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Ultrasound pre-treatment for anaerobic digestion improvement

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ABSTRACT

Prior research indicates that ultrasounds can be used in batch reactors as pre-treatment before anaerobic digestion, but the specific energy required at laboratory-scale is too high. This work evaluates both the continuous ultrasound device performance (efficiency and solubilisation) and the operation of anaerobic digesters continuously fed with sonicated sludge, and presents energy balance considerations. The results of sludge solubilisation after the sonication treatment indicate that, applying identical specific energy, it is better to increase the power than the residence time. Working with secondary sludge, batch biodegradability tests show that by applying 30 kWh/m^3 of sludge, it is possible to increase biogas production by 42%. Data from continuous pilot-scale anaerobic reactors ($V = 100$ L) indicate that operating with a conventional HRT $= 20$ d, a reactor fed with pre-treated sludge increases the volatile solids removal and the biogas production by 25 and 37% respectively. Operating with HRT $= 15$ d, the removal efficiency is similar to the obtained with a reactor fed with non-hydrolysed sludge at HTR $= 20$ d, although the specific biogas productivity per volume of reactor is higher for the pretreated sludge. Regarding the energy balance, although for laboratory-scale devices it is negative, full-scale suppliers state a net generation of 3–10 kW per kW of energy used.

Key words | anaerobic digestion, biodegradability, energy, sludge, solubilisation, ultrasound

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INTRODUCTION

Ultrasounds laboratory-scale research

In large wastewater treatment plants, primary and secondary sludge are stabilised applying anaerobic digestion, resulting in elimination of volatile solids and production of biogas. Hydrolysis is the rate-limiting step of biological degradation of sludge (Li & Noike 1992; Shimizu *et al.* 1993), the process is slow, therefore big digesters are used (>20 day residence time) and large quantities of biosolids are produced (25–50% degradation of organic matter). Pre-treatment of sewage sludge by mechanical, thermal, chemical or biological technologies can promote the methane production and reduce the amount of solids to be disposed (Mukherjee & Levine 1992; Chiu *et al.* 1997; Donányos *et al.* 1997; Mueller *et al.* 1998; Weemaes & Verstraete 1998; Kepp *et al.* 1999; Nah *et al.* 2000; Pérez-Elvira *et al.* 2006).

Ultrasound assisted sludge degradation has been studied in the last decade in laboratory, pilot, and full-scale. Changes in physical, chemical and biological properties of pretreated sludge have been observed, and several recent reports have demonstrated the efficiency of ultrasounds method for disintegration sludge (Bougrier *et al.* 2005; Nah *et al.* 2000) and thereby accelerating the anaerobic digestion process and improving methane yield (Lehne *et al.* 2001; Neis *et al.* 2001; Tiehm *et al.* 2001; Bougrier *et al.* 2005; El-Hadj *et al.* 2007).

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These previous works indicated that the disintegration achieved depends on some operating variables, such as: frequency, horn, sludge type, TS content, operating temperature, ultrasonic density,… The most effective conditions for sludge disintegration were obtained working with secondary rather than primary sludge (Mao *et al.* 2004), for high concentrations of DS in the WAS (Tiehm *et al.* 2001; Onyeche *et al.* 2002; Neyens *et al.* 2004), low frequency, around 20 kHz (Tiehm *et al.* 1997; Tiehm *et al.* 2001), and relatively high ultrasound density (0.4–3 W/mL) and intensity (250–900 J/mL; 10,000–30,000 kJ/kg TS) (Lehne *et al.* 1999; Nickel *et al.* 1999).

Most prior work describe laboratory experiments performed in batch. However, the complexity and variability of sludge points to the necessity of directing the forthcoming research to continuous ultrasonic devices.

Regarding anaerobic digestion, most of the authors run biodegradability tests (Onyeche *et al.* 2002; Bougrier *et al.* 2005; Grönroos *et al.* 2005) or operate semi-continuous reactors controlling the residence time (Tiehm *et al.* 1997; Neis *et al.* 2000; Alonso *et al.* 2001; Nickel & Neis 2007). However, little research has been published on continuous operation of anaerobic digesters fed sonicated sludge (Hogan *et al.* 2004).

Table 1 presents a review of research on ultrasound treatment followed by anaerobic digestion.

Ultrasounds full-scale application

The three main suppliers of ultrasound technology for sludge applications are: Sonico Ltd. UK (Radial Horn US System), Ultra WAVES GmbH (Flat Piezo-Ceramic Transducer), and IWE Tec GmbH (Cascade Sonotrode). The challenge for the suppliers is to maximize, first, the conversion of electrical energy into mechanical vibrations, and second, the conversion of mechanical vibrations to cavitation (thus, minimizing heat losses). The first one depends on the probe technology. Most of the suppliers use piezoelectric (>92% efficiency) or magnetostrictive technology (60% efficiency). Secondly, the cavitation threshold depends on several factors: amplitude, temperature, dry solids content and rheological properties of the sludge, system and vapour pressure, sonotrode shape (Nickel & Neis 2007; Son *et al.* 2009).

Therefore, the first difference between laboratory-scale and full-scale devices is the efficiency. Laboratory ultrasonic systems are inefficient, and therefore, direct use of bench-scale data for full-scale design could be misleading.

The second difference between laboratory-scale and full scale is the way to use ultrasound. Most of the full-scale installations use part-stream sonication (Barber 2003), which consists of treating only a fraction of the sludge stream, with the objective of reducing costs and enhancing final sludge dewaterability (Friedrich *et al.* 1999; Rooksby *et al.* 2002).

Table 2 presents operating data (TS content, sonication duration, ultrasonic density, frequency, amplitude,…) comparing full-scale and laboratory-scale. It can be seen that quantitative data between both scales are very different. The most important thing to notice is that the energy supplied by real equipment is much smaller compared with the laboratory devices, and therefore the energy balance comparing energy generated from biogas increase and ultrasound consumption is positive for fullscale but negative for laboratory-scale.

Table 1 | Sonication and digestion operation conditions from the literature

Reference	Batch/cont.	Time	Power (W)	Energy (J/mL)	Digestion
Nickel & Neis (2007)	Cont.	90 s	3,600	250	Semi-cont
Bougrier *et al.* (2005)	Batch	0–10 min	225	280	Batch tests
Grönroos *et al.* (2005)	Batch	5–30 min	500–3,000	540	Batch tests
Onyeche *et al.* (2002)	Batch	10–60 min	200	900	Batch tests
Neis *et al.* (2000)	Cont.	90 s	3,600	250	Semi-cont
Tiehm *et al.* (1997)	Cont.	64 s	3,600	180	Semi-cont
Alonso *et al.* (2001)	Batch	10–120 s	360	280	Semi-cont
This article	Cont.	6–54 s	100–180	110	Cont.

Table 2 | Sonication and digestion operation conditions from the literature

Parameter	Sonix	WAVE	IWE Tec.	Laboratory-scale	This article
Frequency (kHz)	20 kHz	20 kHz	20 kHz	20 kHz	20 kHz
Power intensity (W/cm^2)	15–50	20–50	<200	No data available	48
Power per sonotrode (kW)	6 kW	2 kW	8 kW	0.2–3.6 kW	0.18 kW
Reactor volume	4 L	29 L	4–5 L	0.1–1 L	15 mL
Power density (kW/L)	4 kW/L	0.17 kW/L	0.5–2 kW/L	0.4–3 kW/L	12 kW/L
Max. sludge TS (%)	9%	<8%	10%	0.5–2%	0.5%
Energy supplied (kJ/L)	4–5 kJ/L	23 kJ/L	18–36 kJ/L	205–900 kJ/L	110 kJ/L
Increase in biogas production	35–55%	30–45%	20–50%	25–100%	37%
Energy balance*	5–10	3–7	<5	Negative	Negative

*Net energy (kW) generated by 1 kW of ultrasonic energy used (considering a cogeneration plant).

A further comparison allows noticing that the full-scale sonotrodes are much more powerful than the laboratory ones. As laboratory reactors are also much smaller, the power density applied is the same order comparing full- and laboratory-scale. However, in this article the sonication cell used was very small, and although the power density becomes higher, probably the ultrasonic energy is not homogeneously introduced into such a small volume, worsening the disintegration effect.

The aim of this paper is to operate a continuous ultrasound device to quantify experimentally the effect of ultrasounds on: i) anaerobic degradation of biological secondary sludge, quantified as biogas productivity (mL biogas/g VSS_{fed}) and ii) removal efficiency (% $VSS_{removed}$, % $COD_{removed}$). An energy balance from the experimental data is presented, discussing the difference with the fullscale balance.

MATERIALS AND METHODS

The laboratory pilot plant consisted of a continuous ultrasound homogeneizer (Hielscher model UP400S) and two continuously fed mesophilic anaerobic digesters (100 L volume). As Figure 1 shows, secondary sludge is continuously pumped using a peristaltic pump, and sonicated in a 15 mL flow cell (commercial cell for the model UP400S) equipped with a sonotrode (24 kHz frequency and 400 W maximum theoretical power), refrigerated with water.

The desired specific energy is fixed by selecting the supplied power (100 W) and flow (56 mL/min). The choice of this operation conditions is justified in the present article. The effluent of the ultrasound reactor is continuously fed to one of the anaerobic reactors (reactor 2), while reactor 1 (control reactor) is fed with fresh secondary sludge.

The control digester was operated at 20 d residence time, and reactor 2 was operated at 20 and 14.5 d. The digestion study was carried out over a period of 6 months. The influent and effluent COD and VS was determined daily, and biogas production was recorded.

Anaerobic biodegradability was also calculated in biodegradability tests, using an automatic equipment and the experimental conditions described in Fdz-Polanco *et al.* (2005).

Sludge solubilization was quantified by means of the increase of the soluble COD (SCOD) using the ratio (% SCOD/COD).

All the analyses were performed following the *Standard Methods for Examination of Water and Wastewater* (2005).

RESULTS AND DISCUSSION

Ultrasound efficiency

To test the efficiency of the ultrasound equipment, a series of experiments were performed with varying refrigeration water flow rate and temperature. The objective was to verify the real power consumed by the sonotrode, and to calculate the percentage of consumed energy used for disintegration (effective power). The power consumption was measured with a commercial wattmeter, and energy balances were

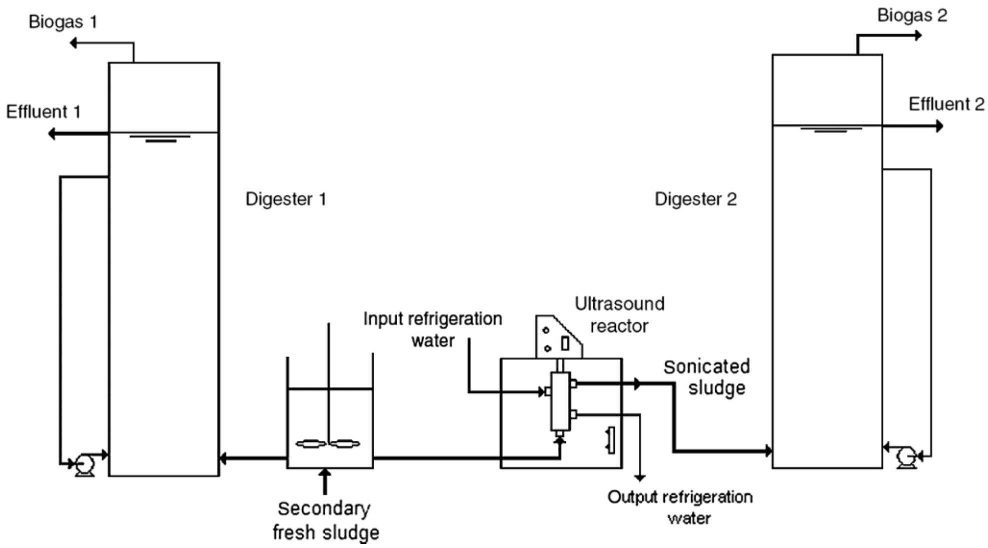

Figure 1 | Experimental lab-pilot plant for sonication and digestion of sludge.

performed fixing the refrigeration water and mixed liquor flow rates and measuring the inlet and outlet temperatures of both streams.

As Figures 2 and 3 show, there is a enormous difference between the energy indicated in the sonotrode and the energy used for disintegration. First, the equipment power is less than half the theoretical, and second, only 19% of this theoretical power is transferred to the solids.

Sonication and sludge disintegration

A series of experiments were conducted to evaluate the influence of ultrasound energy, power and sonication time on sludge characteristics. Secondary sludge (3% SCOD0) was sonicated under different powers and different sonication times, measuring the SCOD after the treatment.

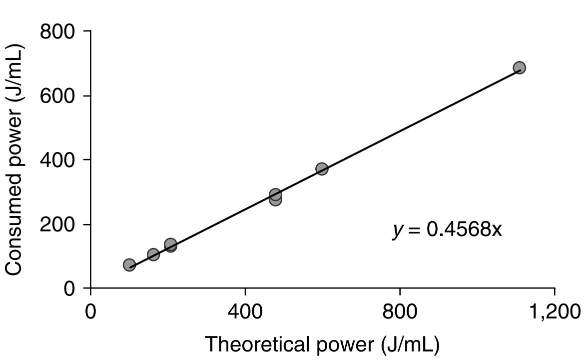

Figure 2 | Real consumed power vs. theoretical power.

Figure 4 clearly shows, first, that solubilisation is directly proportional to the energy applied, and, second, that for the same energy applied is better to increase the power than the residence time. For example, for the same applied energy of 100 J/mL$_{sludge}$, the 180 W, 10 s treatment gave 24% SCOD, while the 26 W, 60 s treatment only allows 7% SCOD.

Batch biodegradability tests

Apart from the solubilisation study, a biodegradability study was performed to determine whether the increase in SCOD also yields a subsequent increase in biogas production. Table 3 presents the sonication conditions of secondary sludge (2.03 g SV/L).

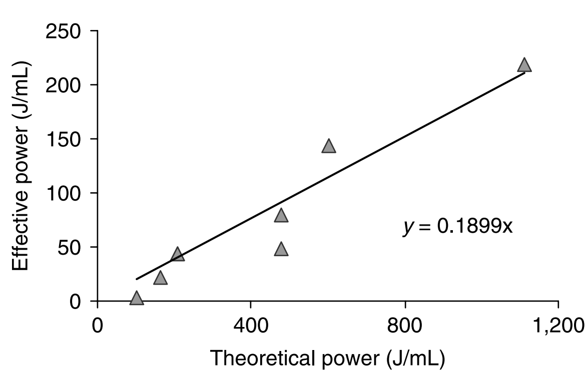

Figure 3 | Effective energy used for disintegration.

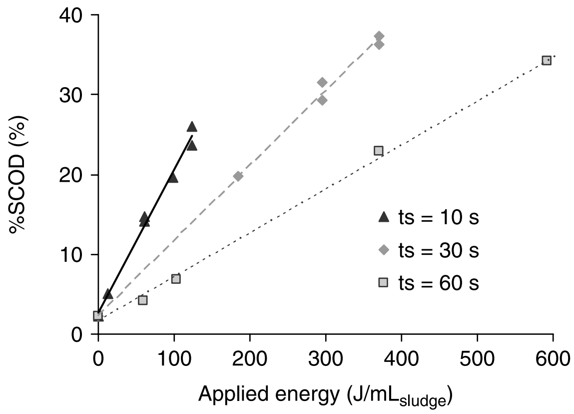

Figure 4 | %SCOD vs. supplied energy, for different sonication conditions (power and time).

Table 3 | Sonication conditions and biogas increase for the batch biodegradability study

		100 W, 2 s	100 W, 6 s	100 W, 12 s	100 W, 16 s
Power	W	100	100	100	100
Sonication time	S	2	6	12	16
Energy applied	J/mL	13	40	80	110
	kWh/m^3	3.7	11.1	22.2	30.0
	kWh/kg TS	1.4	4.0	8.1	10.8
Biogas increase	(%)	6	17	32	42

Figure 5 shows results obtained in biodegradability tests for varying sonication conditions compared with the control (non-sonicated sludge).

As can be observed, ultrasound led to an increase in sludge biodegradability (mL biogas/g SVfed). The higher the energy applied, the higher the increase in biogas production (in agreement with Lehne *et al.* 2001; Neis *et al.* 2001; Tiehm *et al.* 2001; El-Hadj *et al.* 2007). For specific energies under 1.5 kWh/kg VS (100 W, 2 s) only a 6% increase in biogas production is observed compared with the control, which corresponds with the minute increase in sludge solubilisation obtained in previous study. It is supposed that energy was used to reduce flocs size, but not to break cells. When increasing the sonication energy to 8 and 11 kWh/kg VS, the biogas productivity increases by 32 and 42% respectively. It is supposed that for higher supplied energies, the sonication effect is not so dramatic.

Sonication not only increases biogas production, but also increases the rate of degradation, especially during the first days of digestion, due to the increase in the easily degradable organic matter. Biodegradability tests show that the biogas production in the bottles with sonicated sludge at 100 W for 12 or 16 s produced in the first five days nearly the same quantity of biogas than the tests fed with untreated sludge over a time period of 15 days or more. Therefore, shorter retention times can be used in anaerobic digestion.

Continuous digesters performance

To compare the biodegradability of secondary sludge with and without ultrasound pre-treatment the pilot plant showed in Figure 1 was continuously operated during one year. Both reactors were fed with secondary sludge coming weekly from La China (Madrid) facility, operated by Cadagua.

For R1 the feeding was always fresh sludge, while R2 was fed with sonicated sludge (100 W, 16 s, 30 kWh/m^3). The main characteristic of the sludge was the variability in VS concentration and the periodic foaming episodes. In all the experimental foaming periods, the sonicated sludge shows improved behaviour.

The main experimental results obtained in four different experimental periods are presented in Table 4. In order to compare the efficiency of the reactors during period 1, both were fed with fresh sludge, showing a similar behaviour.

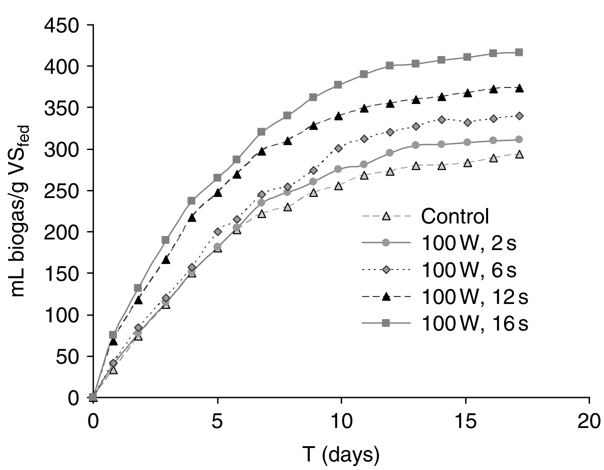

Figure 5 | Biogas productivity in batch biodegradability tests.

Table 4 | Comparison of results for the continuous anaerobic digestion of secondary sludge in reactors R1 (conventional) and R2 (ultrasound pre-treatment)

	Period 1	Period 2		Period 3		Period 4	
	R1 and R2	R1	R2	R1	R2	R1	R2
HRT (d)	20	20	20	20	15	20	20
VS removed (%)	43	44	55	43	44	45	54
COD removed (%)	45	47	65	45	47	49	55
Biogas (mL/g VSS_{fed})	330	335	520	325	335	425	460
Biogas (mL/g VSS_{rem})	790	800	870	770	925	990	900
Biogas (L/d)	43	44	60	42	55	42	58

From these results, the two main conclusions are:

(i) Operating with a conventional HRT = 20 d, reactor 2 fed with pre-treated sludge is more efficient removing solids and producing biogas. On average, the solids elimination increases by 25% while the biogas production increases by 37%. This difference indicates a change in the chemical composition of the biodegradable fraction.

(ii) Even decreasing by 25% the HRT reactor 2 is more efficient than reactor 1. Although the removal efficiency remains almost constant, the specific biogas productivity per unit of removed solid is quite different.

From a practical point of view this behaviour leads to two different possibilities: i) maintaining the HRT it is possible to increase the volatile solids removal efficiency and the specific biogas production ($L_{biogas}/L_{reactor}$ or L_{biogas}/g VS). ii) it is possible to increase the volumetric or organic loading rate maintaining the volatile solids removal efficiency or the biogas production.

Energy feasibility

The economic viability of the ultrasound pre-treatment is directly related to the specific energy applied, with the increase in biogas production and with the decrease in the amount of solids to be removed. Comparing the conventional and the ultrasound processes, the difference in volume of biogas produced and biosolids to be disposed must pay the electrical energy applied.

Considering: (i) secondary sludge (3% TS and 80% VS/TS), (ii) VS removal efficiency 40% for the conventional process and 60% after ultrasound pre-treatment, (iii) biogas production 1 m^3/kg VS_{rem}, iv) 38% efficiency converting heat into electricity, the balances indicate that the increase in biogas production is 4.8 m^3 biogas/m^3 sludge, which, in turn, can produce 11 electrical kWh/m^3 sludge (PCI of biogas: 6 kWh/m^3). This energy is far from the 30 kWh/m^3 sludge required for the ultrasound pre-treatment in our experimental conditions. Taking into account the reduction of biosolids to be removed (4.8 kg VS/m^3 sludge) and accepting a disposal cost of 40 euros per ton of sludge (30% TS) the savings in disposal are close to 0.64 euros/m^3 sludge treated or 9 kWh electrical energy/m^3 sludge.

Therefore, at laboratory-scale the energy balance is negative when treating 3%TS sludge, as the energy consumption is 30 kWh/m^3 sludge, and the income from biogas increase (11 kWh/m^3) and disposal costs reduction (9 kWh/m^3) accounts for 20 kWh/m^3 sludge.

The energy balance could be improved considering a higher sludge concentration, as it is a key factor from an economic point of view. For a higher TS content in the sludge, the sludge volume gets reduced, and therefore the sonication cost decreases (although keeping constant the energy dose, kJ/m^3 sludge). Furthermore, previous work (Barber 2002) have demonstrated that thickening the digesters influent to 7%TS led to 3-fold increase in energy production compared with a sludge containing only 3%TS. For the following calculations, a 40% increase in biogas production after the sonication was considered.

In order to evaluate the influence of sludge concentration on the energy balance, the benefit from biogas increase and reduction in sludge to disposal was calculated for different sludge concentrations. Figure 6 shows the results.

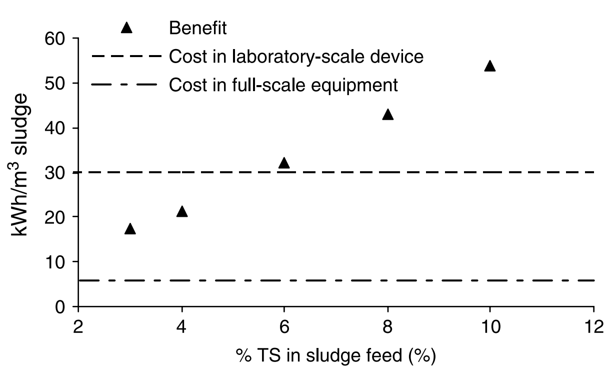

Figure 6 | Energy benefit a function of sludge concentration.

It can be seen that the higher the sludge concentration, the higher the benefit per unit of sludge volume.

As stated before, if savings pay the electrical energy applied in the ultrasounds device, the sonic process will be energetically feasible. If we consider the 30 kWh/m^3 sludge needed in the laboratory device to achieve the 40% biogas increase, the process would only be energetically feasible above 6%TS concentration. For a smaller concentration, the sonication cost is higher than the benefit. This analysis corresponds to the laboratory sonication equipment used and the experimental conditions described.

However, as Table 2 shows, a full-scale device consumes much less energy compared to a labscale device (between 2 and 8 kWh/m^3 sludge). Considering this value, and comparing with the values presented in Figure 6, the process is energetically feasible, as the benefit is higher than the sonication cost.

From a full scale point of view, in the energy balance some other energy requirements should be considered, as the sludge heating to the operation temperature and to compensate for ambient heat loses. Suppliers of full-scale equipments give the net energy (kW) generated by 1 kW of ultrasonic energy used (see Table 2). This ratio is in the range 3–10 kW/kW, for sludge concentrations above 5%TS.

CONCLUSIONS

The larger part of the experimental work found in literature is performed in discontinuous reactors and using extremely high specific energies. Although in this paper a continuous sonication device was used, the apparatus efficiency is very low, conditioning the extrapolation of the experimental results to full-scale.

The application of ultrasound to secondary sludge (3%TS) has a clear effect on disintegration, solubilisation and anaerobic biodegradability. It was observed that applying identical specific energy, it is better to increase the power than the residence time.

The continuous operation of an anaerobic reactor fed with sonicated sludge (30 kWh/m^3) showed first, that maintaining the HRT it is possible to increase the volatile solids removal efficiency and the specific biogas production by 40%, and, second, that it is possible to increase the volumetric or organic loading rate by 25% maintaining the volatile solids removal efficiency or the biogas production.

The technical feasibility of the process is clear, but regarding the economic feasibility, the working scale and equipment efficiency are key factors, as well as the sludge concentration.

A balance considering a 40% increase in biogas production, and the value of 30 kWh/m^3 sludge needed in the laboratory device, shows that the process would only be energetically feasible above 6%TS concentration. However, considering a typical value of 6 kWh/m^3 sludge for a full-scale device, the process is energetically feasible for any sludge concentration, as the benefit is higher than the sonication cost.

Further studies are needed to examine the impact of the ultrasound pre-treatment on sludge dewaterability, settleability, viscosity and sanitation of the sludge after anaerobic digestion.

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