they may be covered with a combined heat and power (CHP) unit fuelled with biogas, together with heat regeneration from the effluent sludge [2]. The conversion of full-scale two-stage digesters from mesophilic to thermophilic operation has shown that heat requirements are fully covered by increased biogas production; and that additionally surplus electric energy is yielded [3].

Since hydrolysis is the rate limiting step of sludge digestion, the process might be further accelerated by sludge pre-treatment through mechanical, thermal or chemical processes [4], being low temperature pre-treatments (< 100ºC) amongst the least energy consuming. Such pre-treatments have been pointed out as effective at increasing biogas production from sewage sludge [4–8]. In theory, extra energy requirements of a thermal pre-treatment step should be fully covered by the extra methane production [7,8].

The objective of this work was to assess the effect of a low temperature pre-treatment (70ºC) on the efficiency of thermophilic anaerobic digestion of sewage sludge in terms of net energy production. Firstly, the effect of sludge pre-treatment time (9–72 h) was evaluated by the increase in volatile dissolved solids (VDS), volatile fatty acids (VFA) and biogas production in thermophilic batch tests. Secondly, semi-continuous process performance was studied in a 5 L continuous stirred tank reactor (CSTR) working at 55ºC and 10 days solids retention time (SRT). Finally, the results were used for the calculation of theoretical energy balances (i.e. full-scale thermophilic digesters with and without pre-treatment step).

MATERIALS AND METHODS

Sewage Sludge

The mixture of thickened primary sludge (PS) and waste activated sludge (WAS) used for this work was obtained from a municipal wastewater treatment plant (WWTP) near Barcelona (Spain). In this WWTP, PS and WAS are thickened and mixed before undergoing

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mesophilic anaerobic digestion. The sampling point was located at the centrifuge pumping the sludge mixture to the digesters. Samples were collected weekly and stored at 4ºC until use.

Low Temperature (70ºC) Pre-treatment

The low temperature pre-treatment was carried out at 70ºC in order to enhance thermal solubilization of particulate material, as well as enzymatic hydrolysis. Beakers containing 0.5 L of sludge were submersed in a thermostatic bath at 70ºC during 9, 24, 48 and 72 h. The beakers were covered with plastic film, to avoid water evaporation, and gently stirred (Heidolph RZR1) to ensure temperature homogeneity. Samples of raw and pre-treated sludge were analysed for total solids (TS), volatile solids (VS), total dissolved solids (TDS), VDS, VFA and pH. The effect of pre-treatment time was assessed by the increase in VDS and VFA. Sludge solubilization was evaluated by the increase in the ratio soluble to total volatile solids (VDS/VS).

Anaerobic Batch Tests

Biogas production was initially determined by means of thermophilic batch tests, using the device described in Ferrer *et al.* [9]. The inoculum was thermophilic digested sludge from a 5 L CSTR. The substrate was either pre-treated sludge (at 70ºC for 9, 24, 48 and 72 h) or raw sludge (control treatment). Each treatment was performed in triplicate. Each bottle-reactor (300 mL, SIGG®) was filled with 100 g of inoculum and 50 g of substrate (the blank treatment contained 150 g of inoculum only) and was subsequently purged with N_2 and sealed. The bottles were incubated at 55ºC and biogas production was followed by the pressure increase in the headspace by means of a SMC Pressure Switch manometer (1 bar), until biogas production ceased. Accumulated volumetric biogas production (mL) was calculated from the pressure increase in the headspace volume at 55 ºC and expressed under normal conditions (20ºC, 1 atm).

Lab-scale Thermophilic Anaerobic Digestion

The effect of 70ºC sludge pre-treatment on semi-continuous process performance was studied in a 5 L CSTR. The experimental set-up is described elsewhere [10]. Prior to the experiments with pre-treated sludge, the reactor was operated at 55ºC for one year, at decreasing SRT from 30 to 10 days. It was then maintained under steady-state conditions at 10 days SRT for 2 months (control treatment). The digester was subsequently fed with pre-treated sludge (at 70ºC, for 9, 24 and 48 h), with a total experimental duration of 6 months (approximately 2 months per pre-treatment). The daily flow rate was 500 mL of sludge, which was pre-treated following the protocol described above (Low temperature (70ºC) pre-treatment Section). The process was followed by on-line measurement of biogas production and by periodical analyses of influent and effluent sludge (TS, VS, VFA, pH and alkalinity) and biogas (% CH_4).

Analytical Methods

The solids content of sludge was determined according to Standard Methods [11]. TS and VS were determined directly from sludge samples, whereas TDS and VDS were determined from the supernatant of samples centrifuged at 7000 rpm. Supernatants underwent vacuum filtration through 1.2 µm nominal pore size glass fibber filters. pH, alkalinity and VFA (acetic, propionic, iso-butyric, n-butyric, iso-valeric and n-valeric acids) were also analysed from the filtrate supernatant. Samples for VFA analysis were further filtered through a 0.45 µm nylon syringe filter. VFA and biogas composition were determined by gas chromatography (Perkin-Elmer AutoSystem XL Gas Chromatograph).

Energy Balance

Theoretical energy balances were calculated by extrapolating experimental data to full-scale digesters.

Description of the System

The digesters were designed as cylindrical tanks with a width to eighth ratio 2:1 [12]. The sludge volume in the digesters (V) was supposed to be 80% of the total volume; leaving the remaining 20% for gas collection. It was assumed that digestion tanks were made of concrete, wall insulation reducing the heat transfer coefficient from 5 to 1 W m^{-2} $ºC^{-1}$ [12]. The pre-treatment step was conceptually defined as the first digester of a two-stage process, and not as a batch pretreatment followed by a single-stage digester.

Two alternatives were assessed in terms of energy recovery: a system with energy recovery from the biogas produced; and a system with energy recovery from the biogas produced and from the effluent sludge. In all cases it was assumed that biogas was fuelled to a CHP unit, generating electricity and heat. Output electricity would cover electricity requirements for sludge pumping and mixing, whereas output heat would be used to heat influent sludge by means of a sludge-to-water heat exchanger. In the system with heat recovery from the effluent sludge, influent sludge would also be heated by means of an additional heat exchanger; while cooling the digested sludge prior to dewatering [13].

Two environmental temperatures were considered, corresponding to warm seasons (20ºC) and cold seasons (0ºC) in a Mediterranean location like Barcelona Metropolitan Area. The minimum sludge temperature was assumed to be 10ºC when environmental temperature was 0ºC [2, 12].

Energy Requirements

Energy requirements of heated completely mixed anaerobic reactors may be divided into input electricity and input heat, calculated according to Equations (1) and (2). Input electricity for sludge pumping and for the stirring of the digester were estimated as 1.8×10^3 kJ m$^{-3}_{sludge}$ and 3×10^2 kJ m$^{-3}_{reactor}$ d^{-1}, respectively [7].

Heat requirements were calculated using Equation (2) which includes the amount of heat needed to raise the influent sludge temperature from ambient to process temperature; and to compensate for heat losses through the walls of the digester [14]. Heat requirements to raise the influent sludge temperature can be calculated assuming that sludge specific density and specific heat are the same as those of water, thus 10^3 kg m^{-3} and 4.18 kJ kg^{-1} ºC^{-1}, respectively [12]. An efficiency of 85% for heat recovery from the effluent sludge was assumed [7]. Heat losses depend on the surface area of the reactor, the heat transfer coefficient and environmental conditions. For the purposes of this study, only the heat losses through the walls of the digester were calculated, since they account for the major energy loss of the system [12].

$$E(input,\ electricity) = Q\theta + V\omega \tag{1}$$

$$E(input,\ heat) = Q\rho\gamma(T_r - T_{sludge})(1 - \lambda) + kA(T_r - T_{env})86.4 \tag{2}$$

where:

$E(input,\ electricity)$ = total electricity requirement (kJ d^{-1})
$E(input,\ heat)$ = total heat requirement (kJ d^{-1})
Q = sludge daily flow rate (m$^3_{sludge}$ d^{-1})
V = volume of sludge in the reactor (m$^3_{reactor}$)
θ = electricity consumption for pumping (kJ m$^{-3}_{sludge}$)
ϖ = electricity consumption for stirring (kJ m$^{-3}_{reactor}$ d^{-1})
ρ = specific density of sludge (kg m$^{-3}_{sludge}$)
γ = specific heat of sludge (kJ kg^{-1} ºC^{-1})
T_r = process temperature (ºC)
T_{sludge} = influent sludge temperature (ºC)
λ = heat recovered from effluent sludge (%)
T_{env} = environmental temperature (ºC)
k = heat transfer coefficient (W m^{-2} ºC^{-1})
A = surface area of the reactor wall (m^2)
86.4 = conversion coefficient of W into kJ d^{-1}

Energy Output

Output electricity and heat were calculated according to Equations (3) and (4). It was assumed that the biogas was fuelled to a CHP unit, with conversion efficiencies of 35% and 55% for electricity and heat, respectively; energy loss accounting for the remaining 10 % [2]. The energy content of methane is 35,800 kJ m^{-3} [12].

$$E(output,\ electricity) = P_{CH_4}V\xi\eta \tag{3}$$

$$E(output,\ heat) = P_{CH_4}V\xi\psi \tag{4}$$

where:

$E(output,\ electricity)$ = the electricity produced (kJ d^{-1})
$E(output)$ = the heat produced (kJ d^{-1})
P_{CH4} = the methane production rate (m$^3_{CH4}$ m$^{-3}_{reactor}$ d^{-1})
V = the volume of sludge in the reactor (m$^3_{reactor}$)
ξ = the lower heating value of methane (kJ m$^{-3}_{CH4}$)
η = the efficiency of CHP for electricity generation (%)
ψ = the efficiency of CHP for heat generation (%)

Calculation of the Energy Balances

In this work, the term energy balance is used to express the difference between the energy output and input of the process, which is calculated by Equations (5)–(7).

$$\Delta E(total) = \mathrm{E}(output) - E(input,electricity) - E(input,heat) \tag{5}$$

$$\Delta E(electricity) = E(output,electricity) - E(input,electricity) \tag{6}$$

Table 1. Parameters used for the Calculation of Theoretical Energy Balances from Experimental Data in Table 3.

Parameter	Value	Source
Pre-treatment temperature + process temperature (°C)	70 + 55	This work (Table 3)
Pre-treatment SRT (h) + process SRT (d)	9, 24, 48 + 10	This work (Table 3)
Sludge daily flow rate ($m^3_{sludge}\ d^{-1}$)	100	Defined for calculation
Environmental temperature, cold season / warm season (°C)	0 / 20	Defined for calculation
Heat transfer coefficient, insulated / non-insulated ($W\ (m^2\ °C)^{-1}$)	1 / 5	[12]
Energy consumption for pumping ($kJ\ m^{-3}$)	1.8×10^3	[7]
Energy consumption rate for stirring ($kJ \cdot m^{-3} \cdot d^{-1}$)	3×10^2	[7]
Specific density of sludge ($kg\ m^{-3}$)	10^3	[12]
Specific heat of sludge ($kJ\ (kg\ °C)^{-1}$)	4.18	[12]
Lower heating value of methane ($kJ\ m^{-3}$)	35,800	[12]
Efficiency of the CHP unit for electricity generation (%)	35	[2]
Efficiency of the CHP unit for heat generation (%)	55	[2]
Efficiency of heat recovery from effluent sludge (%)	85	[7]

$$\Delta E(heat) = E(ioutput,heat) - E(input,heat) \tag{7}$$

Parameters and input data used for the calculation of energy balances are summarised in Table 1.

RESULTS AND DISCUSSION

Low Temperature (70ºC) Pre-treatment

The expected effect after thermal pre-treatment of sludge was an increase in soluble materials (i.e. VDS). The disruption of the complex activated sludge floc structure may release biopolymers such as proteins or sugars from the floc into the soluble phase [15]; while the disruption of microbial cells from WAS should lead to their solubilization into carbohydrates, proteins, lipids and VFA [16]. As shown in Table 2, the concentration of VDS increased from around 1.5 g VDS L^{-1} in the raw sludge to 11.9–13.8 g VDS L^{-1} after 9, 24 and 48 h thermal pre-treatment, resulting in an increase in VDS/VS ratio from 0.05 to 0.44–0.48. In this way, the proportion of soluble to total organic matter increased by almost 10 times, from 5% to 50%. The VFA content increased from about 0 to nearly 5 g L^{-1} after 72 h pre-treatment.

Comparing the evolution of VDS and VFA, there is a sharp increase in VDS, followed by a progressive generation of VFA after 24 h. Sludge solubilization after 70ºC pre-treatment seems to occur rapidly, reaching a maximum VDS within 9–24 h. While some studies suggest even shorter periods (30–60 min) for WAS solubilization at 60–80ºC [16,17], longer pre-treatments at 70ºC may favour the activity of thermophilic or hyperthermophilic bacteria, promoting enzymatic hydrolysis and resulting in a predigestion step [6,7].

Table 2. Composition of the Raw Sludge (0 h) and Sludge Pre-treated at 70ºC (9, 12, 48 and 72 h).

	Pre-treatment Time (h)				
Parameter	0	9	24	48	72
TS ($g\ L^{-1}$)	38.97	38.58	38.70	36.61	32.34
VS ($g\ L^{-1}$)	28.87	28.12	28.78	26.20	22.74
VS/TS	0.74	0.73	0.74	0.72	0.70
TDS ($g\ L^{-1}$)	2.54	13.97	15.72	13.91	9.32
VDS ($g\ L^{-1}$)	1.51	12.49	13.79	11.91	8.11
VDS/TDS	0.59	0.89	0.88	0.86	0.87
VDS/VS	0.05	0.44	0.48	0.45	0.36
Total VFA ($g\ L^{-1}$)	0.11	0.32	0.62	2.86	4.86
Acetate ($g\ L^{-1}$)	0.06	0.25	0.44	1.25	1.89
Propionate ($g\ L^{-1}$)	0.05	0.07	0.15	0.63	0.94
iso-Butyrate ($g\ L^{-1}$)	0.00	0.00	0.00	0.17	0.41
n-Butyrate ($g\ L^{-1}$)	0.00	0.00	0.00	0.29	0.73
iso-Valerate ($g\ L^{-1}$)	0.00	0.00	0.00	0.52	0.89
n-Valerate ($g\ L^{-1}$)	0.00	0.00	0.00	0.00	0.00

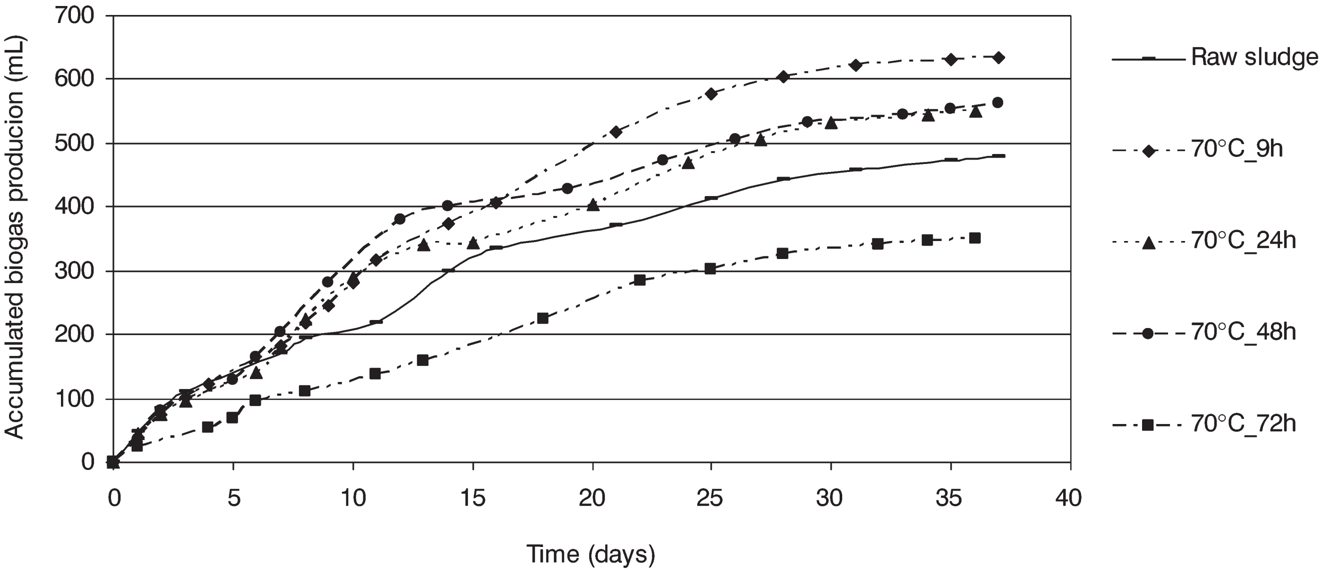

Figure 1. *Biogas production in thermophilic anaerobic biodegradability tests with raw and 70°C pre-treated sludge (9, 24, 48 and 72 h).*

Anaerobic Batch Tests

Figure 1 shows the evolution of accumulated biogas production during thermophilic batch tests. Initial biogas production rate up to day 7 was similar in all cases, except for the 72 h pre-treated sludge. However, at day 10 (i.e. SRT of the CSTR) accumulated production was nearly 300 mL for 9, 24 and 48 h pre-treated samples, almost 50% higher than for the control treatment (200 mL) while it was considerably lower for the 72 h pre-treated. The lowest biogas production obtained with the 72 h pre-treatment could be attributed to a certain biodegradation of organic compounds during the pre-treatment step, which is in accordance with lower VS and VDS concentrations in the sludge (Table 2).

Performance of Thermophilic Anaerobic Digestion at 10 days SRT

The results with pre-treated sludge (Table 3) clearly show that the process was more efficient in terms of biogas production and yield in all cases, with increases in the range of 30–40%, following the tendency observed in the batch tests. Lower increase with the 24 h pre-treatment (10%) may be attributed to lower VS content in the influent sludge obtained from the WWTP during this period. It is observed that, in spite of the variability of solids concentration in the influent sludge, solids concentration in the effluent is fairly similar for all treatments. Apparently, the higher the VS fed, the higher the VS removed, and the higher the biogas production. According to this, increasing the solids concentration in the influent sludge up to of 55 g TS L^{-1} and 30 g VS L^{-1}, allows to increase biogas production (i.e. energy production) maintaining the quality of the effluent. Biogas yield was also enhanced in all cases, being some 30% higher with pre-treated sludge (0.28–0.30 L gVS_{fed}^{-1}) than with raw sludge (0.22 L gVS_{fed}^{-1}). The same pattern described for biogas production applies to methane production. Moreover, methane content in biogas was also always higher after sludge pre-treatment, around 69% vs. 64% with raw sludge.

According to the results, it seems that 70ºC sludge pre-treatment has similar effects in subsequent thermophilic digestion regardless of pre-treatment time. If no additional benefits are obtained, the shorter the pre-treatment time, the lower the costs related to energy consumption and reactor volume. Therefore, 9 h pre-treatment should be enough to enhance thermophilic digestion of sludge at 10 days SRT. Two-stage systems coupling a hyperthermophilic digester (68–70ºC, 2–3 days SRT) and a thermophilic digester (55ºC, 12–13 days SRT) have also been found to be more efficient than single-stage thermophilic digesters (55ºC, 15 days SRT) [6,7]. In such studies, positive effects of low temperature pre-treatments are attributed to accelerated hydrolysis-acidogenesis promoted by the activity of thermophilic bacteria, resulting in the so-called predigestion step. Our study shows that 70ºC pre-treatment time as well as the overall SRT of thermophilic anaerobic digestion can be further reduced, maintaining the efficiency in terms of biogas and methane production.

Energy Considerations

Figure 2 shows the electricity, heat and total energy balances of the single-stage (10 days SRT) and two-stage system; composed of a first 70ºC step (9, 24 or 48 h SRT) and a second 55ºC step (10 days SRT). Graph (a) corresponds to the system with energy recovery from the biogas and graph (b) to energy recovery from the biogas and from the effluent sludge. Within each graph, the balances for environmental temperatures of 20 and 0ºC, for digesters with and without wall insulation, are shown.

According to theoretical calculations, sludge digestion always results in surplus electricity generation. Output electricity obtained by cogeneration with biogas is much higher than electricity consumption for sludge pumping and mixing; thus electricity balances are always positive. The results are better for the 9 and 48 h pre-treatments, which is in accordance with higher biogas and methane production (Table 3). Contrary to electricity balances, heat balances are much affected by environmental temperature and tank insulation. All heat balances and overall energy balances are negative when only energy from biogas is recovered [Figure 2(a)]. The results are worse for the two-stage system, as a result of extra heat requirements for the 70ºC pre-treatment step.

Nevertheless, when energy recovery from the effluent sludge is also accounted for [Figure 2(b)], all balances become positive; except for the non-insulated reactor at 0ºC, which has a negative heat balance but positive overall balance, due to surplus electricity generation. At 20ºC without digester insulation, energy production is almost half of that with insulated digesters, making evident the necessity of digester insulation. Provided that digesters are insulated, environmental temperature (0–20ºC) has little effect on net energy production. By heat regeneration from the effluent, input heat is reduced, hence net energy production results from the stabilisation of sludge in such system. Therefore, successful thermophilic sludge digestion requires energy recovery from the effluent, as suggested by other authors [2,13].

In such a case, the two-stage system would result in higher energy production (Figure 2), which is in accordance with higher methane production rates (Table 3). If we compare the results of mesophilic and thermophilic two-stage systems (data not shown), the highest net energy production (almost double) is obtained with the results of the present work, which corre-

Table 3. Performance of Anaerobic Digestion (55ºC, 10 days SRT) with Raw and 70ºC Pre-treated Sludge.

70°C Treatment Time (h)	**0**	**9**	**24**	**48**
Influent Composition				
TS ($g\cdot L^{-1}$)	38.53 ± 6.26	55.47 ± 11.75	38.33 ± 9.90	54.43 ± 4.43
VS ($g\cdot L^{-1}$)	30.08 ± 2.89	30.45 ± 3.59	26.59 ± 6.63	27.88 ± 2.12
pH	6.92 ± 0.18	6.67 ± 0.46	7.28 ± 0.29	7.15 ± 0.18
Effluent Composition				
TS ($g\cdot L^{-1}$)	31.17 ± 4.93	34.87 ± 5.92	33.95 ± 5.43	36.88 ± 5.64
VS ($g\cdot L^{-1}$)	19.93 ± 1.88	18.95 ± 2.29	19.64 ± 3.52	18.56 ± 1.69
Total VFA ($g\cdot L^{-1}$)	2.40 ± 0.42	1.27 ± 0.38	2.07 ± 0.45	1.42 ± 0.34
Acetate ($g\cdot L^{-1}$)	0.32 ± 0.13	0.15 ± 0.10	0.67 ± 0.23	0.40 ± 0.29
Propionate ($g\cdot L^{-1}$)	1.14 ± 0.12	0.88 ± 0.09	1.11 ± 0.17	0.86 ± 0.10
iso-Butyrate ($g\cdot L^{-1}$)	0.30 ± 0.13	0.05 ± 0.08	0.09 ± 0.04	0.07 ± 0.04
n-Butyrate ($g\cdot L^{-1}$)	0.00 ± 0.00	0.00 ± 0.00	0.01 ± 0.01	0.00 ± 0.00
iso-Valerate ($g\cdot L^{-1}$)	0.53 ± 0.09	0.18 ± 0.13	0.19 ± 0.14	0.11 ± 0.02
n-Valerate ($g\cdot L^{-1}$)	0.00 ± 0.00	0.00 ± 0.00	0.00 ± 0.00	0.00 ± 0.00
pH	8.22 ± 0.10	8.27 ± 0.10	8.32 ± 0.13	8.25 ± 0.12
Removal Efficiency				
TS removal (%)	26.89 ± 6.07	31.16 ± 15.44	28.35 ± 15.38	30.66 ± 8.70
VS removal (%)	33.23 ± 5.49	36.55 ± 5.72	24.64 ± 9.09	32.61 ± 4.27
Biogas Characteristics				
Biogas production ($L\cdot LR^{-1}\cdot day^{-1}$)	0.63 ± 0.06	0.87 ± 0.17	0.69 ± 0.18	0.81 ± 0.15
Biogas yield ($L\cdot gVS_{fed}^{-1}$)	0.22 ± 0.04	0.30 ± 0.04	0.28 ± 0.05	0.29 ± 0.05
Biogas yield ($L\cdot gVSr_{emoved}^{-1}$)	0.61 ± 0.16	0.82 ± 0.17	0.81 ± 0.13	0.94 ± 0.14
Methane content (%)	63.73 ± 3.52	69.77 ± 3.36	68.73 ± 5.48	67.84 ± 5.13

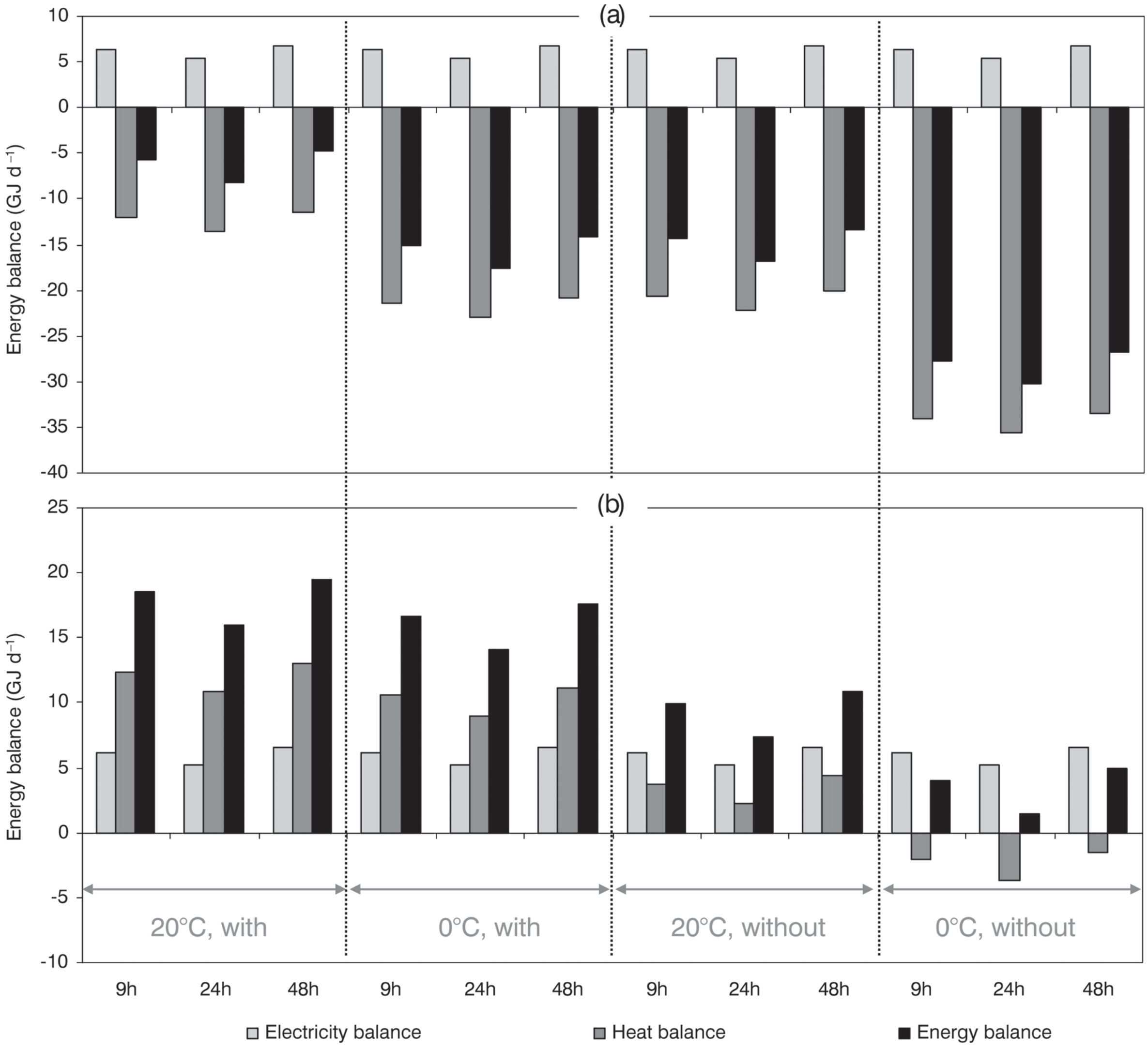

Figure 2. *Theoretical Electricity, heat and total energy balance (kJ d^{-1}) as a function of 70°C pre-treatment time, in two-stage (70°C/55°C) anaerobic digesters treating 100 m$^3_{sludge\ d}$$^{-1}$; with energy recoveries from biogas (a) and from biogas and the effluent sludge (b). Environmental temperature is either 20 or 0°C, for digesters with and without wall insulation.*

spond to the lowest SRT for the first and second stage. Apparently, similar energy production would be expected from thermophilic digesters at SRT of 10–20 days and mesophilic digesters at SRT of 20 days. This is a matter of concern, since lowering the SRT enables to reduce the reactor volume, hence its capital cost, and consequently the costs of sludge and wastewater treatment. Throughout this work it has been shown that thermophilic sludge treatment at SRT of 10 days results in stable and efficient performance.

CONCLUSIONS

The thermophilic anaerobic digestion of sewage sludge, with and without a 70ºC pre-treatment step, was assessed from an energy perspective, by calculating theoretical energy balances using experimental data. The main conclusions of this study are summarised as follows:

1. Sludge solubilization after 70ºC pre-treatment was shown by the increase in VDS and VDS/VS ratio (from 5 to 50%), already after the shorter pre-treatment assayed (9–24 h). However, VFA generation was only enhanced after 24 h, which might be the threshold for the so-called predigestion step. From this moment, VFA concentration increased up to almost 5 g VFA L^{-1} after 72 h.
2. During thermophilic batch tests, initial biogas production rate was similar for raw and 9–48 h

pre-treatments; but accumulated biogas production at day 10 was 50% higher for 9–48 h pre-treatments.

3. Sludge pre-treatment at 70ºC enhanced biogas and methane production through thermophilic digestion at 10 days SRT. Biogas yield was some 30% higher (0.28–0.30 vs. 0.22 L gVS_{fed}^{-1}). Methane content in biogas ranged between 60–70% in all cases.
4. Thermophilic sludge digestion in insulated digesters, with energy recovery from biogas and effluent sludge, would result in net energy production regardless of environmental temperature (0–20ºC). Additional surplus energy production would be expected by incorporating a 70ºC pre-treatment step.
5. According to the results, a short period (9 h) low temperature pre-treatment should be enough to improve methane and energy production through thermophilic anaerobic digestion of sludge.

Bearing in mind that the best results were obtained for the 9 h pre-treatment; the evaluation of shorter pre-treatments at 70ºC should be of interest for future work. Furthermore, the results would be improved using experimental data from pilot-scale reactors, leading to a more accurate energy assessment.

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