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Full-stream and part-stream ultrasound treatment effect on sludge anaerobic digestion

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ABSTRACT

The use of ultrasound as pre-treatment to improve anaerobic digestion of secondary sludge has been established as a promising technology. There are great differences between lab scale and full-scale devices, regarding the relationship between the disintegration achieved and the energy supplied. Based on economic aspects, most of the full-scale plants use partial-stream instead of the full-stream sonication, which affects biogas production and digestate dewatering characteristics. A laboratory scale operation combining ultrasound and anaerobic digestion (batch tests) has been performed, determining the relationship between the ratio of sonicated sludge fed and the methane production, SCOD removal and capillary suction time after 20-day anaerobic biodegradation, in order to check the possible benefits of part-stream versus full-stream sonication. Additional incubation was also evaluated, searching for an optimum process combining ultrasound and 24-h incubation pretreatment. Results showed that by sonicating fresh WAS at 25,700 kJ/kg TS biogas yield increased linearly with the percentage of sonicated WAS in the substrate, from 248 (control reactor) to 349 mL CH_4/g VS (41% increase in full-stream sonication). By incubation (24 h, 55°C), 325 mL CH_4/g VS were obtained (31% increase), but the digestion of the soluble compounds generated during incubation of sonicated sludge appeared to be less degradable compared to those solubilised by ultrasound or incubation alone, which showed no benefit in combining both treatments. Post-digestion dewatering deteriorated for both part-stream and full-stream sonication, and CST values were constant (74% higher than the control digestate) from 30% to 100% sonicated sludge.

Key words | anaerobic digestion, biogas, dewaterability, disintegration, part-stream, sludge, ultrasound

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ACRONYMS AND ABBREVIATIONS

COD	chemical oxygen demand
CST	capillary suction time
DD_{COD}	disintegration degree (Equation (3))
DS	dry solids
P	methane productivity (mL CH_4/g VS)
PCOD	particulate chemical oxygen demand
R_m	biogas production rate (mL CH_4/g VS d)
SCOD	soluble chemical oxygen demand
S_{COD}	COD solubilisation (Equation (2))
TCOD	total chemical oxygen demand
TS	total solids
VS	volatile solids
WAS	waste activated sludge
WWTP	wastewater treatment plant
λ	lag time (d)

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INTRODUCTION

Ultrasound and sludge treatment

In conventional anaerobic digestion, cell lysis is the rate limiting stage (Del Borghi *et al.* 1999). It has been shown that the extreme conditions produced during ultrasonic cavitation cause cell disruption, which releases intracellular organics that become accessible to the anaerobic microbial population in the digester, thus enhancing the digestion process.

Various parameters including sludge type, TS content, energy, frequency, duration and power intensity have been studied for their effects on the characteristics of sludge, showing some important features. High effectiveness of disintegration is observed at high concentrations of DS in the WAS (Tiehm *et al.* 2001; Onyeche *et al.* 2002; Neyens *et al.* 2004). The efficiency of sludge disintegration decreases with increasing frequency (Tiehm *et al.* 1997, 2001), obtaining the best results at 20 kHz. Release of SCOD can be correlated to the ultrasound energy input (Bougrier *et al.* 2005; Dewil *et al.* 2006; Na *et al.* 2007). For efficient sludge disintegration, ultrasound density is apparently more important than the sonication time (Grönroos *et al.* 2005; Pérez-Elvira *et al.* 2009).

Several researches also proved that the disintegration leads to a positive impact on the anaerobic digestion process (Lehne *et al.* 2001; Neis *et al.* 2001; Tiehm *et al.* 2001; Bougrier *et al.* 2004; El-Hadj *et al.* 2007).

Regarding dewaterability, previous studies have reported that ultrasonication can have both positive and negative effects on sludge dewatering (Dewil *et al.* 2006). The effects seems to be subject to energy doses: low-energy doses enhance sludge dewaterability (Yin *et al.* 2006; Na *et al.* 2007), while high-energy dosage significantly deteriorates sludge dewaterability (Clarke 1999; Dewil *et al.* 2006; Wang *et al.* 2006).

As a consequence of all this, ultrasonic treatment is one of the most promising recent technologies to reduce sludge production in WWTP, also due to its reliability of operation (high degree of research and development), no odour generation, no clogging problems, and easiness to implement. But unfortunately there are some negative effects, such as erosion of the sonotrode, and the negative energy balance due to the very high energy consumption of the equipment. In order to solve this second limitation, both the optimisation of the equipment and the way to use ultrasound are two important features.

Ultrasound devices and energy efficiency

In an ultrasound device, there are two efficiencies to consider: conversion of electrical energy to mechanical vibration, and conversion of mechanical vibration into cavitation. It is very important to optimise both, in order to minimise electrical losses to heat.

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.

The study presented in this paper is done in laboratory equipment, where both the electrical and the cavitation efficiencies are too low compared to full-scale ultrasound devices. Therefore, it is nonsense to present in this paper an energy balance (comparing kW generated from biogas increase with kW used by ultrasound) from the lab-scale operation, as it will be useless from a practical point of view.

Part-stream vs. full-stream

There are currently two approaches of how to employ ultrasound, based on the quantity of the stream to be sonicated: full-stream and part-stream sonication. The full-stream approach involves treating the entire stream with ultrasound, whereas a part-stream approach involves treating only a fraction of the sludge stream. Most of the suppliers of ultrasound devices (IWEtec, Ultrasonus, Ultrawaves, Sonico) use part-stream approach due to lower running costs.

Some articles (Barber 2003) state similar benefits in both technologies with respect to biogas yields (kW generated/kW consumed). Forster *et al.* (2000) suggest that biogas yield rises to a threshold value, and then remains constant even when a greater value of the stream is sonicated.

And Friedrich (2002) stated that the greatest biogas production is achieved when treating only a fraction of the stream, as it was observed that biogas yield increased up to a certain fraction sonicated, and then decreased.

This unexpected behaviour of the biogas data could be explained as a reduction in the biological activity at the higher fractions, and would suggest that the mechanisms involved in sonication include not only breakage of sludge aggregates and release of cell contents, but also enhanced enzymatic activities.

Furthermore, sonication has also been documented to deteriorate dewaterability characteristics of sludge (Clarke 1999; Feng *et al.* 2009), while part-stream sonication presents a better dewaterability compared to fully sonicated sludges (Friedrich *et al.* 1999; Rooksby *et al.* 2002).

A first aim of the paper is to quantify the effect of ultrasound power input on the release of soluble COD from sludge with the equipment used, and assure a high disintegration in order to investigate the influence of ultrasound disintegration on biodegradation.

The second aim of this research is to explore both full- and partial-stream pretreatment options, quantifying the impact of the treatment on biogas production and volatile solids destruction, in order to check the possible benefits of part-stream versus full-stream sonication. 55°C temperature storage was also evaluated, searching for an optimum process combining ultrasound and additional incubation.

Finally, dewaterability aspects for full and part-stream sonication digestates are also analysed in this article.

MATERIALS AND METHODS

Sludge samples

The study was performed using waste activated sludge from a conventional municipal wastewater treatment plant (Palencia, Spain), including screening, primary clarification, and secondary treatment by activated sludge. Thickened secondary sludge (WAS) was sampled and characterised before and after the ultrasound treatment.

Table 1 presents the average values for the untreated sludge.

Table 1 | Average characteristics of the untreated thickened secondary sludge

Origin	TCOD (mg/L)	SCOD (mg/L)	TS (g/L)	VS (g/L)
Municipal WWTP	45,870	1,283	35.8	29.7

Ultrasound disintegration equipment

The ultrasound apparatus used was a continuous ultrasonic homogeniser, Hielscher model UP400S. The equipment consists of a flow cell of 15 mL utile volume, equipped with a sonotrode (frequency 24 kHz and maximal theoretical power 400 W), refrigerated with water.

Sludge was continuously pumped through the cell, and the desired specific energy (E_s) was selected by varying the supplied power (P) and the residence time in the cell (t).

$$E_S = \frac{P\cdot t}{V\cdot TS_0}\left(\frac{\text{kJ}}{\text{kg}\cdot\text{VS}}\right) \qquad (1)$$

Previous studies showed that sonication power increase is better than time increase for the same energy consumption (Grönroos *et al.* 2005; Pérez-Elvira *et al.* 2009), and therefore the higher sonication power allowed in the equipment was established for the research. A previous study about the influence of the energy supplied by the equipment on sludge solubilisation was done, and is presented in this paper. Substrate samples were treated with varying ultrasonic energy from 0 to 25,700 kJ/kg TS_0 (Bougrier *et al.* 2005; Grönroos *et al.* 2005) to select the sonication conditions.

Full-stream and part-stream sonication

In order to compare part-stream with full-stream sonication and evaluate the possible positive effect of additional incubation, two groups of tests were prepared: Tests A and B.

Tests A were prepared using as a substrate different mixtures of non-sonicated/sonicated WAS, as shown in Table 2. Therefore, in A_0 the substrate is fresh sludge (control), in A_6 the sludge is sonicated sludge (full-stream sonication) and A_1–A_5 are fed with different sonicated/non-sonicated ratios (part-stream sonication).

Test B is equivalent to test A, but maintaining the substrate (non-sonicated/sonicated WAS mixtures) at 55°C for 24 h before beginning the test, in order to evaluate the

Table 2 | Fractions of sonicated sludge in tests A and B

% sonicated sludge in test substrate	Tests A	Tests B
0	A_0	B_0
10	A_1	
30	A_2	B_2
50	A_3	
70	A_4	B_4
90	A_5	
100	A_6	B_6

55°C temperature storage effect. B_0 corresponds to incubation only, B_6 is total sonication + incubation, and B_2–B_4 correspond to partial-stream sonication + incubation.

Process performance

Analytical methods

Organic matter and solids analyses were performed using the procedures given in Standard Methods for Examination of Water and Wastewater (APHA 2005).

COD was measured in the total sludge (TCOD) and in the supernatant fraction (SCOD). By difference between TCOD and SCOD the particulate COD (PCOD) was calculated.

COD solubilisation and disintegration degree

Sludge solubilisation was quantified by means of the increase in soluble COD (SCOD). The way to express this solubilisation is double: COD solubilisation and disintegration degree.

The COD solubilisation (S_{COD}) represents the transfer of COD from the particulate fraction of the sludge to the soluble fraction, and is calculated by using the difference between soluble COD (SCOD) and initial soluble COD ($SCOD_0$) compared to the initial particulate ($PCOD_0$):

$$S_{COD} = \frac{SCOD - SCOD_0}{PCOD_0} \quad (2)$$

The degree of disintegration (DD_{COD}) defined by Müller & Pelletier (1998) is a comparison between the SCOD increase by sonication and the maximum possible SCOD increase obtained by alkaline hydrolysis ($SCOD_{NaOH}$). For alkaline hydrolysis, sludge was mixed with NaOH (1 mol/L) for 24 h, at room temperature, as described by Tiehm *et al.* (2001), and Gonze *et al.* (2003).

$$DD_{COD} = \frac{SCOD - SCOD_0}{SCOD_{NaOH} - SCOD_0} \quad (3)$$

If the COD solubilisation calculation permits the evaluation of the effectiveness of an ultrasonic treatment, the disintegration degree permits the evaluation of the maximum level of sludge solubilisation.

Anaerobic biodegradability

Batch anaerobic digestion tests were carried out to assess sludge biodegradability. Serum bottles of 160 mL were filled with 80 mL, respecting a substrate/inoculum ratio of 0.5 g VS/g VS. The inoculum used was anaerobic sludge (13.7 g VS/L) from a pilot-scale digester treating mixed sludge from a municipal WWTP.

A first group of serum bottles (A) was prepared, adding as substrate: i) fresh thickened WAS (*"control"*), ii) sonicated WAS at the selected operation conditions (*"full-stream sonication"*), iii) different fractions of fresh WAS + sonicated WAS (*"part-stream sonication"*).

In order to evaluate a possible positive effect when combining ultrasound with 55°C incubation of disintegrated sludge, a second group (B) was prepared, adding as substrate the same i), ii) and ii) options, but kept for 24 h at 55°C before the beginning of the test.

All the tests were made in triplicate.

Specific methane production was recorded, and the content of each flask was characterised after 20 days' digestion, in terms of organic matter, solids, and dewaterability (CST).

In order to compare the biodegradability curves, kinetic parameters were determined, using a *Reaction Curve* (RC) equation:

$$B = P \cdot \left(1 - \exp\left(\frac{-R_m(t - \lambda)}{P}\right)\right) \quad (4)$$

where P is the maximum biogas production (mL), R_m maximum biogas production rate, and λ the lag time (d).

This type of model has been implemented in anaerobic digestion in some cases (Redzwan & Banks 2004; Lopez & Borzacconi 2008). Nonlinear optimization by least squares procedure is applied to calculate the unknown parameters by minimising a cost function (using Matlab® 7.0), which measures the difference between the experimental measurements and the corresponding simulated value.

Capillary suction time (CST)

The capillary suction time was measured to evaluate sludge dewatering behaviour, as it indicates how fast sludge releases its water. A long CST means a high cake specific resistance.

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 CST was taken as the time (in s) needed to wet the filter paper from a radius of 6 to 12 mm. Each sludge was analysed 3 times and the results averaged, before being standardised to the TS concentration as detailed in Standard Methods (APHA 2005).

RESULTS AND DISCUSSION

Selection of optimal specific energy input

Sonication conditions

A first series of experiments were done to evaluate the influence of ultrasound energy on disintegration and subsequent biodegradation, in order to select the sonication conditions for the full-stream and part-stream sonication study.

Specific energy was increased by increasing sonication time for a constant power of 200 W (maximum value allowed in the equipment), measured with a wattmeter. It is important to remark that previous studies with this equipment (Pérez-Elvira *et al.* 2009) showed that only 30% of the communicated power is really transferred to the solids, the rest being thermal losses.

Table 3 shows the sonication time and energy, and the sludge SCOD after the treatment.

Table 3 | Sonication conditions and solubilisation results (%SCOD = fraction of soluble COD in the sludge) for different supplied energies

		Energy		
	t (s)	kWh/m^3	kJ/kg$_{TS}$	% SCOD
US1	2	12	1,127	6.4
US2	30	129	12,646	32.2
US3	60	263	25,687	34.3
NaOH	0	0	0	67.2

Effect of sonication energy on disintegration

The application of ultrasound did not change total matter quantity, as total solids concentration (TS) remained constant (33.3 g/L). No evaporation phenomenon or mineralisation took place, as total organic solids (VS) also remained constant (27.5 g/L). However, while total organic matter (TCOD) was constant (40,000 mg/L), soluble COD in the supernatant increased a lot (from 2.4% to 34.3%) by increasing the supplied energy, meaning that the sludge is being disintegrated and solubilised (Figure 1).

For supplied energy under 1,000 kJ/kgTS, solubilisation was low (2.9% S_{COD}, $DD_{COD} = 4.5\%$), meaning that cell disruption was poor. An intense increase in the DD_{COD} was observed until 12,000 kJ/kgTS, but it was maintained in the range 36.1–41.8% at higher energy.

This solubilisation degree matches with the results obtained by other authors (Müller & Pelletier 1998; Wang *et al.* 1999; Neis *et al.* 2000; Lehne *et al.* 2001; Tiehm *et al.* 2001; Bougrier *et al.* 2005; El-Hadj *et al.* 2007).

Although no significant DD_{COD} increase was observed over 15,000 kJ/kg TS, the sonication condition US3 (60 s, 25,687 kJ/kg TS) was chosen for the following study to assure the highest COD increase for the sonicated sludge.

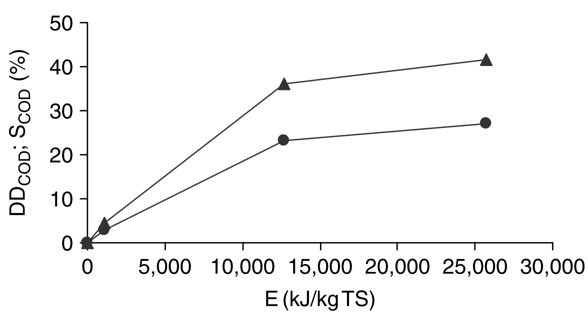

Figure 1 | Solubilisation (●) and disintegration degree (▲) vs. energy, for 200 W and different sonication time.

However, for full scale application, a compromise between solubilisation increase and energy consumption should be considered, and therefore the value where the increase in DD_{COD} begins to be smaller should be selected.

Full-stream and part-stream sonication

Ultrasound and 55°C storage pre-treatments

A laboratory scale operation combining ultrasound (US3 operation condition – 25,687 kJ/kg TS) and anaerobic digestion was performed.

As described in *Methods*, two groups of tests were prepared: tests A and B. Tests A were prepared using as a substrate different mixtures of non-sonicated and sonicated WAS, as shown in Table 2. Tests B are equivalent to tests A, but keeping the substrate at 55°C for 24 h before beginning the test, in order to evaluate the additional incubation effect.

Characterisation of substrates (total and volatile solids and COD solubilisation) was done prior to anaerobic digestion tests. Methane production, COD removal, volatile solids reduction, and CST were determined after 20-day biodegradability tests.

Pre-treatment performance evaluation

The characterisation of the different mixtures A_0–A_6 and B_0–B_6 showed some interesting features (see Figure 2).

First, the disintegration factor (DD_{COD}) comparing A_0 (fresh WAS) and A_6 (sonicated WAS, at 25,687 kJ/kg TS) is 40%, which matches with the results presented in Figure 1.

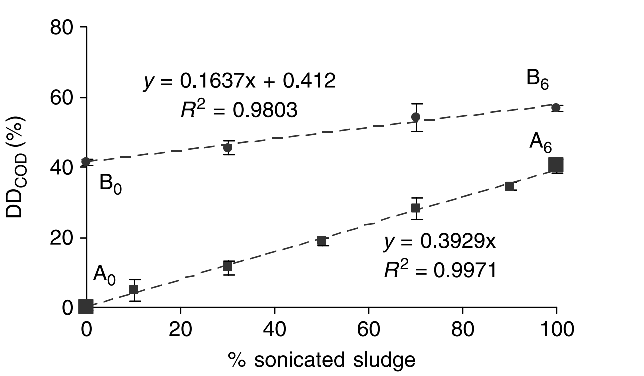

Figure 2 | Disintegration degree vs. % sonicated sludge of sludge feed for tests A (■) and B (●).

On the other hand, the same value of DD_{COD} (41%) was obtained with the 24-h incubation treatment of fresh sludge (B_0). However, the combination of ultrasound and additional incubation (B_2–B_6) was not as effective as both pre-treatments separately, and B_6 only increased DD_{COD} to 57%.

Moreover, as could be expected from the linearity of the mixtures' preparation, the results for A and B followed a linear relationship (Figure 2). However, the slope for test A (0.39) is much higher compared to test B (0.16), which again means that the incubation effect on sonicated sludge is small. Therefore, there is no evidence to state that enzymes generated during ultrasound treatment act during incubation at 55°C. In contrast, when sonicating the sludge, less enzymes seem to be generated in the subsequent incubation, and therefore less DD_{COD} increase is obtained in tests B compared to tests A.

Anaerobic digestion performance

Biogas production. Figure 3 shows the model fit (solid line) with the experimental data from each assay (circles), for both A and B tests.

Table 4 presents the kinetic parameters obtained in the optimisation process.

Comparing the biogas production values (P), the results of the biodegradability tests match with the disintegration results: for a higher percentage of sonicated WAS in the substrate, a higher DD_{COD} of the substrate was obtained, and therefore the increase in biogas productivity (L CH_4/kg TS) was higher. The relationship is again linear (see Figure 4).

However, comparing A and B curves, it can be noticed that while test A presents a sharp slope, for test B the trend is nearly flat. These trends show, first, that the compounds solubilised by sonication and 55°C temperature storage separately are easily digested: for test A (only sonication) biodegradability increases by 41% (A_6) with respect to the control (A_0), and by 31% for test B_0 (24-h incubation). On the other hand, curve B shows that the soluble compounds generated during incubation of sonicated sludge are not better degradable compared to those solubilised by ultrasound or incubation alone. While the

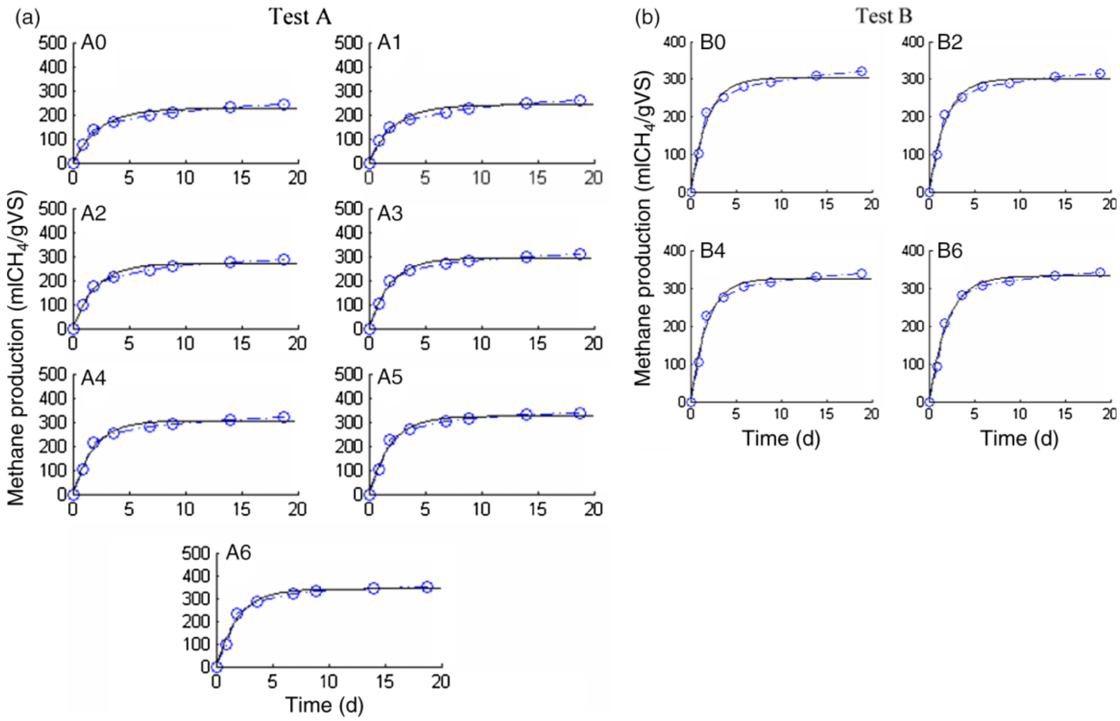

Figure 3 | Model fit to experimental data of biogas production for tests A and B.

slope of curve A is similar in Figures 2 and 4, for curve B, the slope is smaller in Figure 4 compared to Figure 2.

Therefore, combination of ultrasound and additional incubation seems to have no interest at the operation conditions used (25,687 kJ/kg TS sonication, and 24 h at 55°C for incubation).

Table 4 | Kinetic parameters calculated from the theoretical model for tests A and B

		P mL CH_4/g VS	R_m mL CH_4/g VS d	**λ** d	R^2
Tests A	A_0	248	94.2	1.8×10^{-10}	0.9805
	A_1	266	107.1	4.2×10^{-11}	0.9755
	A_2	294	132.5	7.4×10^{-11}	0.9849
	A_3	315	151.9	3.9×10^{-9}	0.9865
	A_4	325	164.8	1.4×10^{-2}	0.9864
	A_5	342	172.2	1.8×10^{-2}	0.9873
	A_6	349	178.9	3.9×10^{-2}	0.9882
Tsts B	B_0	325	167.2	0.011	0.9829
	B_2	331	166.4	0.016	0.9854
	B_4	348	183.3	0.023	0.9850
	B_6	350	167.0	0.038	0.9893

The same behaviour was observed when comparing biogas production rate values (R_m), as shown in Figure 5.

In test A, the addition of sonicated sludge substrate increases linearly the biogas production rate, from 92 mL CH_4/g VS d in the control (A_0) to 179 mL CH_4/g VS d when feeding with 100% sonicated sludge (A_6).

The 55°C storage treatment also increased the biogas production rate, to 167 mL CH_4/g VS d. However, the incubation of sonicated sludge (tests B) did not modify

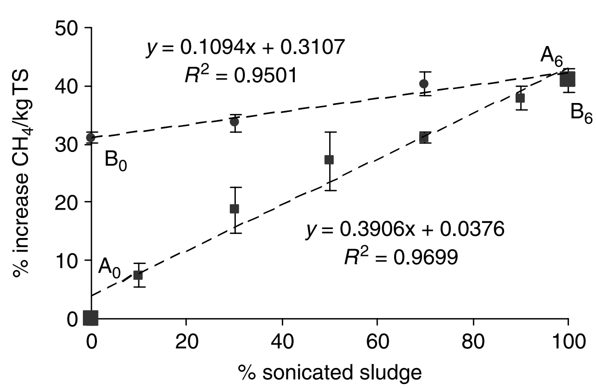

Figure 4 | % increase of L CH_4/kg TS vs. % sonicated sludge for tests A (■) and B (●).

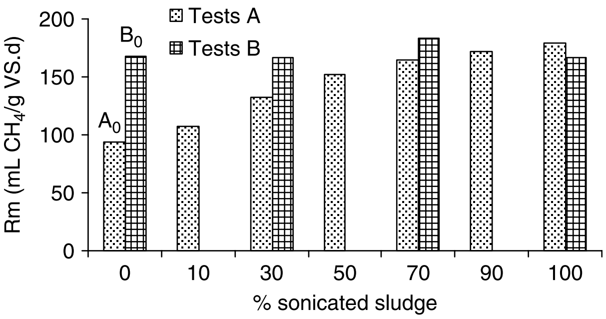

Figure 5 | Maximum biogas production rates from kinetic model fit for tests A and B.

the biogas production rate with respect to the enzyme incubation of fresh sludge.

Lag time values, although very small, show that for tests A sonicated substrate reduces the lag time, while for tests B the behaviour is just the contrary.

Finally, sludge disintegration and biogas production were compared in order to correlate the soluble organic matter and the volume of biogas produced. Figure 6 shows that the correlation is linear, which means that the quality of the biodegradable matter released after sonication is the same whatever the pretreatment. These results match with those obtained by Bougrier *et al.* (2005), and G. Zhang *et al.* (2007).

Soluble COD removal. Figures 7 and 8 show that in all the bottles COD is removed in the digester, except for the control (A_0), where SCOD increases after the digestion. This can be explained due to the release of dispersed fines and biocolloids in the hydrolysis of the untreated sludge, which caused an increase in SCOD.

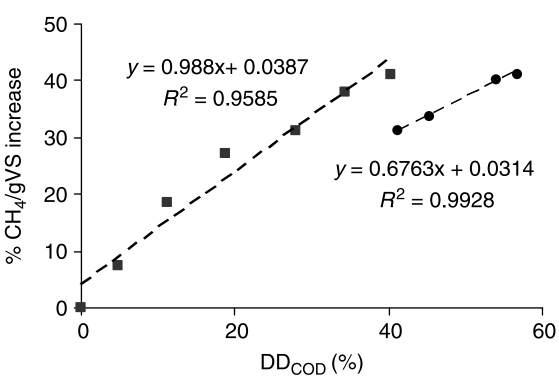

Figure 6 | Biogas production vs. disintegration degree for tests A (■) and B (●).

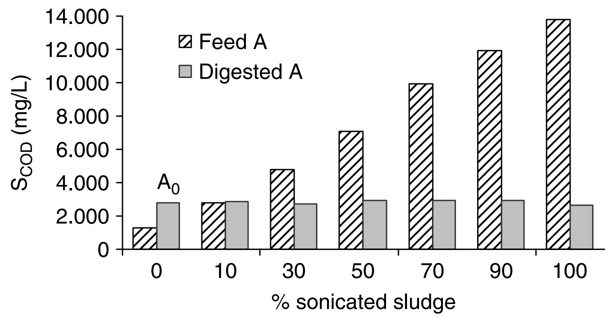

Figure 7 | SCOD for sludge feeds and digested sludge from tests A.

Figure 7 shows that, despite the higher SCOD values of sonicated feed, the digested sludge in the different tests presented similar concentration compared to the digestate from the one fed with non-sonicated sludge (control, A_0).

The same behaviour was observed in tests B (Figure 8), although, as was previously presented, in this case the concentration of the different feeds was similar to the B control (B_0).

Dewaterability of digested sludge

CST determination for fresh WAS and sonicated WAS showed a significant worsening of the dewaterability of the sludge after sonication. The ultrasonic treatment at 200 W for 60 s increased CST of raw sludge from 12 to 1,884.

After the digestion, the CST of each test was also measured. Figure 9 shows a different behaviour for tests A (only sonication) and B (sonication + 55°C incubation), which again matches with all the previous results.

For test A, the higher the sonicated sludge ratio fed to the digester, the higher the CST, which means a worse

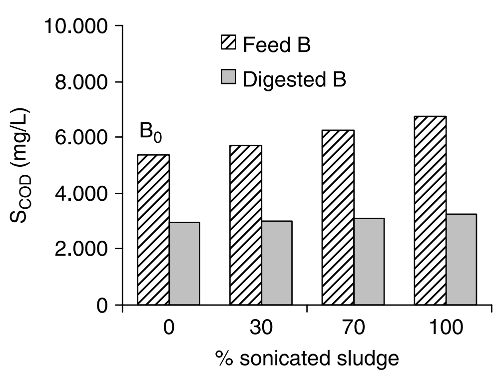

Figure 8 | SCOD for sludge feeds and digested sludge from tests B.

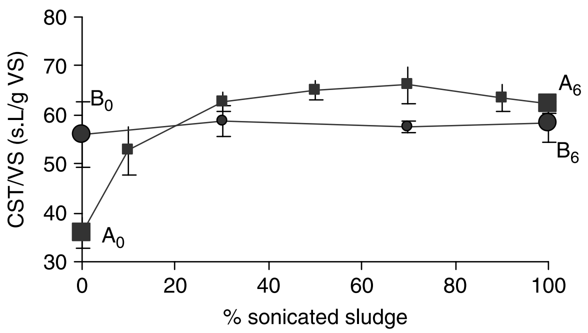

Figure 9 | CST vs. % sonicated sludge for digested sludge from tests A (■) and B (●).

dewaterability for the tests fed with sonicated sludge, from CST/VS = 36 in A_0, to 62 in A_6. This increase in the CST is a consequence of the worsening of the dewaterability of the sludge after sonication. However, in contrast with the previous results, the trend in this case is not linear, and for 30% sonicated sludge in the feed CST/VS was already 62, and constant to higher ratios of sonicated sludge.

For tests B, the initial CST/VS for B_0 was 56, which means a worsening of more than 50% in dewaterability when feeding with 24-h incubated sludge with respect to the fresh sludge feed (control, A_0). Feeding with ratios of sonicated and incubated sludge did not affect the CST results for digested sludge.

CONCLUSIONS

This study shows that sonication is an effective way for disintegrating the sludge, and that neither part-stream sonication nor incubation of sonicated sludge (24 h at 55°C) proved to be advantageous to full-stream sonication.

A 40% increase in DD_{COD} was obtained when sonicating fresh WAS at 25,700 kJ/kg TS, and with the incubation of the sludge (24 h, 55°C). The compounds solubilised by sonication and incubation separately were easily digested, as biodegradability increased in both cases by 41% with respect to the control.

The study of part-stream sonication showed that, considering the sonication alone, the higher the percentage of sonicated WAS in the substrate, the higher DD_{COD} of the substrate was obtained, and therefore the higher the increase in biogas productivity (L CH_4/kg TS). The relationship was linear, achieving the greatest biogas production for full-scale sonication (41 increase). This behaviour shows that part-stream sonication is not advantageous to full-stream sonication from the point of view of biogas production.

The combination of ultrasound and 55°C storage showed no evidence to state that enzymes generated during sonication act during incubation at 55°C (DD_{COD} only increased to 57%). Soluble compounds generated during incubation of sonicated sludge were less degradable compared to those solubilised by ultrasound or 55°C storage alone. Therefore, combination of ultrasound and incubation seems to have no interest at the operation conditions used.

Finally, dewaterability of anaerobically digested sludge of part-stream and full-stream digestion was worse compared to the control reactor. The higher the quantity of sludge sonicated in the feed, the worse the dewaterability. The relationship with the ratio of sonicated sludge fed was not linear in this case, and for 30% sonicated sludge in the feed the CST increased as much as for full-stream sonication.

An economic balance comparing energy consumption costs and benefits in additional energy production from biogas should be done based on data from full-scale ultrasound devices.

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