

# Enhancement of the conventional anaerobic digestion of sludge: comparison of four different strategies

S. I. Pérez-Elvira, M. Fdz-Polanco and F. Fdz-Polanco

## ABSTRACT

Anaerobic digestion (AD) is the preferred option to stabilize sludge. However, the rate limiting step of solids hydrolysis makes it worth modifying the conventional mesophilic AD in order to increase the performance of the digester. The main strategies are to introduce a hydrolysis pre-treatment, or to modify the digestion temperature. Among the different pre-treatment alternatives, the thermal hydrolysis (TH) at 170 °C for 30 min, and the ultrasounds pre-treatment (US) at 30 kJ/kg TS were selected for the research, while for the non-conventional anaerobic digestion, the thermophilic (TAD) and the two-stage temperature phased AD (TPAD) were considered. Four pilot plants were operated, with the same configuration and size of anaerobic digester (200 L, continuously fed). The biogas results show a general increase compared to the conventional digestion, being the highest production per unit of digester for the process combining the thermal pre-treatment and AD (1.4 L<sub>biogas</sub>/L<sub>digester</sub>·day compared to the value of 0.26 obtained in conventional digesters). The dewaterability of the digestate became enhanced for processes TH + AD and TPAD when compared with the conventional digestate, while it became worse for processes US + AD and TAD. In all the research lines, the viscosity in the digester was smaller compared to the conventional (which is a key factor for process performance and economics), and both thermal pre-treatment and thermophilic digestion (TAD and TPAD) assure a pathogen free digestate.

**Key words** | anaerobic digestion, sludge, temperature phased, thermal/ultrasound pre-treatment, thermophilic

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## INTRODUCTION

A new paradigm can be established by considering sewage sludge as a valuable by-product instead of a residue to disposal. From a sustainable point of view, both energetic and agronomic potential can be taken into account, and therefore it is very important to exploit the valorisation possibilities of the sludge.

Anaerobic digestion (AD) is the preferred choice for sludge stabilisation, but the conventional process presents a low yield (<40% sludge reduction and biogas production) due to the hydrolysis limiting step (Li & Noike 1992; Shimizu *et al.* 1993), and do not guarantee the quality of the final biowaste (bad dewaterability, pathogen presence, ...). In an effort to improve sludge hydrolysis and biodegradability, many studies have been performed utilizing different methods of sludge pre-treatment. Another option is to modify the conventional mesophilic AD.

Among all the pre-treatment alternatives (Mukherjee & Levine 1992; Chiu *et al.* 1997; Dohanyos *et al.* 1997; Tanaka *et al.* 1997; Weemaes & Verstraete 1998; Kepp *et al.* 1999; Pérez-Elvira *et al.* 2006), thermal hydrolysis (175 °C and 30 min, selected according to Fdz-Polanco *et al.* 2008) and ultrasounds (30 kWh/m<sup>3</sup>, according to Pérez-Elvira *et al.* 2009) have proven to be of major interest (Li & Noike 1992; Kepp *et al.* 1999; Lehne & Müller 1999; Kepp & Solheim 2001; Nickel & Neis 2007; Fdz-Polanco *et al.* 2008), and both Sonix™ and CAMBI® are well contrasted technologies, with several full scale plants. Ultrasound technology presents the advantage of simplicity, but the drawback of energy consumption, while thermal process is more complex but presents the great advantage of using thermal energy, which allows to an energetically self-sufficient process with proper energy integration.

The main non-conventional AD processes consist of thermophilic digestion (van Lier *et al.* 2003; Bousková *et al.* 2005) or two-stage temperature-phased systems (Ghosh *et al.* 1995; Han & Dague 1997; Han *et al.* 1997).

All these alternatives are widely investigated in the literature from a laboratory-scale point of view, regarding biodegradability (Li & Noike 1992; Kepp *et al.* 1999; Kepp & Solheim 2000; Fdz-Polanco *et al.* 2008), and there are some full-scale plants operating these technologies. Most of the studies on AD alternatives concentrate on the sludge disintegration (in the case of pre-treatment processes) and biodegradability, quantified by means of batch tests. However, there are some other properties of great importance from a full scale point of view (such as dewaterability, rheology and sanitation), that can only be evaluated while operating continuous anaerobic digesters.

The aim of this research is to compare the main alternatives to conventional AD with the conventional process, from the point of view of biogas production and digestate characteristics (dewaterability, viscosity and coliform reduction), operating continuous anaerobic digesters.

The alternatives selected for the study are the combination of thermal or ultrasound pre-treatment with mesophilic AD, thermophilic AD and two-stage temperature-phased AD.

## MATERIALS AND METHODS

For the research, four pilot plants were operated, corresponding to the four process configurations: Process I (TH + AD) consisted of a thermal hydrolysis unit, followed by a mesophilic anaerobic digester. In process II (US + AD) the pre-treatment was performed in a laboratory ultrasound device, prior to a mesophilic digester. Process III (TAD) consisted of a thermophilic digester. And process IV was a two stage AD system, the first stage thermophilic, and the second one mesophilic.

The same configuration of anaerobic digester was used in all the alternatives studied (Figure 1): 200 L volume, provided with sludge and biogas recirculations to assure mixing and avoid sludge setting inside the digesters. Biogas production was automatically recorded, and the digester performance and effluent characteristics were recorded from laboratory analysis (COD, solids, pathogens, dewaterability and viscosity). For the start-up, all the digesters were inoculated with thickened anaerobic digested sludge.

The different sludge feedings, pre-treated (I and II) or not (III and IV), were continuously fed to the corresponding anaerobic reactor.

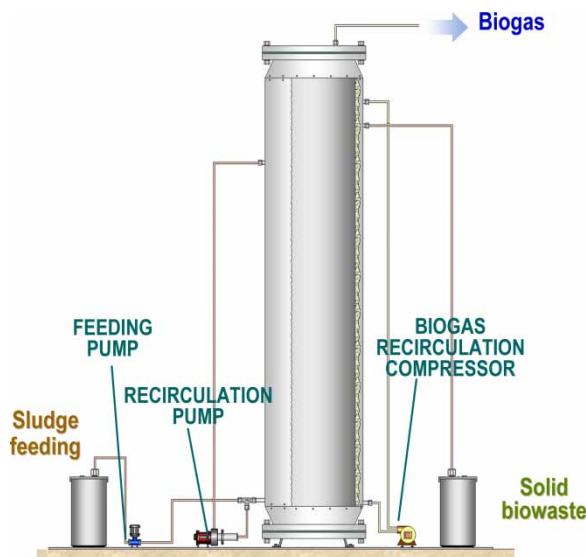


Figure 1 | Scheme of the anaerobic digesters.

The pilot plants and operation conditions of the four processes are described above, and Figure 2 presents images of them.

### Process I: Thermal hydrolysis pre-treatment and mesophilic AD

#### Thermal hydrolysis pilot plant

The thermal hydrolysis unit was operated at the Municipal Wastewater Treatment Plant of Valladolid (Spain), and treated only the thickened waste activated sludge fraction (and not mixed sludge, according to Pérez-Elvira *et al.* 2008).

Secondary sludge (TWAS) was directly fed to the thermal hydrolysis pilot plant shown in Figure 2(a), consisting of a feeding tank, a progressive cavity pump ( $P_{max} = 12$  bar), a steam boiler, a 20 L total volume hydrolysis reactor ( $V_{useful} = 10$  L) connected to a flash tank ( $V = 100$  L) with outlet pipes for steam and hydrolyzed sludge. When the sludge (10 L) was pumped into the reactor, the pressure-temperature control was activated, allowing the entrance of steam from the boiler to keep 170 °C. The plant was operated in a batch mode, controlled with a data acquisition and control system that controlled the reactor pressure and the residence time. At the end of the 30 min reaction time, the decompression valve automatically opened and the hydrolyzed sludge flowed to the flash tank. The operation conditions in the thermal hydrolysis unit were fixed at 170 °C and 30 min according to Fdz-Polanco *et al.* (2008).



**Figure 2** | Pilot plants operated. (a) Thermal hydrolysis unit in process I. (b) Ultrasound equipment in process II. (c) Thermophilic anaerobic digester (process III). (d) Thermophilic and mesophilic digesters (process IV).

## Anaerobic digestion

The hydrolysed sludge was fed to mesophilic anaerobic digester I, operated at 9 days residence time during the final phase.

### Process II: Ultrasound pre-treatment and mesophilic AD

#### Sonication equipment

The ultrasound apparatus used was a continuous ultrasonic homogenizer, Hielscher model UP400S, shown in Figure 2(b). The equipment consisted of a flow cell of 50 ml utile volume, equipped with a sonotrode (frequency 24 kHz and maximal theoretical power 1,000 W), refrigerated with water.

Sludge was continuously pumped through the cell, and the specific energy was established at 30 kJ/kg TS, according to previous studies about the influence of the energy supplied by the equipment on sludge solubilisation (Pérez-Elvira et al. 2009).

#### Anaerobic digestion

The sonicated sludge feeded mesophilic anaerobic digester II, operated at 20 days residence time.

### Process III: thermophilic AD

The thermophilic digester (Figure 2(c)) was inoculated with mesophilic digested sludge, and converted to thermophilic by means of a progressive temperature increase, from 35 to 55 °C, according to van Lier et al. (2003). At the beginning the digester was operated at 25 days residence time, but during the operation phase considered in this study the residence time was 16 days.

### Process IV: temperature-phased AD

The pilot plant (Figure 2(d)) consists of two anaerobic digesters operated in series, operated at thermophilic temperature in the first stage and mesophilic temperature in the second stage. The thermophilic digester was operated at 2 days residence time in order to act as a hydrolytic reactor that prepared the sludge for the mesophilic methanogenic digester, operated at 20 days residence time.

#### Analytical methods

Laboratory analysis and tests were performed to the different feedings and digestates in order to characterize the global process. All the analyses were done using the procedures given in ‘Standard Methods for Examination of

Water and Wastewater' (APHA, AWWA, WPCF 2005), except for those non-standardized, described below.

### Dewaterability determination

The dewaterability of the sludge was assessed in filtration tests, and capillary suction time (CST) determination.

Filtration tests were performed in a filtering equipment (Millipore), maintaining a pressure of 2 bar and measuring the volume filtered with respect to time. The filtration constant was calculated using Coulson's mathematical study from the slope, plotting filtrate volume ( $V^2$ ) versus filtration time ( $t$ ). Results are standardised to the TS concentration. The higher the FC\*TS values, the better the dewaterability.

The CST was determined using a Triton Electronics Ltd. (Type 319). A stainless-steel tube with an inner radius of 0.925 cm and Whatman No 17 filter paper were used. The filter paper was taken as the time (in s) needed to wet the filter paper from a radius of 6–12 mm. The results were standardised to the TS concentration. High CST/TS values mean a high cake specific resistance (bad dewaterability).

### Viscosity measure

Rheology tests were performed using a rotational viscosimeter (Brookfield LVDV-1+). The rheometer worked in a controlled shear rate mode. The temperature was kept constant at 25 °C.

**Table 1** | COD and solids characterization of the sludge used in the different processes

Research line	Sludge type	Municipal WWTP	TCOD (g/L)	SCOD (g/L)	TS (g/L)	VS (g/L)
I (TH + AD)	Fresh sludge I	Valladolid	68,749	13,056	58.3	37.1
	Pretreated sludge I	TH pilot	63,815	20,388	51.7	33.3
II (US + AD)	Fresh sludge II	Madrid	42,521	1,995	38	27.5
	Pretreated sludge II	US device	40,861	7,625	34.6	24.7
III (TAD)	Fresh sludge III	Burgos	41,501	5,454	33.8	24.8
IV (TPAD)	Fresh sludge IV	Valladolid	37,308	4,438	30.5	21.5

**Table 2** | Dewaterability, viscosity and sanitation characteristics of the sludge used in the different processes

Research line	Sludge type	FC*TS	CST/TS	Total coliform (ufc/100 ml)	$\mu$ (cp/gTS)
I (TH + AD)	Fresh sludge I	0.58	10.2	2.00E + 07	320
	Pretreated sludge I	0.73	7.6	0	14
II (US + AD)	Fresh sludge II	0.87	1.8	3.2E + 07	253
	Pretreated sludge II	0.04	43	5.1E + 06	192
III (TAD)	Fresh sludge III	0.12	8.8	3.2E + 08	315
IV (TPAD)	Fresh sludge IV	0.34	3.7	1.3E + 09	294

### Pathogens quantification

Total and faecal coliforms were determined in order to evaluate the hygienisation of the final biowaste.

### Sludge samples

The study was performed using thickened mixed sludge from different municipal wastewater treatment plants in Spain (Valladolid, Madrid and Burgos). Therefore, the origin of the sludge varied for the different research lines, and correspondingly the characteristics, as is shown in Tables 1 and 2.

As will be commented upon, the quantitative relative performance of the processes could be different if the same sludge had been used in all the processes, although the qualitative results can be considered independent of the fact of different sludge origins.

## RESULTS AND DISCUSSION

### Characterization of sludge feedings

Twice a week, samples of the different feedings were characterized regarding their organic and solids content, dewaterability, viscosity and hygienization.

**Table 1** presents the organic carbon and solids content of the sludge used in the different treatment options (I, II, III and IV). In the processes that include a thermal or ultrasounds pre-treatment (research lines I and II), the sludge characteristics change after the treatment. Therefore, for TH + AD and US + AD processes, **Table 1** presents the characteristics of both fresh and pretreated sludge.

It can be observed that the concentration of the sludge feeding is similar in all the plants, except for process I, where it is higher. This is due to the use in this process of a pilot centrifuge, which thickened the sludge before feeding the unit. The objective is to work at the highest possible concentration, as this is a very important factor from the point of view of the process economics.

**Table 2** presents the dewaterability, viscosity and sanitation characteristics.

From these values, some conclusions can be drawn about the influence of the pre-treatment on sludge characteristics.

## Solubilisation

The values presented in **Table 1** show that after the pre-treatments, thermal or ultrasound, the soluble COD increased, meaning that during the pre-treatment some cells are disrupted, liberating the intracellular matrix to the media. The SCOD increased from 19 to 32% thanks to the thermal pre-treatment and from 4 to 20% after the sonication. From these values, the effect of the thermal hydrolysis seems smaller than that corresponding to the sonication, but there is a double reason to justify this behaviour. Firstly, the initial solubilisation of the feeding to the US process was very low, and therefore the effect of any pre-treatment on this sludge is higher. And, secondly, only the secondary fraction of the sludge was thermally treated in the TH unit (and then mixed with the untreated primary sludge), while the ultrasound device treated all the mixed sludge.

## Dewaterability

The results of both filtration (FC\*TS) and capillary suction time (CST/TS) tests presented in **Table 2** show a different trend for thermal treatment and sonication. In the case of the thermal hydrolysis, the FC\*TS value increased by 30% (from 0.58 to 0.73), meaning that the dewaterability of the hydrolysed sludge is better. A corresponding 30% decrease in the CST/TS value can be observed (from 10.2 to 7.6), meaning that water release was faster after the TH. However, after the sonication the sludge

dewaterability was 20-fold worse: CF\*TS parameter decreased from 0.87 to 0.04 while CST/TS increased from 1.8 to 43.

## Sanitation

The coliform study showed that the thermal hydrolysis killed all the pathogens present in the sludge, while the ultrasound pre-treatment did not.

## Rheology

The experimental curves suggest that sludge behaves as a non-newtonian fluid, and viscosity decreased strongly with the shearing rate. Comparing the apparent viscosity of the feeding to processes I and II, it can be seen that the thermal hydrolysis process radically decreases the sludge viscosity, while the sonication has a slight effect on it. This is a very important aspect from a full scale point of view, as mixing efficiency and cost depend directly on sludge rheology.

## Performance of the AD

**Figure 3** shows the evolution of the volumetric load (VL) and biogas production in the different research lines. For processes I and II, phase 1 corresponds to the initial ‘control’ operation when the digester was fed with non pre-treated fresh sludge, and phase 2 corresponds to the combined process: TH + AD in process I and US + AD in process II.

In digesters III and IV, the graphs correspond to the stationary operation, after the initial start-up phase.

Comparing the graphs for the combined processes I and II, it can be observed that the operation strategy followed in both processes was different. In the TH + AD process the volumetric organic load was nearly doubled from phase I to phase II (from 1.4 to 2.5 kg VS<sub>fed</sub>/m<sup>3</sup> day), while in the US + AD process the load was kept constant (around 1 kg VS<sub>fed</sub>/m<sup>3</sup> day).

Therefore, the efficiency of the digester, measured as the biogas production per unit of digester, depends on both the organic load and the biogas productivity, as **Table 3** shows.

From **Figure 3** and **Table 3** it can be inferred that:

- Most of the reactors were operated at moderate HRT (15–20 days) and volumetric loads (1–1.5 kg VS<sub>fed</sub>/m<sup>3</sup> day). Only process I (TH + AD) was forced to operate at half the residence time (and corresponding double load).
- As **Figure 3** shows, the increase in the feeding load in this digester I did not affect the biogas productivity, which continued 30% above the value for phase 1

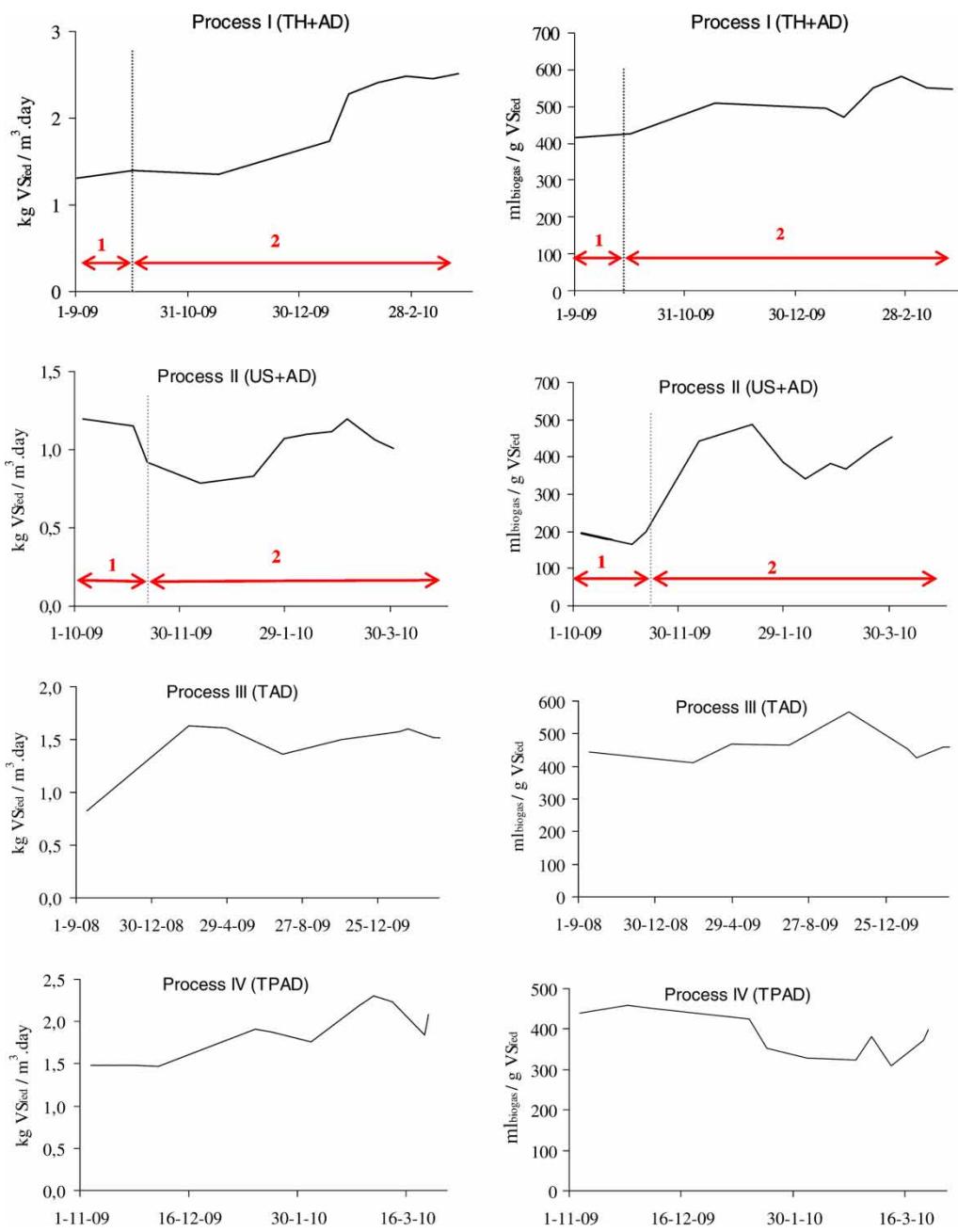
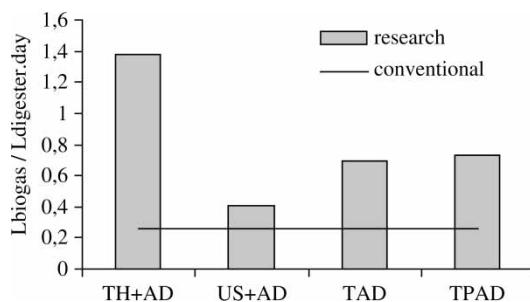


Figure 3 | Performance of the digesters I, II, III and IV.

Table 3 | Biogas production in the different processes

Process		HRT (days)	$\text{kg VS}_{\text{fed}}/\text{m}^3 \cdot \text{day}$	$\text{ml biogas/g VS}_{\text{fed}}$	$L_{\text{biogas}}/L_{\text{digester}} \cdot \text{day}$
I (TH + AD)	Phase 1	17	1.4	420	0.59
	Phase 2	9	2.5	550	1.38
II (US + AD)	Phase 1	19	1.1	187	0.21
	Phase 2	21	1.0	410	0.41
III (TAD)		16	1.5	463	0.69
IV (TPAD)		2 + 20	1.9	386	0.73



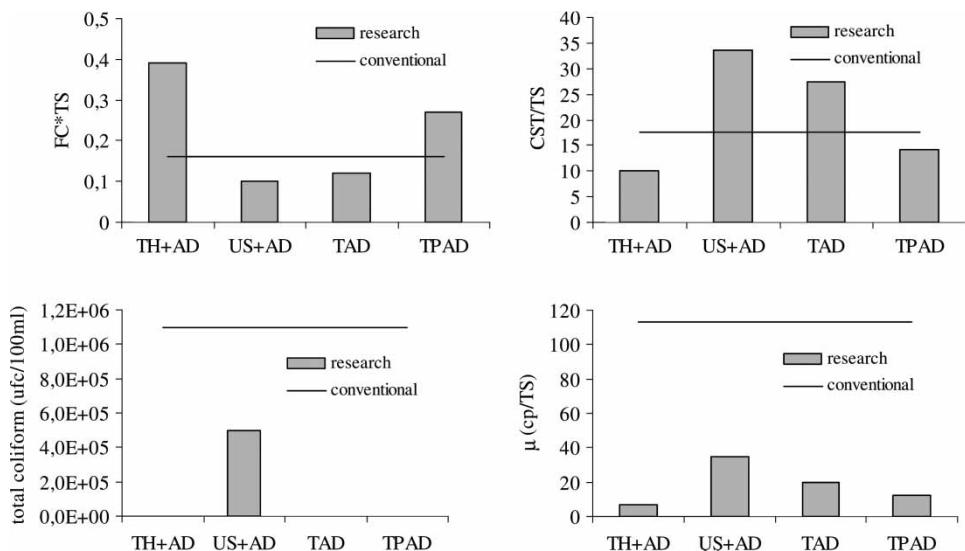
**Figure 4** | Comparison of biogas productivity among the research digesters and conventional mesophilic AD.

**Table 4** | COD and solids characterization of the digestates from the different processes

Process	TCOD (g/L)	SCOD (g/L)	TS (g/L)	VS (g/L)
I (TH + AD)	30,871	5,239	39.5	20.4
II (US + AD)	23,105	2,368	25.1	16.2
III (TAD)	20,286	4,641	21.7	13.2
IV (TPAD)	15,309	1,033	17.1	8.8

**Table 5** | Dewaterability, viscosity and sanitation characteristics of the digestates from the different processes

Process	FC*TS	CST/TS	Total coliform (ufc/100 ml)	$\mu$ (cp/gTS)
I (TH + AD)	0.39	10.1	0	7
II (US + AD)	0.10	33.6	5.0 E + 05	35
III (TAD)	0.12	27.5	0	20
IV (TPAD)	0.27	14.2	0	12



**Figure 5** | Comparison of dewaterability, hygienization and viscosity among the research digesters and conventional mesophilic AD.

(550 ml<sub>biogas</sub>/g VS<sub>fed</sub> compared to 420). Considering both the biogas production increase and the organic load increase, the performance of the digester became 4-fold better in phase 2 compared to phase 1.

- In process II, the biogas production increased a lot (from 187 to 410 ml<sub>biogas</sub>/g VS<sub>fed</sub>) when the feed changed from fresh to sonicated sludge. This sharp increase is due to the fact that the biodegradability of the fresh sludge was small, and therefore a pre-treatment has a higher effect on the sludge digestibility.
- In both combined processes I and II, the process performance was better in phase 2 (double biogas production per unit of digester), when feeding with pre-treated sludge.
- The biogas productivity of the non-conventional digestion processes studied, thermophilic and dual phase, was similar, around 0.7 L<sub>biogas</sub>/L<sub>digester</sub>·day.

It is interesting to compare the values of biogas production per unit of reactor obtained in processes I, II, III and IV with the production of a conventional mesophilic anaerobic digester (Figure 4).

As Figure 4 shows, the biogas production obtained in all the research lines was higher than the biogas obtained in conventional mesophilic AD. However, the relative performance among the systems could vary if all the processes had received the same sludge. In spite of this, the combination of thermal hydrolysis pre-treatment and AD was clearly better compared to the other alternatives (and over 5-fold more productive than the conventional

digestion), and this result would not vary qualitatively because of the feeding.

### Characterization of digestates

The same characterisation done to the feedings was performed to the digestates. Tables 4 and 5 present average values.

These results are compared with those obtained from a conventional mesophilic digester in Figure 5.

The results show that:

- The best dewaterability was for the digestate from the TH + AD process, while the worst was for process II (US + AD).
- The digestate from the thermal pre-treatment and the temperature-phased AD presented a better dewaterability than the digestate from a conventional digester.
- The combination of ultrasounds and mesophilic AD did not kill the pathogens present in the sludge, while the thermal pretreatment at 170 °C and the thermophilic AD (55 °C) achieved a coliform-free digestate.
- The viscosity of the digestates from the research processes was much smaller than in the conventional process. The smallest value was for process II.

### CONCLUSIONS

Two types of processes were operated in this research: processes combining a pre-treatment unit before the AD, and processes that consist of modifications in the conventional digestion temperature.

Regarding the combination of a pretreatment unit and AD, the two alternatives studied, thermal (TH + AD) and ultrasounds (US + AD), showed a different effect on the sludge. The thermal treatment enhanced the sludge dewaterability by 30%, reduced the viscosity drastically, and hygienized the sludge by killing all the coliforms. In the case of an ultrasounds pre-treatment, the dewaterability became worse, and pathogens were not destroyed. Therefore, when feeding the treated sludges to the corresponding digesters (I and II), the characteristics of the digestate matched the observed behavior: better dewaterability for TH + AD process, while worse for US + AD process, and pathogen free digestate for TH + AD process, but not for the US + AD one.

In the non-conventional AD processes, the characteristics of the digestate became better compared to the conventional digestate regarding viscosity and sanitation.

The dewaterability was better for the two-stage temperature phased (TPAD) digestate, while worse for the thermophilic (TAD) digestate.

Regarding the biogas production, all the research lines drove to an increase compared to the conventional digestion. The highest value per unit of digester was for the process combining the thermal pre-treatment and AD (1.4 L<sub>biogas</sub>/L<sub>digester</sub>·day compared to the value of 0.26 obtained in conventional digesters).

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