Anaerobic co-digestion of the organic fraction of municipal solid waste with FOG waste from a sewage treatment plant: recovering a wasted methane potential and enhancing the biogas yield

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Abstract

Anaerobic digestion is applied widely to treat the source collected organic fraction of municipal solid wastes (SC-OFMSW). Lipid-rich wastes are a valuable substrate for anaerobic digestion due to their high theoretical methane potential. Nevertheless, although fat, oil and grease waste from sewage treatment plants (STP-FOGW) are commonly disposed of in landfill, European legislation is aimed at encouraging more effective forms of treatment. Co-digestion of the above wastes may enhance valorisation of STP-FOGW and lead to a higher biogas yield throughout the anaerobic digestion process. In the present study, STP-FOGW was evaluated as a co-substrate in wet anaerobic digestion of SC-OFMSW under mesophilic conditions (37ºC). Batch experiments carried out at different co-digestion ratios showed an improvement in methane production related to STP-FOGW addition. A 1:7 (VS/VS) STP-FOGW:SC-OFMSW feed ratio was selected for use in performing further lab-scale studies in a 5L continuous reactor. Biogas yield increased from 0.38±0.02 L g VS_{feed}^{-1} to 0.55±0.05 L g VS_{feed}^{-1} as a result of adding STP-FOGW to reactor feed. Both VS reduction values and biogas methane content were maintained and inhibition produced by long chain fatty acid (LCFA) accumulation was not observed. Recovery of a currently wasted methane potential from STP-FOGW was achieved in a co-digestion process with SC-OFMSW.

Keywords: Anaerobic digestion; co-digestion; municipal solid waste; organic fraction, FOG waste.

1 Introduction

Anaerobic digestion of the organic fraction of municipal solid waste (OFMSW) has been widely implemented in Europe throughout the last decade (De Baere, 2006). The main factors underlying this increase include: i) European legislation limiting landfill treatment of biodegradable waste (99/31/EC), ii) increase in source sorted collection of waste, and iii) anaerobic treatment of biodegradable fraction resulting in enhanced energetic valorisation.

Considering these favourable circumstances, co-digestion of organic waste has become an active area of research due to its potential advantages compared to conventional anaerobic digestion: the main improvement would be in the methane yield of the process, and it would also be a way of valorising certain co-substrates. Moreover, existing facilities could be used with no need for new investment (Mata-Alvarez et al., 2000; Hartmann and Ahring, 2005; Bolzonella et al., 2006; Cuetos et al., 2008; Macias-Corral et al., 2008).

Nowadays, lipid-rich waste, also called fat, oil and grease (FOG) waste, has become an interesting substrate for anaerobic digestion because it is produced in large quantities by several industries. Its high theoretical methane potential in comparison with other substances makes FOG waste a desirable substrate to treat in anaerobic digestion processes (Angelidaki and Sanders, 2004). However, problems associated with the anaerobic treatment of lipids have been reported: on one hand, operational problems like biomass washout due to flotation (Hwu et al., 1998; Rinzema et al., 1993), and on the other hand, inhibitory and toxic effects produced by long chain fatty acids (LCFA) generated from the hydrolysis of lipids, which have been extensively reported and

discussed in the literature over the years (Koster and Cramer, 1987; Angelidaki and Ahring, 1992; Rinzema et al., 1994, Hwu and Lettinga, 1997; Lalman and Bagley, 2000; Alves et al., 2001). Nevertheless, recent studies have shown that inhibition in methane production caused by LCFA could be non-permanent and reversible, and acclimation has been mentioned as a key factor in avoiding these hypothetical negative effects in microbial communities (Pereira et al., 2004; Pereira et al., 2005; Cavaleiro et al., 2008).

The importance of studying real and complex FOG wastes, not just synthetic mixtures of LCFA or the simple FOG wastes that are widely reported in the literature, in order to face the complexity and heterogeneity of real FOG waste has recently been highlighted (Jeganathan et al., 2006). Expanding the range of suitable substrates has also been mentioned as a way of giving anaerobic technologies more importance in the bioenergy market (Alves et. al., 2009).

Complex FOG waste is present in sewage, and must be removed during the first steps of sewage treatment plants (STP) in order to avoid mechanical problems caused by the increase in solid sludge throughout the treatment process, biological problems due to possible inhibitions, or oxygen mass transfer difficulties, as well as odour problems. It is usually separated in the first stage of the STP (skimming tank) using aeration combined with mechanical separation, then it is partially dried in situ and often then transported to landfill or incinerated. However, to our knowledge there is no specific literature on the anaerobic treatment of STP-FOG waste (STP-FOGW).

Co-digestion of STP-FOGW with OFMSW appears to be a feasible option, especially bearing in mind European legislation. Unlike landfill, this would be an environmentally friendly treatment of a biodegradable waste. In addition, adding waste with high-lipid content to SC-OFMSW, a waste that already contains a certain amount of FOG, could be a way of improving the yield of the whole anaerobic digestion process.

The main purpose of this study was to investigate the mesophilic anaerobic co-digestion of SC-OFMSW and STP-FOGW in a lab-scale reactor. Prior to the anaerobic co-digestion treatment, anaerobic biodegradability batch assays were carried out to determine possible inhibitory or toxic effects and to establish an appropriate STP-FOGW feed content for the subsequent studies in a continuous lab reactor.

2 Methods

2.1. Inoculum, SC-OFMSW and STP-FW

The inoculum for the batch tests was obtained from the accumulated outlet of a mesophilic continuous lab reactor treating SC-OFMSW in a steady-state operation (hydraulic retention time (HRT)= 16d; organic loading rate (OLR)= 3 kg VS $m^{-3}d^{-1}$) for 8 months. Total solids (TS) and volatile solids (VS) were 13.7 g L^{-1} and 9.4 g L^{-1} respectively and volatile fatty acid (VFA) concentration was 1.28 g L^{-1} of only acetate.

The inoculum for the lab-scale reactor study was obtained from the aforementioned mesophilic reactor while batch tests were being carried out. TS and VS content of the reactor inoculum were 8.5 g L^{-1} and 5.6 g L^{-1}

respectively. Only acetate was detected in a concentration of 1.87 g L^{-1}.

SC-OFMSW was obtained from the municipal solid waste treatment plant Ecoparc II, in Montcada i Reixac (Catalunya, Spain). TS and VS were 370.4 g kg^{-1} and 275.3 g kg^{-1} and its total FOG content was 11% (w/w, dry basis). Total organic carbon (TOC) percentage was 45% (w/w, dry basis) and total Kjeldahl nitrogen (TKN) was 3.2% (w/w, dry basis). The free LCFA contained in the original sample is shown in Table 1, and palmitate and stearate were present in the highest concentrations. SC-OFMSW was ground, diluted with tap water to achieve the desired TS feed content and stored at -18ºC until use.

STP-FOGW was collected from the primary skimmer of the Sabadell STP (Catalunya, Spain). TS and VS values were 120.2 g kg^{-1} and 99.4 g kg^{-1} respectively. No VFA was detected. FOG content was 48% (w/w, dry basis), TOC content was 56% (w/w, dry basis) and TKN was 2.4% (w/w, dry basis). Table 1 shows the average for the free LCFA content of the original sample, and palmitate was clearly the most abundant. FOG waste was stored at -18 ºC until use.

2.2 Biodegradability batch assays

Discontinuous assays were performed in duplicate in order to evaluate the effect of STP-FOGW on wet anaerobic degradation of SC-OFMSW and thus, in turn, to choose an appropriate feed ratio for further lab-scale studies.

Anaerobic batch tests were based on Field et al. (1988), adapted in accordance with Ferrer et al. (2004) and taking into account some points from Angelidaki et al. (2009). Batch reactors were commercial aluminium bottles with a total volume of 600 mL and with a modified cap to include a manual valve for biogas measures. Biogas production was measured according to the pressure increase in the headspace by means of an SMC Pressure Switch manometer (1 bar, 5% accuracy). Biogas samples were taken periodically to analyze the methane content by gas chromatography.

Accumulated volumetric biogas production was calculated from the pressure increase in the headspace volume at 37ºC and expressed in standard temperature and pressure conditions. The net values of methane production used to calculate methane yields were obtained by subtracting the biogas production of the blank assay (only inoculum) from the biogas production of each treatment.

Different SC-OFMSW:STP-FOGW (VS/VS) co-digestion ratios were tested: 16:1, 7:1, 2:1, 1:0 and 0:1, corresponding to STP-FOGW/total feed (VS/VS) percentages of 5%, 15%, 35%, 100% and 0%. The 100% and 0% assays were performed in order to compare them with the co-digestion ratios and assess any differences in the typical parameters (VS reduction, methane yield) or detect

hypothetical inhibitory effects. Ratios higher than 35% were not evaluated as unrealistic because of the low production of STP-FOGW compared with the large quantities of SC-OFMSW that are produced nowadays.

The initial contents of the VS are shown in detail in Table 2 as well as the initial VFA concentration and pH values. After each batch reactor was filled up, they were flushed with nitrogen to remove air and afterwards incubated at 37 ºC.

2.3. Continuous lab reactor: experimental set-up and procedure

Anaerobic co-digestion was carried out in a 5L glass jacketed reactor connected to a thermostatic bath through which the temperature was controlled (Ferrer et al., 2008) in order to maintain mesophilic conditions (37ºC). The biogas channel, the feeding inlet tube, and the extracting and/or sampling outlet tube were all located in the stainless steel cap of the reactor. The reactor was fed once a day, always following the same extraction/feed routine: first the established volume was extracted with a vacuum pump connected to a vessel also linked to the outlet tube, and then, immediately afterwards, the feeding mixture was added through the inlet channel. Automatic stirring was established as 20 minutes every 2 hours and programmed through a simple commercial controller. The biogas produced was measured on line volumetrically by water displacement, by means of an electric counter connected to a sensor level.

The anaerobic digester was operated for roughly 7 months and three experimental periods can be defined. The start-up (Period I) lasted 36 days, in

which the reactor was fed with diluted SC-OFMSW (TS= 40 g L^{-1}, VS= 35 g L^{-1}) maintaining a flow rate of 310 mL d^{-1}, which corresponds to an HRT of 16 d, a conventional value used in municipal solid waste treatment plants. The OLR was around 2 kg VS $m^{-3}d^{-1}$. Next, the TS feed concentration was increased to 70 g L^{-1} to reach the feed values of OFMSW wet anaerobic digestion that are usual in industrial plants (Period II) and the OLR was therefore increased to 4 kg VS m^{-3} d^{-1}. The FOG content from the SC-OFMSW in the feed was 11% (w/w, dry basis). This period (Period II) lasted until stable values of biogas production and VS, TS removal efficiencies were achieved (which was 27 days, from process day 55 to 82).

Finally, a third operation period (Period III) began when STP-FOGW was added, and lasted for 74 days. As a result of the addition, the total FOG feed concentration was then increased to 18% (w/w, dry basis), the OLR raised to 4.5 kg VS $m^{-3}d^{-1}$ and the HRT reduced to 14.5 d.

Stability criteria in order to determine the average values for each period were established as follows: a minimum of one HRT has to be accounted for and variations in VFA, biogas yield, VS and TS reduction percentages have to be lower than 10%.

2.4 Analytical methods and monitoring parameters

TS and VS were determined according to Standard Methods (APHA, 1999). TOC content was determined using a solid commercial TOC analyzer (Solids TOC Analyzer, O I Analytical, USA). TKN content was determined in accordance with Standard Methods (APHA, 1999).

VFAs (acetic, propionic, butyric, valeric and *n*-valeric acids) were determined by gas chromatography in a Hewlett Packard Chromatograph (HP 5890) equipped with a flame ionization detector (FID) and a Teknocroma (25% NPGA, 2% H_3PO_4) 2.7m x 1/8" column. Nitrogen was the carrier gas at 230 kPa, and the oven, injector and detector temperatures were 130, 250 and 260ºC respectively. Samples were previously centrifuged (30 min, 13500 rpm, Beckman), filtered (0.45 µm, Millipore) and then mixed (1/1, v/v) with a 0.2% pivalic acid solution as an internal standard. A total sample volume of 1 µL was used for chromatography. The detection range was from 0.5 to 8 g L^{-1}.

Methane and carbon dioxide content in the biogas were analyzed by means of a Hewlett Packard Chromatograph (HP 5890) equipped with a thermal conductivity detector (TCD) and a Supelco Porapack Q (250ºC) 3m x 1/8" column. Helium was the carrier gas at 338 kPa, and the oven, injector and detector temperatures were 70, 150 and 180ºC respectively. A total sample volume of 100 µL was used for chromatography.

Total FOG content (lipids and also free LCFA primarily contained in the original sample) of the samples was determined gravimetrically after extraction with *n*-heptane (99% purity, Panreac, Spain) as an organic solvent. FOG extraction was performed in commercial Soxhlet extraction equipment (Extraction system B-811, Büchi, Switzerland).

Free LCFA (palmitate, oleate, stearate and myristate) concentrations contained in the original FOG sample were determined by gas chromatography after the total extracted FOG was taken up in a known heptane volume and filtered (0.45 µm, Millipore). A Hewlett Packard Chromatograph (HP 6890) equipped with a flame ionization detector (FID) and a HP-Innowax (30m x 0.25 mm) column was used. The carrier gas was Helium (500 kPa) with a split ratio of 13 (column flow: 5 mL min^{-1}). An initial oven temperature of 235ºC was maintained for 7 min, then increased to 260ºC at 20 min $ºC^{-1}$ and maintained at this temperature for another 7 min. Injector and detector temperatures were 250ºC and 260ºC respectively. The system was calibrated with commercial solutions (Sigma-Aldrich) of the aforementioned free LCFA within the range of 50 to 1000 mg L^{-1}. A total volume of 5 µL was used.

3 Results and discussion

3.1 Biodegradability batch assays

The evolution of net methane production during the 35 days of assay is shown in Figure 1 (inoculum methane production has been withdrawn). Average values are shown, all with a maximum standard deviation of 10%.

Due to the remains of a high content of easily biodegradable organic matter in the inoculum, net methane production was not observed until almost day 10 in the 0%, 5% and 15% reactors. The 35% and 100% reactors, with higher STP-

FOGW content, required 12 and 14 days respectively (negative values in net methane production are marked with zeros).

All reactors, except the 100% one, registered higher net methane production values when the STP-FOGW percentage in the feed increased. The slight lag phase of 2 days in the 35% assay and the following recovery could be the result of a slight reversible inhibition, previously reported in other works (Pereira et al., 2005; Cavaleiro et al., 2008; Palatsi et al., 2009), that could be related to the LCFA content, particularly to palmitate, since it is the most abundant LCFA in STP-FOGW, followed by oleate and stearate (see Table 1).

In the final batch assay results (see Table 3) palmitate was also the most abundant free LCFA found in all reactors at the end of the experiment. This is a reasonable result considering that it is also an intermediate of oleic acid degradation, which is described as a fast and non-limiting step (Lalman and Bagley, 2000; Pereira et al., 2002).

VS elimination (see also Table 3) decreased coupled with the addition of STP-FOGW, achieving reduction values within the range of 58 to 65% in the 0%, 5% and 15% assays. Total FOG reduction was clearly lower in the 35% assay (34%) while higher values, between 42 and 50%, were achieved in the 0%, 5% and 15% assays.

The increase in methane yields as the STP-FOGW increased, except in the 35% and 100% assays, indicates that co-digestion of SC-OFMSW and STP-FOGW could increase the biogas yield in a continuous digestion process.

In the 100% assay, lower methane production was obtained even in comparison with the 0% assay. The final results (see Table 3) showed low VFA concentrations (below 0.5 g L^{-1}) in the 100% assay, which rules out a VFA inhibition of methanogenic bacteria. The final free LCFA values analyzed were similar to the ones obtained in the 35% assay, showing no accumulation of free LCFA at this point and excluding hypothetical problems in their degradation to acetate (β-oxidation step). Moreover, a very low FOG reduction percentage was obtained. These results indicate that the hydrolytic step in the 100% assay was slow and FOG remained in the reactor, probably due to a low inoculum/substrate ratio in this particular assay .

In line with the results presented above and bearing in mind the real production of both wastes, STP-FOGW and SC-OFMSW, a 15% STP-FOGW (VS) feed content was selected to carry out further continuous lab-scale studies.

3.2 Continuous lab reactor experiment

During Period I, the start-up period, after 6 days for inoculum acclimation, the reactor was fed with SC-OFMSW at a low concentration (TS=4%), maintaining an OLR of around 2 kg VS m^{-3} d^{-1} (Figure 2). This operation was maintained until low values of VFA were achieved, which allowed a further increase in solid feed content. The low reduction in VS (between 40 and 55%), as well as the relatively high values of VFA (up to 2 g L^{-1}), are related to the acclimation of microorganisms during the start-up period (Ahring, 1994).

Period II started with an increase in solid feed content (TS=7%) to achieve an OLR of 4 kg SV m^{-3} d^{-1}; the HRT was 16 d and the FOG feed content was 12%, since only SC-OFMSW was fed. The whole period lasted from process day 36 to 82 but only values from day 52, after one complete HRT, were considered stable enough to characterize this period. An initial upturn of total VFA due to the increase in the OLR was noticed on day 43, when VFA (only acetate was present) increased to 1.3 g L^{-1} (see Figure 2). Afterwards, the VFA returned to values lower than 0.5 g L^{-1}, which were maintained throughout Period II, therefore showing stable reactor performance. Biogas production was around 8 L d^{-1} and biogas yield was 0.38 L biogas g VS_{feed}^{-1}, corresponding to a methane yield of 0.24 L CH_4 g VS_{feed}^{-1} (202 Nm^3 CH_4 ton VS_{feed}^{-1}). TS and VS reductions of 61 and 66% respectively were obtained (see Table 4).

Several values for VS and TS reduction, methane content in the biogas and methane yield can be found in the literature on anaerobic digestion of OFMSW. Focusing on methane yield, Davidsson et al. (2007) reported a wide range from 200 to 600 Nm^3 CH_4 ton VS_{feed}^{-1}, including both thermophilic and mesophilic treatments. Hartmann and Ahring (2006) also compiled values for different processes of anaerobic digestion of OFMSW. Significant differences and variability among compiled values mean that, apart from operational conditions, OFMSW characteristics and the sorting, collecting, and pre-treatment procedures are also determinant factors in obtaining certain methane yield values, as well as other parameters during the anaerobic digestion process. The VS reduction percentage and methane yields obtained in the present study

are similar to some of those referenced in the literature. In the free LCFA and FOG evolution throughout Period II, FOG was reduced by a total of 50% and only palmitate was found (9.1 mg L^{-1}) in the effluent in a low concentration (see Table 4).

The co-digestion period (Period III) started at process day 82 when STP-FOGW was added to the reactor feed, increasing the OLR from 4 to 4.5 kg VS m^{-3} d^{-1} and raising the total FOG feed content to 18%. This first addition of STP-FOGW caused an immediate increase in total VFAs to 1.25 g L^{-1} that dropped again below 0.5 g L^{-1} on process day 92 (see Figure 2). From that day on there were negligible values of VFA below 0.5 g L^{-1} throughout the co-digestion period.

Furthermore, biogas production increased due to STP-FOGW addition and reached an average value of 13 L biogas d^{-1} during Period III, almost twice as much as the production in Period II (see Figure 2). Methane content remained around 63%. An immediate increase in both biogas and methane yields was observed after day 82, which remained fairly constant throughout the period and reached average values of 0.55 L biogas g VS_{feed}^{-1} and 0.35 L CH_4 g VS_{feed}^{-1} (317 Nm^3 CH_4 ton VS_{feed}^{-1}) respectively (see Figure 2 and Table 4). These results indicate a 45% enhancement of biogas and methane yields in comparison with values obtained in Period II (0.38 L biogas g VS_{feed}^{-1} and 0.24 L CH_4 g VS_{feed}^{-1}). This is in accordance with other co-digestion experiments using complex FOG wastes that also showed improvements in methane yield when a similar HRT and OLR were applied in order to treat FOG waste with

sewage sludge (Davidsson et al., 2008; Luostarinen et. al., 2009; Kabouris et. al., 2009).

The average VS reduction percentage obtained was 65%, which is very similar to the one previously achieved in Period II (66%). This shows that STP-FOGW did not have a negative effect on VS destruction, although, as a result of the addition, the OLR increased from 4 to 4.5 kg VS m^{-3} d^{-1} and the HRT decreased from 16 to 14.5d with regard to Period II (see Table 4).

Enhancement of methane yield without remarkable improvement in VS destruction was observed when co-digestion of sewage sludge with FOG waste was compared with anaerobic digestion of sewage sludge only (Luostarinen et al., 2009), and similar results were obtained also when a continuous reactor was fed with synthetic dairy wastewater: an increase in the applied OLR was coupled with an improvement in the methane yield while the VS reduction remained stable (Cavaleiro et al., 2009).

The FOG reduction percentage increased during Period III with regard to Period II (56% as opposed to 50%) and free LCFA concentrations in the effluent remained in spite of STP-FOGW addition. These results suggest that FOG from STP-FOGW was degraded and there was no accumulation in the sludge, which would explain the remarkable increase in methane yield during the co-digestion period (Cavaleiro et al., 2009)

From the results stated above and to reinforce the idea of the feasibility of co-digestion of STP-FOGW with SC-OFMSW instead of sewage sludge, it should

be remembered that both wastes always have a low or moderate percentage of non-organic refuse (even when OFMSW comes from a source-collection management system). This means that using STP-FOGW as a co-substrate in an anaerobic digestion process of SC-OFMSW will not imply potential operational problems. Moreover, it should be considered that composting is usually applied to digested SC-OFMSW in industrial plants, which already includes a post-treatment step to separate refuse from compost material.

4. Conclusions

Mesophilic co-digestion of STP-FOGW with SC-OFMSW at a feed ratio of 15% (VS) carried out in a 5L lab-scale reactor resulted in an improvement both in terms of biogas production (72% higher) and methane yield (46% higher) in comparison with anaerobic treatment of SC-OFMSW. During the co-digestion process, a stable reactor performance was observed and there was no inhibition either in LCFA accumulation or in VFA excess. VS and TS reduction percentages were stable and around 65% and 57% respectively, and the methane content in biogas was 63%. These results suggest that anaerobic co-digestion is a feasible and efficient way of managing STP-FOGW. Moreover, it is an environmentally friendly treatment in comparison with the landfill option and allows a methane potential that is presently being wasted to be recovered.

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References

Ahring, B.K., 1994. Status on science and application of thermophilic anaerobic digestion. Water Sci. Technol. 30(12), 241-249.

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Alves, M.M., Mota Vieira, J. A., Álvares Pereira, R.M., Pereira, M.A., Mota, M., 2001. Effect of lipids and oleic acid on biomass development in anaerobic fixed-bed reactors. Part I: Biofilm growth and activity. Water Res. 35, 255-263.

Alves, M.M., Pereira, M.A., Sousa, D.Z., Cavaleiro, A.J., Picavet, M., Smidt, H., Stams, A.J.M., 2009. Waste-lipids to energy: how to optimize methane production from long chain fatty acids (LCFA).Microb. Biotech. 2(5), 538-550.

Angelidaki, I., Ahring, B.K., 1992. Effects of free long-chain fatty acids on thermophilic anaerobic digestion. Appl. Microbiol.. Biot. 37, 808-812.

Angelidaki, I., Alves, M., Bolzonella, D., Borzacconi, L., Campos, J.L., Guwy, A.J., Kalyuzhnyi, S., Jenicek, P., van Lier, J.B., 2009. Defining the biomethane potential (BMP) of solid organic wastes and energy crops: a proposed protocol for batch assays. Water Sci. Technol. 59(5), 927-934.

Angelidaki, I., Sanders, W., 2004. Assessment of the anaerobic biodegradability of macropollutants. Rev. Environ. Sci. and Biotechnol. 3, 117-129.

APHA, AWWA, WPCF, 1999. Standard Methods for the Examination of Water and Wastewater, 20th ed. American Public Health Association, American Water Works Association, Water Environment Federation, Washington, DC.

Bolzonella, D., Battistoni, P., Susini, C., Cecchi, F., 2006. Anaerobic codigestion of waste activated sludge and OFMSW: the experiences of Viareggio and Treviso plants (Italy). Water Sci. Technol. 53 (8), 203-211.

Cavaleiro, A.J., Salvador, A.F., Alves, J.I., Alves, M., 2009. Continuous high rate anaerobic treatment of oleic acid based wastewater is possible after a step feeding start-up. Environ. Sci. Technol. 43(8), 2931-2936.

Cavaleiro, A.J., Pereira, M.A., Alves, M., 2008. Enhancement of methane production from long chain fatty acid based effluents. Biores. Technol. 99, 4086-4095.

Cuetos, M.J., Gómez, X., Otero, M., Morán, A., 2008. Anaerobic digestion of solid slaughterhouse waste (SHW) at laboratory scale: Influence of co-digestion with the organic fraction of municipal solid waste (OFMSW). Biochem. Eng. J. 40, 99-106.

Davidsson, Å., Gruvberger, C., Christensen, T., Hansen, T.L., Jansen, J.l.C., 2007. Methane yield in source-sorted organic fraction of municipal solid waste. Waste Manage. 27, 406-414.

Davidsson, Å., Lövstedt, C., Jansen, J.l.C., Gruvberger, C., Aspegren, H., 2008. Co-digestion of grease trap sludge and sewage sludge. Waste Manage. 28, 986-992.

De Baere, L., 2006. Will anaerobic digestion of solid waste survive in the future?. Water Sci. Technol. 53 (8), 187-194.

Ferrer, I., Fornés, O., Ferrer O., Gordillo, M.A., Font, X., 2004. Sistema efectivo y económico para la determinación de la producción de biogás en ensayos en discontinuo. Tecnología del Agua 253, 50-54.

Ferrer, I., Ponsá, S., Vázquez, F., Font, X., 2008. Increasing biogas production by thermal (70ºC) sludge pre-treatment prior to thermophilic anaerobic digestion. Biochem. Eng. J. 42, 186-192.

Field, J., Sierra, R., Lettinga, G., 1988. Ensayos anaerobios. *Proc. of 4th Symp. on Wastewater Anaerobic Treatment,* Valladolid, Spain, 52-81.

Hartmann, H., Ahring, B.K., 2006. Strategies for the anaerobic digestion of the organic fraction of municipal solid waste: an overview. Water Sci. Technol. 53, 7-22.

Hwu, C.-S. and Lettinga, G., 1997. Acute toxicity of oleate to acetate-utilizing methanogens in mesophilic and thermophilic anaerobic sludges. Enzyme Microb. Tech. 21, 297-301.

Hwu, C.-S., Tseng, S.-K., Yuan, C.-Y., Kulik, Z. and Lettinga, G. 1998. Biosorption of long-chain fatty acids in UASB treatment process. Wat. Res., 32, 1571–1579.

Jeganathan, J., Nakhla, G, Bassi, A., 2006. Long-term performance of high rate anaerobic reactors for the treatment of oily wastewater. Environ. Sci. Technol. 40, 6466-6472.

Kabouris, J.C., Tezel, U., Pavlostathis, S.G., Engelmann, M., Dulaney, J., Gilette, R.A., Todd, A.C., 2009. Methane recovery from the anaerobic codigestion of municipal sludge and FOG. Biores. Technol. 100, 3701-3705.

Koster, I.W. and Cramer, A., 1987 Inhibition of methanogenesis from acetate in granular sludge by long-chain fatty acids. Appl. Environ. Microb. 53, 403-409.

Lalman, J. A., Bagley, D.M., 2000. Anaerobic degradation and methanogenic inhibitory effects of oleic and stearic acids. Water Res. 35, 2975-2983.

Luostarinen, S., Luste, S., Sillanpää, M., 2009. Increased biogas production at wastewater treatment plants through co-digestion of sewage sludge with

grease trap sludge from a meat processing plant. Biores. Technol.100, 79-85.

Macias-Corral, M., Samani, Z., Hanson, A., Smith, G., Funk, P., Yu, H., 2008. Anaerobic digestion of municipal solid waste and agricultural waste and the effect of co-digestion with dairy cow manure. Biores. Technol. 99, 8288-8293.

Mata-Alvarez, J., Macé, S., Llabrés, P., 2000. Anaerobic digestion of organic solid wastes. An overview of research achievements and perspectives. Biores. Technol. 74, 3-16.

Palatsi, J., Laureni, M., Andrés M.V., Flotats, X., Nielsen, H.B., Angelidaki, I. 2009. Strategies for recovering inhibition caused by long chain fatty acids on anaerobic thermophilic gas reactors. Biores. Technol. 100, 4588-4596.

Pereira, M.A., Sousa, D.Z.; Mota, M. and Alves, M.M., 2004. Mineralization of LCFA associated with anaerobic sludge: kinetics, enhancement of methanogenic activity and effect of VFA. Biotechnol. Bioeng. 88, 502-511.

Pereira, M.A., Pires, O.C., Mota, M. and Alves, M.M., 2005. Anaerobic biodegradation of oleic and palmitic acids: evidence of mass transfer limitations caused by long chain fatty acid accumulation onto the anaerobic sludge. Biotechnol. Bioeng. 92, 15-23.

Pereira, M.A., Pires, O.C., Mota, M. and Alves, M.M., 2002. Anaerobic degradation of oleic acid by suspended and granular sludge: identification of palmitic acid as a key intermediate. Water Sci. Technol. 45, 139-144.

Rinzema, A., Alphenaar, A. and Lettinga, G., 1993. Anaerobic digestion of long-chain fatty-acids in UASB and expanded granular sludge bed reactors. Process Biochem. 28, 527-537.

Rinzema, A., Boone, M. Van Knippenberg, K. and Lettinga, G., 1994. Bactericidial effect of long chain fatty acids in anaerobic digestion. Water. Environ. Res. 66, 40-49.

Figure captions

Figure 1 Time course of accumulative net methane production for batch assays. (▽) 0% STP-FOGW, (○) 5% STP-FOGW, (▲) 15% STP-FOGW, (□) 35% STP-FOGW, (●) 100% STP-FOGW.

Figure 2 Evolution of (●) VS reduction (%), (◊) Biogas production (L bg d^{-1}), (+) pH, (—) OLR (Kg VS $m^{-3} \cdot d^{-1}$), (O) Methane yield (L CH4 g VS $added^{-1}$) and (▲) Total VFA (g L^{-1}) in the continuous lab-scale reactor experiment.

Table 1

Free LCFA content in STP-FOGW and SC-OFMSW (dry basis).

Free LCFA	STP-FOGW(mg/g)	SC-OFMSW (mg/g)
Palmitate	23.8 ± 0.4	6.7 ± 0.5
Oleate	7 ± 1	3.6 ± 0.4
Stearate	6.0 ± 0.7	5.4 ± 1.5
Myristate	3.1 ± 0.1	0.53 ± 0.01

Table 2 Initial VS, VFA and pH values of batch assays.

		Initial VFA (g L^{-1})		VS composition (mg)		
Assay	**Initial pH**	**Acetate**	**Propionate**	**Inoculum**	**SC-OFMSW**	**STP-FOGW**
Blank	7.8	1.3 ± 0.1	< 0.5	2800	4100	0
0%	7.7	1.4 ± 0.1	< 0.5	2800	4100	0
6%	7.7	1.3 ± 0.1	< 0.5	2800	4100	252
15%	7.6	1.2 ± 0.2	< 0.5	2800	4100	604
52%	7.9	1.3 ± 0.1	< 0.5	2800	4100	2114
100%	7.2	1.9 ± 0.2	0.68 ± 0.3	2800	0	4027

Table 3 Characterization of the batch reactors at the end of the assay.

Assay	pH	Final VFA (g L^{-1})	Final free LCFA (ppm)				FOG reduction (%)	VS reduction (%)	Net methane yield (mL CH4 gVS $feed^{-1}$)
			Palmitate	Oleate	Stearate	Myristate			
0%	7.8	<0.5	n.d	n.d	n.d	n.d	50 ± 3	65.2 ± 0.2	298 ± 21
5%	7.7	0.92 ± 0.01	n.d	n.d	n.d	n.d	51 ± 2	60.0 ± 0.7	301 ± 4
15%	7.7	0.93 ± 0.01	33 ± 8	8.96 ± 0.02	6 ± 1	n.d	42 ± 3	58.1 ± 0.4	318 ± 27
35%	7.6	1.24 ± 0.03	78 ± 7	19 ± 2	10 ± 3	9.5 ± 0.4	34 ± 1	36.2 ± 0.6	277 ± 24
100%	7.9	<0.5	75 ± 2	22 ± 9	18 ± 3	6 ± 1	32 ± 2	28.2 ± 0.1	278 ± 18

n.d: not detected

Table 4

Characterization of Periods II and III.

Parameters	Period II (days 52-81)	Period III (days 131-205)
Type of feed	SC-OFMSW	SC-OFMSW + STP-FOGW
OLR (kg VS m^{-3} d^{-1})	~ 4	~ 4.5
HRT (days)	16	14
STP-FOGW in feed (%VS)	0	15
pH	7.2 ± 0.1	7.6 ± 0.1
Biogas (L d^{-1})	7.9 ± 0.6	14 ± 1
Methane content in biogas (%)	62 ± 1	63 ± 1
Total VFA (g L^{-1})	< 0.5	< 0.5
Effluent free LCFA content (mg L^{-1})		
Palmitate	9.1 ± 0.9	14 ± 2
Myristate	n.d	4.4 ± 0.2
Oleate	n.d	n.d
Stearate	n.d	n.d
TS reduction (%)	61 ± 4	56 ± 3
VS reduction (%)	66 ± 4	64 ± 3
Biogas yield (L g VS_{feed}^{-1})	0.38 ± 0.02	0.57 ± 0.04
Methane yield (L g VS_{feed}^{-1})	0.24 ± 0.01	0.36 ± 0.02
Total FOG reduction (%)	50	56

n.d: not detected

Figure
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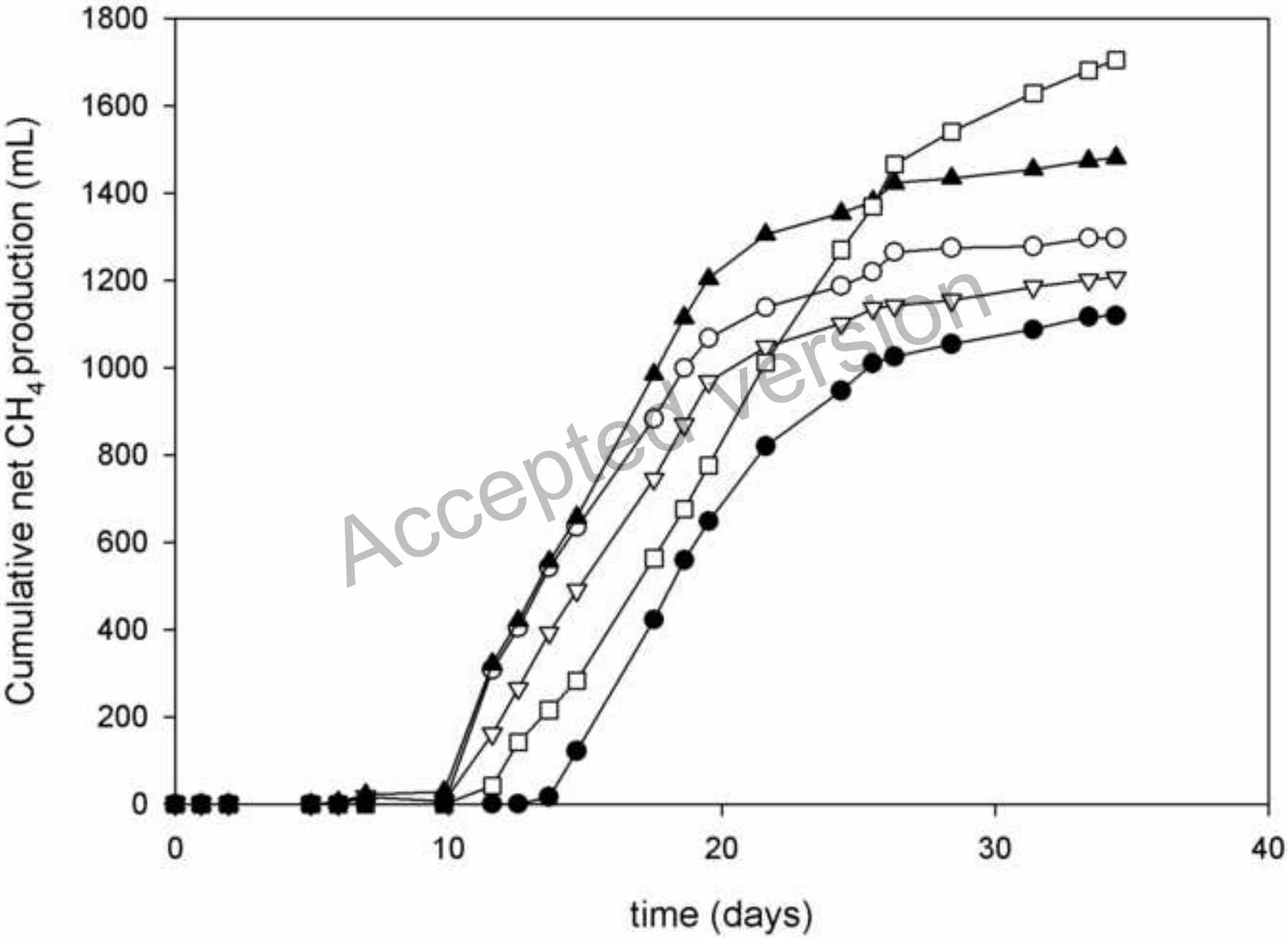

Figure

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