

High-solids anaerobic digestion: comparison of three pilot scales

J. Guendouz, P. Buffière, J. Cacho, M. Carrère and J.-P. Delgenes

ABSTRACT

Two experiments were undertaken in three different experimental set-ups in order to compare them: an industrial 21-m³ pilot reactor, a new 40-ℓ laboratory pilot reactor and bmp type plasma bottles. Three consecutive batch dry digestion tests of municipal solid waste were performed under mesophilic conditions with the same feedstock in all vessels. Biogas and methane production at the end of the tests were similar (around 200 m³ CH₄STP/tVS) for both pilot reactors and were different from the bottle tests. The dynamics of methane production and VFA accumulation concurred. However, the maximal levels of VFA transitory accumulation varied between reactors and between runs in a same reactor. Ammonia levels were similar in both reactors. These results show that the new reactor accurately imitates the conditions found in the larger one. Adaptation of microorganisms to the waste and operating conditions was also pointed out along the consecutive batches. Thermophilic semi-continuous tests were performed in both reactors with similar conditions. The methane production efficiencies were similar.

Key words | anaerobic digestion, high-solids, MSW, reactor, solid waste

J. Guendouz
J. Cacho
M. Carrère
 Centre de Recherche sur la Propreté (VEOLIA),
 Zone Portuaire de Limay,
 291 Avenue Dreyfous Ducas, Limay F78250,
 France
 E-mail: guendouz@supagro.inra.fr

J.-P. Delgenes
 INRA, UR50, Laboratoire de Biotechnologie de
 l'Environnement,
 Avenue des Etangs,
 Narbonne F11100,
 France
 E-mail: delgenes@supagro.inra.fr

P. Buffière (corresponding author)
 INSA Lyon,
 LGCIE, 9, rue de la physique F-69621 Villeurbanne
 Cedex,
 France
 E-mail: pierre.buffiere@insa-lyon.fr

INTRODUCTION

Resorting to anaerobic digestion for the treatment of the organic fraction of Municipal Solid Waste (MSW) is rapidly gaining interest in Europe. The number of plants has more than doubled between 2000 and 2006 (De Baere 2006) and the installed capacity has risen from 1 million tons per year to almost 4 million (Seghier 2006). The EU has set binding targets for 2020: at least 20% of energy used in the EU coming from renewable sources and 10% of the fuels used in transport being biofuels (Reuters 2007). In this context, anaerobic digestion with biogas valorization is a good answer to today's environmental challenges (Chynoweth 1996). Indeed, it allows the possibility of accomplishing two complementary objectives: MSW treatment and renewable energy production. Moreover, anaerobic digestion with energy recovery produces less greenhouse gases than incineration or landfilling (Edelmann 2003), and solid by-products can be composted and used as organic amendment for agriculture. However, this technology needs

enhancement of reliability in operation to become more sustainable (De Baere 2006). Specifically, at the industrial scale, performance in relation to waste characteristics is still difficult to predict (Cecchi *et al.* 1988; Mata-Alvarez *et al.* 2000). Consequently, difficulties may occur for sizing and operating industrial digesters. Therefore, tools are needed for applied and fundamental research in the field of anaerobic digestion of MSW in order to improve expertise. Notably, a deeper insight into the mechanisms of hydrolysis attack, effects of different treatments and prediction of bioconversion and effluent quality would be of importance (Mata-Alvarez 2003).

In “dry” anaerobic digestion, also called “high-solids”, the total solids account for 20–40% of the reactor medium. High-solids technology has become attractive because it requires less pre-treatment and added water (De Baere 2000). It also allows a higher organic loading rate and gas production efficiency. However, high-solids anaerobic

digestion of MSW causes many inhibition problems (Liu *et al.* 2006) and is harder to control. In particular, bacterial biomass cannot be separated from waste solids and a soluble fraction must be extracted before most analyses can be made. In addition, the medium is heterogeneous in structure, composition and size of the solids (Buffière *et al.* 2005). Thus, few in-line measurements are possible and it is impossible to directly access the reaction yield. Few laboratory-scale high-solids studies have been conducted on the anaerobic digestion of MSW (Kayhanian & Rich 1995; Hartmann & Ahring 2006). Furthermore, most of those studies use synthetic and/or finely ground or blended wastes (Rivard *et al.* 1990; Poggi-Varaldo & Oleszkiewicz 1992). On the other hand, the problem with larger scale experiments, apart from higher costs and less practical operation, is that complete mixing is never achieved. For that reason, a completely mixed laboratory-scale reactor for high-solids anaerobic digestion of real MSW that can compare to larger scale reactors would be useful for studies aimed at improving anaerobic digestion of solid waste. The objectives of the present study is to compare such a laboratory pilot reactor (i) to an industrial pilot reactor and (ii) to a plasma bottle laboratory test, commonly used for BMP assays. Biogas and methane yields, chemical oxygen demand (COD) and volatile solids (VS) degradation and VFA and ammonia accumulation and degradation are considered for comparison.

METHODS

Reactor design and operation

The laboratory-scale reactor designed for this study was a 40- ℓ stainless steel horizontal cylinder, 35 cm in diameter and 40 cm in length. The working volume was 20 to 30 ℓ . The contents of the reactor were completely mixed by an eccentric paddle mixer, 27 cm in diameter and 30 cm in length driven by a 1.1 kW motor with 683 Nm torque. The speed of the mixer was set to 3.2 rpm. The reactor was heated by a thermostatically regulated water jacket and insulated with a 50 mm thick neoprene insulation. A room-temperature bottle was installed on the outlet gas line to trap moisture from the exiting gas. A volumetric water

displacement electronic gas meter was used to measure biogas production continuously. The reactor was also equipped with ports for filling and sampling. The pilot-scale reactor used for comparison was a 21-m³ dry anaerobic digester located in France and belonging to the VEOLIA Environmental Services Research Center (CRP). It was previously described by Lemaire *et al.* (2005). This unit is composed of two interconnected tubular parts, the digesting medium being moved upward in one of these parts by an endless screw, and downward in the other part by gravity. The mixing of the reactor is provided by the endless screw.

First experiment

Three successive batches were conducted in each reactor, the small one and the large one. Both reactors were operated at mesophilic temperature and mixed discontinuously: 5 minutes every 2 hours for the lab-scale reactor, 1 hour per day for the pilot scale reactor. Samples were taken regularly for analyses in both reactors.

Second experiment

Both reactors were operated in semi-continuous mode at 35% TS under thermophilic conditions. Feeding was performed twice per week in the laboratory reactor and three times per week in the industrial reactor. The feeding ratio was around 70 g of VS in the feed/kg of VS in the digesting medium/day.

Feedstock and inoculum

The pilot-scale reactor was inoculated at start-up with residue from an industrial anaerobic digester. The laboratory-scale reactor was inoculated at start-up with digestate from the pilot-scale reactor. Then, each batch was inoculated with residue from the preceding batch. To minimize variations in waste composition between experiments, the same stock of MSW was used in all the experiments. It was shredded and sieved to 40 mm. The initial waste to inoculum ratio was 0.35 kg VS of waste per kg VS of inoculum (Table 1). Water was added to adjust the total solids in the reactors to 35 \pm 3%.

Table 1 | Initial conditions for the batch tests

	Lab-scale			Pilot-scale		
	Run #1	Run #2	Run #3	Run #1	Run #2	Run #3
%Total solids (TS)	32.1	32.2	33.8	36.9	39.7	33.2
%VS (on TS)	34.4	33.9	38.7	38.7	46.5	38.1
Waste/inoculum ratio (kgVS/kgVS)	0.343	0.342	0.198	0.268	0.359	0.347

Analyses

Gas samples were taken periodically for composition analysis by gas chromatography (GC-14A, Shimadzu, colon CTR I, Alltech). Methane production is expressed under standard conditions (0°C; 1.013×10^5 Pa). Total solids (TS) were determined on fresh products by drying at 105°C for 48 h; volatile solids (VS) were obtained by dry sample weight loss at 550°C for 12 h. The other parameters were measured on a diluted sample of digestate prepared by mixing 1 part digestate sample with 3 parts deionised water (on mass basis) at room temperature for 30 min. The liquid fraction was recovered through a 1 mm sieve, and centrifuged for 15 min at $25,000 \times g$. Volatile fatty acids (VFA) were determined by gas chromatography (GC 8000, Fisons Instruments). Ammonia was measured according to the titrimetric method after distillation with the Büchi apparatus.

The biochemical methane potential (BMP) of the MSW was performed according to Owens & Chynoweth (1993) and Angelidaki & Sanders (2004). The assays were conducted in triplicate (and one blank) in 500 mL serum bottles at 37°C mixed with an orbital shaker. They were filled with synthetic growth medium containing nutrients and trace elements, and inoculated with anaerobic sludge coming from a batch stock reactor fed with various waste mixtures. The final sludge concentration in the bottles was 20 gVS/L. The bottles were loaded with 6 g MSW (corresponding to 1.9 gVS). Biogas production and composition were measured daily. Methane production is expressed under standard condition and accounts for the variation of

gas content in the headspace of the bottles. These tests were run using (i) original waste shredded and sieved to 40 mm and (ii) lyophilized waste finely ground on a 1 mm grate.

RESULTS AND DISCUSSION

First experiment

The overall final biogas and methane productions were similar for all six experiments (Table 2): the average final methane yield was $200 \pm 10 \text{ m}^3 \text{ STP/tVS}$. In the BMP flask test, a close yield is obtained for the original waste: $220 \text{ m}^3 \text{ STP/tVS}$ but a very higher yield is obtained when the waste is finely ground as is usually done in BMP tests: $365 \text{ m}^3 \text{ STP/tVS}$. This goes to show the importance of particle size and thus the need for a laboratory reactor that can handle realistic wastes. It should be noted that, for comparison purposes, the BMP tests values do not account for residual (endogenous) methane production measured with the blank assay as it is not accessible for the reactor tests.

The evolution of biogas and methane productions are strikingly similar in both reactors (Figure 1). Indeed, during the start-up batch (Run #1) a lag can be observed in methane production in both reactors. Then, during the subsequent batches the lag becomes less and less pronounced as the reaction becomes quicker. This phenomenon can be attributed to an adaptation of the microorganisms to the waste and to the conditions of the experiment. In the pilot-scale start-up batch an abnormally

Table 2 | Methane yield at the end of the batch tests

	Lab-scale			Pilot-scale			BMP	
	Run #1	Run #2	Run #3	Run #1	Run #2	Run #3	Original waste	Ground waste
$\text{M}^3\text{CH}_4/\text{tVS}$ (STP)	193	211	187	193	205	212	220 ± 10	365 ± 10

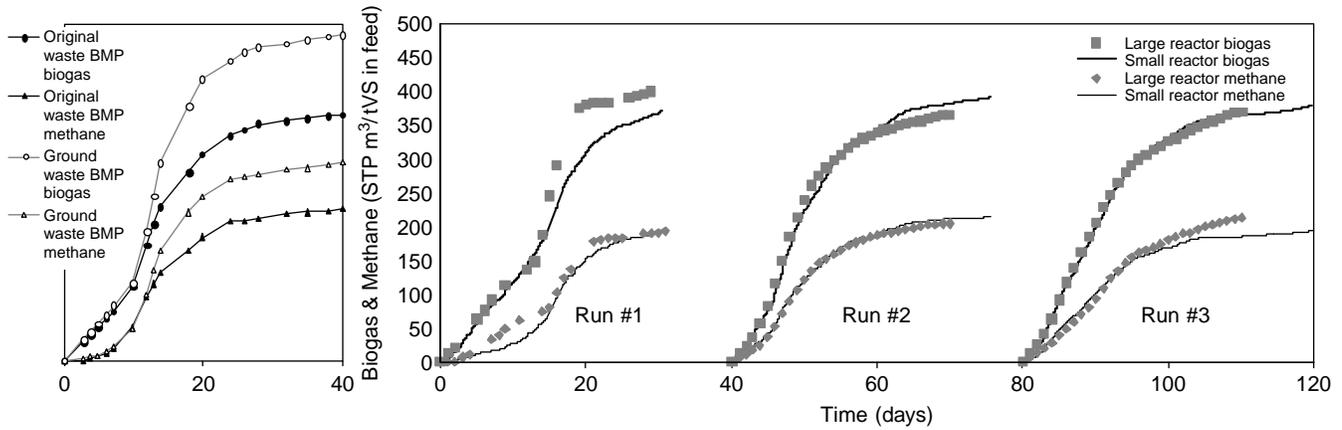


Figure 1 | Biogas and methane productions for batch experiments conducted on 3 different scales.

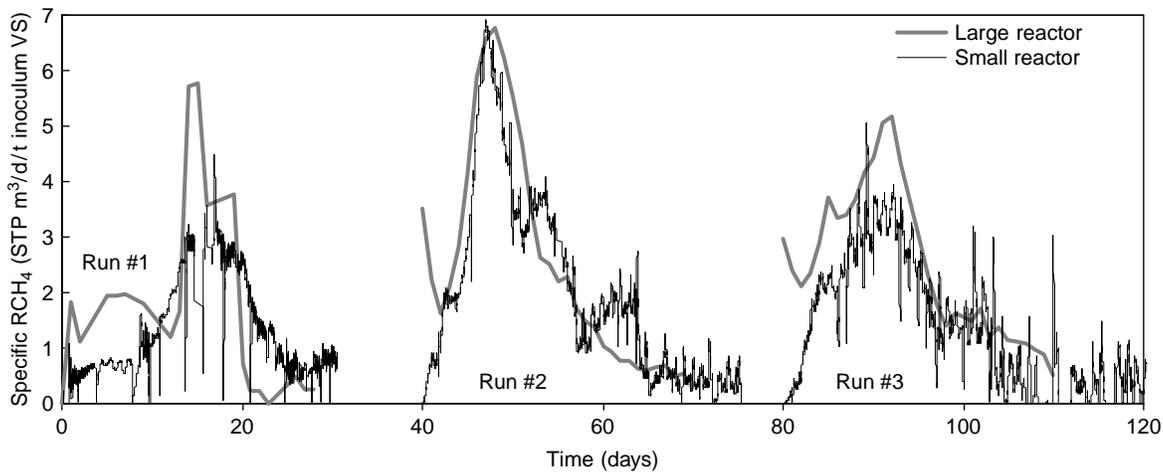


Figure 2 | Methane specific production rate for batch experiments conducted on two different scales.

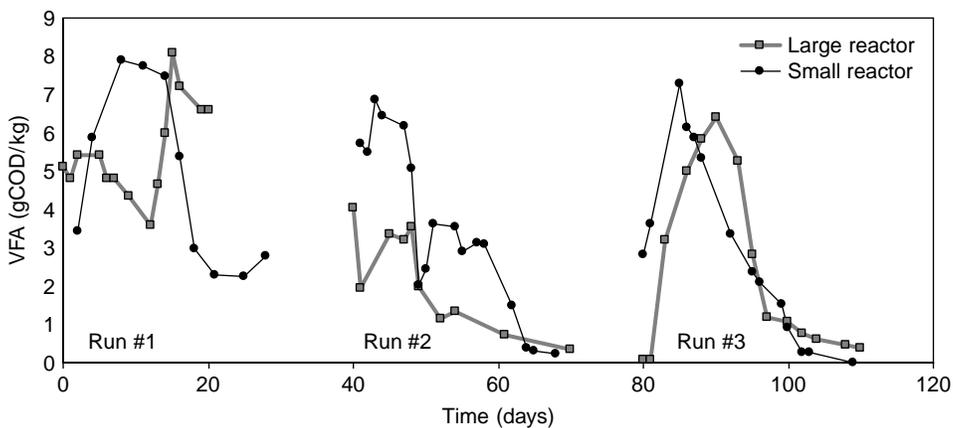


Figure 3 | VFA levels for batch experiments on two different scales.

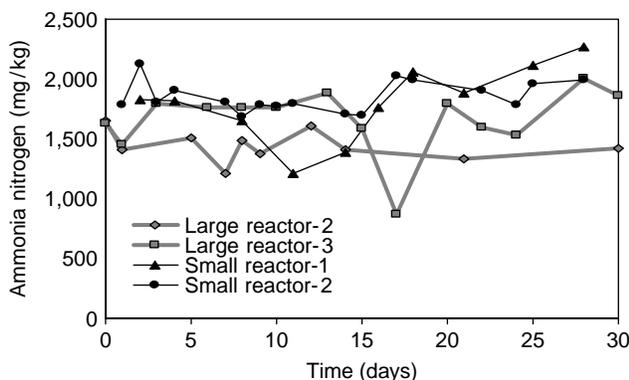


Figure 4 | Ammonia levels for batch experiments on two different scales.

high production of CO_2 occurred around the 15th day and accounts for the higher final biogas production.

The evolutions of methane production rates (based on the amount of initial VS in the inoculum) concurred considerably (Figure 2). They did not follow an expected first order kinetic which would mean that the degradation rate is controlled by hydrolysis. Apparently, there were at least two stages in the methane production. This behavior was already observed for food wastes under low-solid digestion (Buffière *et al.* 2005). For the pilot reactor, the methanogenic activity exhibited a first peak after 2–3 days, and then a higher peak around day 10. At the laboratory scale, the occurrence of the first peak is less obvious.

VFA profiles (Figure 3) are expressed as equivalent COD (sum of the COD of each individual VFA) per unit mass of digesting medium. In most cases there was a transitional VFA accumulation closely followed by a degradation. This evolution can be correlated to some extent with the biogas production profiles. For instance, most VFA peaks tally with specific activity peaks. Nevertheless, there is some

discrepancy between the levels of the VFA peaks which varied as much between runs of the same reactor as between reactors. The transitory accumulation of VFA during the batch tests indicates that not only hydrolysis is the limiting step of solid waste digestion. VFA uptake may also play a crucial role in the whole degradation kinetics. It is not clear, however, whether anaerobic sludge (biomass) adaptation favors more the hydrolytic step or the methanogenic step. On a side note, in the pilot-scale run #1, the sizeable VFA peak that took place around the 15th day could be related to an overload-like problem which would explain the abnormal CO_2 production aforementioned. Yet, the circumstances of this possible problem are not known.

A possible cause for different VFA levels between two consecutive batch tests on the same reactor with the same feedstock could be the various ammonia levels during the tests: indeed, depending on the recent history of the reactors, ammonia levels may differ from one test to another (Figure 4). As can be seen, ammonia concentrations vary from 1,200 mgN-NH₄ to 2,000. The ammonia level during one batch is quite stable (the slight fluctuations are attributed to experimental deviation). The values obtained are not supposed to be high enough to create inhibition. The high operating pH (generally above 8) might have been responsible for the presence of free ammonia in the digesting medium, and partial inhibition could be possible (Kayhanian 1999).

Second experiment

Figure 5 shows the methane flows for both reactors in semi-continuous mode in $\ell_{\text{STP}}/\text{h}/\text{kg}$ medium. They are in

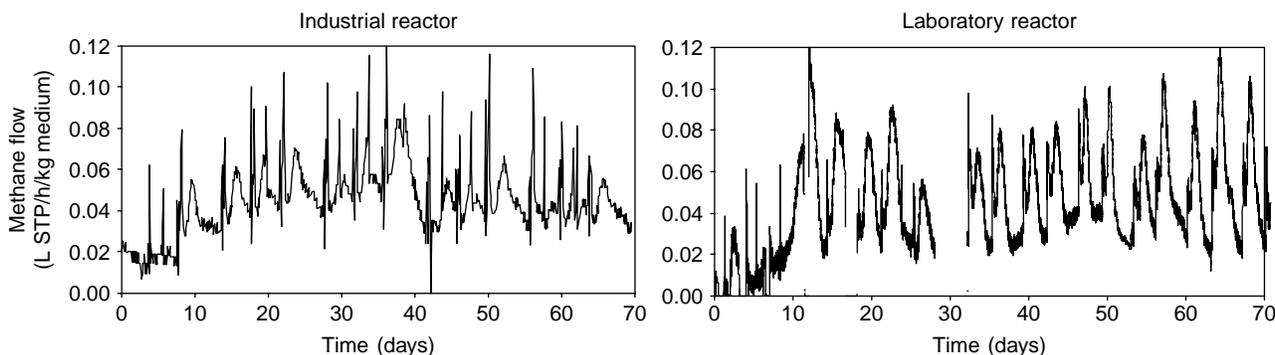


Figure 5 | Scaled methane flow in semi-continuous digestion for two scales.

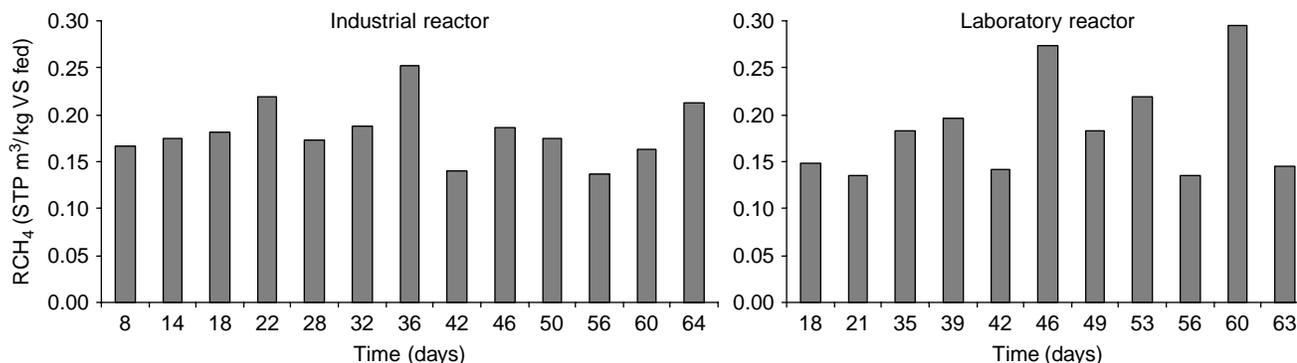


Figure 6 | Methane yields in semi-continuous digestion for two scales.

the same range for both reactors: between 0.02 and 0.10 $\ell_{\text{STP}}/\text{h}/\text{kg}$. The mean flows after startup phases are 0.0487 $\ell_{\text{STP}}/\text{h}/\text{kg}$ for the industrial reactor and 0.0492 $\ell_{\text{STP}}/\text{h}/\text{kg}$ for the laboratory reactor which are close values. Meanwhile, the evolutions are somewhat different. As seen in the batch tests, the two-step gas production is more pronounced in the industrial reactor whereas the peaks are sharper in the laboratory reactor. These differences could be due to a better mixing in the laboratory reactor.

Figure 6 shows the methane yields for both reactors in semi-continuous mode in STP $\text{m}^3/\text{kg VS fed}$. Each value corresponds to one feeding of the reactor. It is calculated by dividing the cumulative methane production by the VS input after having subtracted the quantity of methane due to residual activity. On the X-axis are the feeding dates. These values are in the same range and the mean values are very close: 0.182 ± 0.017 STP $\text{m}^3/\text{kg VS}$ for the industrial reactor and 0.187 ± 0.033 STP $\text{m}^3/\text{kg VS}$ for the laboratory reactor. The values are slightly more scattered for the laboratory reactor. That could be due to a smaller scale inducing smaller sampling sizes.

CONCLUSION

A new laboratory-scale anaerobic digester has been developed to digest solid waste under conditions close to industrial high-solids anaerobic digestion. This digester has been operated alongside an industrial-scale digester in similar conditions in order to test its accuracy to imitate large-scale behavior. Biogas and methane production were measured and samples were taken regularly for VFA and ammonia

measurements. Biogas and methane production at the end of the tests were similar (around 200 $\text{m}^3\text{CH}_4\text{STP}/\text{tVS}$), and the dynamics of methane production concurred considerably which was not the case for bottle BMP tests. Only VFA production and uptake levels varied between runs of the same reactor and between reactors. Ammonia levels were relatively low and similar in both reactors. Semi-continuous tests exhibit similar performances between the two reactors but it is difficult to further discuss them.

The repeated batch tests clearly indicate that hydrolysis is not the only limiting step during dry anaerobic digestion of solid waste, even of slowly biodegradable MSW as used in the present study. Mechanisms associated with VFA uptake might play an important role in the process. The importance of particle size has also been underlined.

These results are quite promising because they show that the new laboratory-scale reactor compares to larger scale reactors. Therefore, it will be useful as a “guinea pig” to carry out experiments in real industrial conditions that cannot be done in larger reactors, notably for practical reasons. This will help understanding and controlling the mechanisms of the anaerobic digestion of MSW and, in turn, improve the industrial operation of solid waste digesters

REFERENCES

- Angeladiki, I. & Sanders, W. 2004 *Assessment of the anaerobic biodegradability of macropollutants*. *Rev. Environ. Sci. Biotechnol.* **3**, 117–129.
- Buffière, P., Loisel, D., Bernet, N. & Delgenes, J.-P. 2005 *Towards new indicators for the prediction of solid*

- waste anaerobic digestion properties. *Water Sci. Technol.* **53**(8), 233–241.
- Cecchi, F., Traverso, P. G., Mata-Alvarez, J., Clancy, J. & Zaror, C. 1988 State of the art of R&D in the anaerobic digestion process of municipal solid waste in Europe. *Biomass* **16**, 257–284.
- Chynoweth, D. P. 1996 Environmental impact of biomethanogenesis. *Environ. Monit. Assess.* **42**, 3–18.
- De Baere, L. 2000 Anaerobic digestion of solid waste: state-of-the-art. *Water Sci. Technol.* **41**(3), 283–290.
- De Baere, L. 2006 Will anaerobic digestion of solid waste survive in the future? *Water Sci. Technol.* **53**(8), 187–194.
- Edelmann, W. 2003 Products, impacts and economy of anaerobic digestion of OFMSW. In: Mata-Alvarez, J. (ed.) *Biomethanization of the Organic Fraction of Municipal Solid Wastes*. IWA Publishing, London, pp. 265–301.
- 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**(8), 7–22.
- Kayhanian, M. & Rich, D. 1995 Pilot-scale high solids thermophilic anaerobic digestion of municipal solid waste with an emphasis on nutrient requirements. *Biomass Bioenergy* **8**(6), 433–444.
- Kayhanian, M. 1999 Ammonia inhibition in high-solids biogasification: an overview and practical solutions. *Environ. Technol.* **20**, 355–365.
- Lemaire, O., Buffière, P., Milhau, C., Arribas, R. & Carrère, M. 2005 Biomethanisation expertise improvement by pilot and full scale unit follow-up: project development and first results. *Anaerobic Digestion Solid Waste*, 195–200.
- Liu, G. T., Peng, X. Y. & Long, T. R. 2006 Advance in high-solid anaerobic digestion of organic fraction of municipal solid waste. *J. Central South Univ. Technol.* **13**, 151–157.
- Mata-Alvarez, J., Mace, S. & Llabres, P. 2000 Anaerobic digestion of organic solid wastes. An overview of research achievements and perspectives. *Bioresour. Technol.* **74**(1), 3–16.
- Mata-Alvarez, J. 2003 Fundamentals of the anaerobic digestion process. In: Mata-Alvarez, J. (ed.) *Biomethanization of the Organic Fraction of Municipal Solid Wastes*. IWA Publishing, London, pp. 1–20.
- Owens, J. M. & Chynoweth, D. 1993 Biochemical methane potential of MSW components. *Water Sci. Technol.* **27**(2), 1–14.
- Poggi-Varaldo, H. M. & Oleszkiewicz, J. A. 1992 Anaerobic co-composting of municipal solid waste and waste sludge at high total solids levels. *Environ. Technol.* **13**, 409–421.
- Reuters 2007 Europe's '2020 vision' to lead climate change battle. <http://environment.newscientist.com/channel/earth/climate-change/dn11343-europes-2020-vision-to-lead-climate-change-battle.html> (accessed 09/03/2007).
- Rivard, C. J., Himmel, M. E., Vinzant, T. B., Adney, W. S., Wyman, C. E. & Grohmann, K. 1990 Anaerobic digestion of processed municipal solid waste using a novel high solids reactor: maximum solids levels and mixing requirements. *Biotechnol. Lett.* **12**(3), 235–240.
- Seghier, C. 2006 L'usine de bio méthanisation de Calais est opérationnelle (Calais' biomethanisation plant is operational). http://www.actu-environnement.com/ae/news/methanisation_usine_dechet_valorisation_2160.php4 (accessed 22/12/2006).