Two-phase anaerobic digestion of source sorted OFMSW (organic fraction of municipal solid waste): performance and kinetic study

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Abstract The results of a two-phase system operated in different conditions, treating the source-sorted organic fraction of municipal solid waste (SS-OFMSW), coming mainly from fruit and vegetable markets, are presented . Hydraulic retention time (HRT) in the hydrolytic reactor and in the methanogenic reactor and also the temperature in the hydrolytic reactor (mesophilic and thermophilic conditions) are varied in order to evaluate the effect of these factors. The methanogenic reactor is always operated within the thermophilic range. Optimum operating conditions are found to be around 12 days (total system) using the mesophilic range of temperature in the first reactor. Specific gas production (SGP) in these conditions is around 0.6 m^3/kgTVS.

A kinetic study is also carried out, using the first and the step diffusional models. The latter gives much better results, with fitted constants comparable to other studies. Finally, a comparison with a one-phase system is carried out, showing that a two-phase system is much more appropriate for the digestion of this kind of highly biodegradable substrate in thermophilic conditions.

Keywords Anaerobic; biomethanisation; biogas; volatile fatty acids; hydrolysis; thermophilic; first order

Introduction

Biotechnologies offer sustainable approaches to the problem of the organic fraction of municipal solid wastes (OFMSW). Within the European Union, dumping this fraction in sanitary landfills will be severely limited by a new European Directive. Thus, many landfills are due to close in the near future and there is a significant increase in the number of separate collections of OFMSW. Once these organic wastes have been collected, they need to be treated by biological methods, in order to promote recycling and maximum recovery of their components. Composting and anaerobic digestion are the most appropriate technologies. Wet wastes such as OFMSW separated at source or OFMSW from markets (without yard wastes), are better treated by anaerobic digestion than by composting. Without entering into energy considerations, composting such wastes requires a considerable amount of structuring material and its high biodegradability makes the final yield very poor.

Anaerobic digestion applied to the treatment of OFMSW, especially wet OFMSW, is within the philosophy of sustainability (Cecchi and Mata-Alvarez, 1993). The energy obtained from such treatments is renewable and the effluent can be returned to the soil, with the recovery of the rest of the organic matter and nutrients. There are many methods of anaerobic digestion treatment at industrial scale. Yet, there is room for further improvements, both in the process and in the pre- and postreatment of the influent and effluent, respectively. Studies on the yields and kinetics of the anaerobic digestion of different qualities of OFMSW have been carried by the authors since 1984 (see for instance Cecchi and Mata-Alvarez, 1992).

Within the scenario of the anaerobic digestion of solid waste as a mature technology, the aim of this study is to present the pilot scale results of the biomethanisation of highly biodegradable OFMSW in a two-phase digestor and to compare them with results from a one-phase system. Additionally, the effect of temperature will be examined and the kinetic aspects of the processes will be considered.

Materials and methods

Experimental device

Experiments were carried out in a two-phase pilot system composed of a hydrolytic reactor and a methanogenic reactor. The hydrolytic reactor was a completely stirred 0.8 m^3 digestor fed discontinuously, 4 times a day. Substrate feed operation was carried out from the shredder to the storage tank with a screw pump, and from this to the hydrolytic reactor by means of a membrane pump. The methanogenic reactor was another completely stirred reactor of 1 m^3 of working volume. A second membrane pump transferred the contents of the first reactor to the second. Reactors were electrically heated and the temperature was kept at the desired level within a range of ±1°C.

Substrate

The substrate used for the experimentation was source sorted OFMSW (SS-OFMSW) coming from the food market of the city of Treviso (Italy). Table 1 shows the most important characteristics of the substrate. As can be seen it is a highly wet material and also due to its source (fruit and vegetables) it is highly biodegradable.

Analytical methods

The digestion process was monitored following the analytical procedures of Standard Methods for the examination of water and wastewater (1992) and of the CNR Instructions (1985). Total volatile fatty acids (TVFA) were determined daily by a gas-chromatographic method (Chromatograph Vega serie 6000 Carlo Erba). Conditions of this analysis were:

Capillary column type Nukol, length 15 m, internal diameter 0.53 mm; Injector temperature, 200°C; Detector -flame ionisation- temperature, 220°C; Air pressure 120 kPa, H_2 pressure 70 kPa; Temperature program (isotherm): 106°C; Duration, 6 minutes; Carrier pressure 30 kPa. Every other day, TS (Total solids); TVS (Total volatile solids); STS (Soluble total solids); SVS (Soluble volatile solids) and alkalinity (at pH 6 and 3.8) were measured. Every 15 days, Total Kjeldahl Nitrogen (TKN) and total phosphorus (P) were determined. Biogas produced in the second phase was continuously measured (flow rate and composition) and stored in a data acquisition system, where other parameters such as temperature were also registered. No significant biogas production was detected in the first phase.

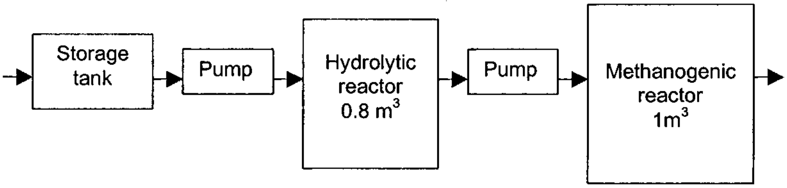

Figure 1 Basic scheme of the two-phase system used in the experimental station in Treviso. Storage tank receives shredded OFMSW

Table 1 Main characteristics of the source-sorted OFMSW coming from the market of the city of Treviso (Italy), used during the experimentation with the two-phase system

	Average value	Range Max.	Min.	Number of samples	Std. Deviation
TS (g/kg)	81.8	132.7	54.4	9	15.7
TVS/TS (%)	81.9	92.0	78.2	96	11.3
TCOD (gO_2/gTS)	1.0	1.5	0.7	32	18.1
TKN (%TS)	2.1	3.3	1.4	23	0.5
P (%TS)	2.8	3.3	1.3	23	0.5

Results and discussion

A two-phase system allows a control on the acidogenic load of the methanogenic flora. In this case, hydrolytic reactor operated around 35ºC and methanogenic reactor at around 55ºC. Another set of experiments was also carried out using the thermophilic temperatures for the hydrolytic reactor. During these experiments the substrate fed to the system was SS-OFMSW (100%).

A large range of operating conditions were tested during this study. HRT in the first reactor varied from 1 day to 6.6 days and HRT in the second reactor, from 7.7 to 18.4 days. As a consequence, a large range of organic loading rates (OLR) were tested: from 4.1 to 36.2 kgTVS/m^3.d in the hydrolytic reactor and from 4.1 to 9.5 kgTVS/m^3.d in the methanogenic reactor.

The operating conditions of the system are presented in Table 2. They can be structured in accordance with three ranges: A, B and C. The first experiment (not reported here) can be considered as a start-up period with HRT between 6 and 18 days and with a hydrolytic reactor temperature of about 23ºC. During the first range, A, in which the highest HRT of the system was studied, HRT of the methanogenic reactor was kept at 12 days and hydraulic retention time in the hydrolytic reactor varied from 6 to 1 day (Periods 1A to 5A). During the second range, B, the behaviour of the system at low HRT was checked. Thus, the overall HRT was set to around 12 days, using acidogenic HRT's from 2.8 to 4.6 and using methanogenic HRT's from 7.7 to 9.5. A third range C was also experimented (Periods 8C to 10C), in order to verify the influence of the thermophilic range in the acidogenic phase, maintaining a methanogenic HRT of around 8 days.

During the first part of the experiments (periods 1A to 5A), HRT was decreased in the first reactor, while HRT in the methanogenic reactor was kept around 12.5–13.5 days. As can be seen in Table 3, where the main results are presented, in range A, GPR seems to be correlated with the OLR in the second reactor. In addition, it is clear that reactor performance parameters are not influenced by the total volatile fatty acids (TVFA) load coming from the hydrolytic-fermentative reactor, which ranges from about 10 to 30 g/L in the five conditions studied. It is also clear that the hydrolytic reactor works quite well even at the extremely high OLR applied to it (68.5 kgTVS/m^3.d, see period 4A). Yields of the overall system were quite good in terms of the specific gas production (SGP). (This parameter is given in two units, one referred to the volatile solids fed to the methanogenic reactor and the other referred to the volatile solids fed to the system.) However, in this last period, the decrease to 1 day HRT in this reactor, which doubled the OLR in the first reactor, possibly overloaded the hydrolytic reactor and TVFA produced in it were lower and yields decreased. Best results were obtained in Run 5A. This fact can be linked to the better quality of the OFMSW used due to a seasonal effect (summer months, more fruits in the blend), and also to the fact that the hydrolytic reactor worked at 6.6 days. Thus, the larger amounts

Table 2 Experimental conditions tested with the two-phase system

RUN	Temp (°C) 1st/2nd reactor	HRT (d) 1st Reactor	HRT (d) 2nd. Reactor	OLR (kg TVS/m^3.d) 1st Reactor	2nd. Reactor	Overall
1A	34.1/56.3	4.1	12.5	16.4	4.7	4.1
2A	34.6/53.7	4.4	13.7	14.0	4.1	3.4
3A	34.6/54.9	2.1	13.1	35.8	4.8	5.0
4A	34.1/55.1	1.0	12.5	68.5	4.7	5.1
5A	34.6/54.9	6.6	12.5	12.6	5.7	4.3
6B	34.3/54.9	4.6	7.7	16.4	7.4	6.1
7B	34.8/54.9	2.8	9.5	31.2	6.9	7.1
8C	54.8/54.4	4.9	7.7	17.1	9.5	6.7
9C	54.8/54.7	3.1	8.1	24.7	7.9	6.8
10C	55.1/54.8	1.0	8.0	77.9	7.7	8.7

of readily biodegradable fraction fed to the second phase significantly increase the OLR, which was the highest in this period and this was reflected in the yields observed. These changes are also observed in Figure 2, commented on below in terms of kinetic behaviour, where the biogas production profiles are presented.

A second set of experiments was carried out decreasing the HRT of the second reactor and thus increasing the OLR in the methanogenic reactor. Quality of the feed was also high, especially in period 7A, and in this period, the maximum GPR was achieved, but also the values of SGP were considerably high. TVFA production in the first reactor was also high and the yield can be considered very good, even significantly reducing the overall reaction volume (about 33%, HRT from 18 to 12 d).

However, if the HRT in the second phase is reduced from 12 to 8 days, the methanogenic phase seems to become overloaded (see period 6A, the value of TVFA=3.5 g/L), although the system is still working (GPR=4.9 m^3/m^3/d and SGP=0.63 m^3/kg TVS). If the HRT in the second reactor is increased a little up to 9.5 days and the HRT in the first one is set to 3.5 (Period 7B) a quite balanced operation condition is achieved. The corresponding yields are also quite satisfactory, with SGP=0.72 m^3/kgTVS, and the stability parameters show the good digester health. The TVS removal reaches values around 75%, 5% less than the previous tests, but this evidence can be neglected considering the valuable volume reduction and the biogas yields achieved following this last approach This can lead to the conclusion that, at mesophilic (hydrolytic reactor) and thermophilic (methanogenic reactor) temperatures, optimum operating retention times, seem to be around 2–3 days in the first reactor and around 8–9 days in the second reactor. At this conditions, the same results which were reached using longer HRT of the system (Range A) can be obtained.

Finally a third range was tested, raising the hydrolytic reactor temperature to 55°C. Other conditions were similar to the previous periods. As can be seen, in Table 3, results were a little different, even if the influence of the OLR over the methanogenic reactor is the same. At thermophilic conditions, the production of TVFA in the first phase was significantly lower than at mesophilic conditions (about one tenth). These facts can be linked to the different kinetics of the bioreactions in the thermophilic range, which have probably started to consume part of TVFA also in the first phase, even if the pH conditions seem not quite adequate (pH=4–5). Unfortunately, no gas production was monitored in the first phase. However, the 10 times lower TVFA load coming from the first phase induced only slightly lower yields in the second phase. Another possible explanation can be found considering that thermophilic conditions applied to the first phase lead to less degraded products, such as monomers, but more experiments would be necessary to prove this hypothesis.

Table 3 Results obtained with the two-phase system

RUN	GPR ($m^3/m^3/d$)	SGP m^3/kgTVSf1	SGP m^3/kgTVSf	Overall TVS rem (%)	VFAa g/L	TVFA1st Reactor g/L	TVFA2nd Reactor g/L	Lactic Ac. g/L	Lactic Ac. g/L	Lactic Ac. g/L
1A	2.5	0.53	0.43	76.5	8.8	15.5	0.43	5178	8092	0.012
2A	2.3	0.57	0.47	69.2	14.5	18.6	0.94	8360	9044	0.004
3A	3.3	0.67	0.46	78.1	6.6	11.0	0.264	3617	5131	0.000
4A	2.5	0.54	0.34	83.5	3.9	16.9	0.191	1820	11649	0.021
5A	4.4	0.78	0.70	82.1	3.7	29.3	0.459	2220	15432	0.000
6B	4.9	0.62	0.56	74.1	3.2	19.9	3.458	1567	9472	0.000
7B	5.1	0.73	0.50	77.3	4.6	22.6	0.554	3027	11633	0.000
8C	5.4	0.57	0.56	73.7	1.8	2.7	0.727	2666	4405	0.000
9C	4.9	0.59	0.50	67.2	1.6	2.3	0.587	3856	3326	0.000
10C	3.9	0.47	0.31	76.5	1.7	3.5	0.275	3349	12452	0.000

Comparison with the results obtained with one-phase system

A series of comparable results were obtained in a previous study carried out with different sources of separated OFMSW in Treviso, but using only one completely stirred reactor of 3 m^3, situated in the same experimental station described here (Cecchi *et al.*, 1986).

The characteristics of the different substrates are presented in Table 4. As can be seen they are not quite the same as compared with the OFMSW used here (Table 1), due to a different source of collection. In these previous experiments, waste was also collected in canteens and restaurants.In this study, the waste used was mainly collected in supermarkets and fruit markets, in which fruit and vegetables fraction were the main components (Cecchi *et al.*, 1986). The biodegradability of the feed strongly influences the performance of the system (Mata-Alvarez *et al.*, 1990). The source-sorted OFMSW (SS-OFMSW) has lower biodegradability than that of the SS-OFMSW coming from fruit and vegetable markets, so that the upper limit for OLR is higher than that for the less biodegradable OFMSW. Table 5 presents the main results obtained with the different OFMSW tested. A complete stable operation was obtained with the one phase system, using SS-OFMSW diluted up to 6–7% TS and then working with a HRT of around 14–15 days, so as to have a OLR around 4 kg TVS/m^3.d (see yields in Table 5). A limit at mesophilic conditions for the OLR was found to be around 6.9 kg TVS/m^3.d. (Cecchi *et al.*, 1986).

In fact, an additional experiment was carried out in the study presented here, using only the first reactor of the two-phase system described before. It was not possible to stabilise the reactor as it acidified rapidly with concentrations of TVFA of around 17 g/L (OLR tested was only around 3.3 kgTVS/m^3.d). However, acidogenic conditions were quickly removed (2 days) when the process was switched to a two phase system, which was the start of the experiments described in the previous section.

A previous negative experience working with a laboratory one phase system at thermophilic conditions with fruit and vegetable wastes was also described by Bernal *et al.* (1992). With a load of 2 TVS/m^3.d the system was already overloaded (TVFA around 6000 mg/L). Thus, using OFMSW coming from fruit and vegetable markets it is advisable to work with a two-phase reactor and the system can be perfectly operated with loads up to 7–8 kg TVS/m^3.d using two conventional stirred reactors.

Kinetic considerations

First order and step diffusional models are suitable to represent the biodegradation process of OFMSW (Cecchi *et al.*, 1991a). The step-diffusional model has been tested to fit differ-

Table 4 Characteristics of other OFMSW tested in other studies

	MS-OFMSW	SS-OFMSW	SC-OFMSW
TS (g/kg)	767.9	200.1	163.2
TVS/TS (%)	42.9	88.2	88.1
TCOD (gO_2/gTS)	19.6	109.0	117.0
TKN (%TS)	1.8	3.2	22

Table 5 Results with different fractions of OFMSW in one-phase system with a perfectly stable operation (SC-OFMSW*: Mixture with 20% sewage sludge)

	MS-OF	MSW	SS-OFMSW	SC-OFMSW*
Temp (Mes.or Therm.)	M	T	M	M
OLR (kg TVS/m^3.d)	4.1	6.9	4.2	3.9
HRT (days)	16.2	11.7	13.6	14.5
% CH_4 in biogas	63.4	62	62.5	61
SGP (m^3/kgTVS)	0.230	0.410	0.637	0.661
TVS rem. (%)	27	43	69	71

ent types of substrates yielding quite good results (Cecchi *et al.*, 1991a). The kinetic constants obtained with different substrates such as sewage sludge, OFMSW from different sources and mixtures of these substrates are quite comparable. The first-order kinetic model is very easy to use and fit. However, the fitting is not always possible, as in the case presented here. The first-order kinetic model is more appropriate for complex wastes in which hydrolysis plays an important role.

Figures 2a, 2b and 2c present the profiles of biogas production obtained after feeding the second digester (the methanogenic reactor) for three selected periods, each one representative of the three ranges studied (A, B and C). These figures also include the fitting line corresponding to the first order kinetic model (solid line) and the step diffusional model (discontinuous line). Looking at the profiles it can be seen that gas production rate (L/h) decreases with time, and there are sharp changes after about 2 hours after feeding and after 4 hours. This, in accordance with the step diffusional model, corresponds to the degradation of easily biodegradable carbon sources (during the first 2 hours) which is followed by the degradation of other monomers (following 2 hours), finally followed by the degradation of polymers. This trend is observed in ranges A and B. However, profiles in range C, obtained with the hydrolytic reactor operated at thermophilic temperatures, are a little different during the first minutes after feeding. The level of TVFA is very low, compared with the previous ranges, and the profiles present an initial period of increasing gas production for about the first 30 minutes and then decrease, following a similar profile to the preceding ranges. This could be explained following the two approaches mentioned earlier: (a) part of the readily biodegradable fraction produced is already biogasified in the first reactor, (b) an increased production of monomers higher than TVFA in the hydrolytic reactor and the conversion of the former to the latter during this initial period, in the methanogenic reactor. However, both explanations need further experimental evidence.

Table 6 presents the fitting results for both models (values of the first order kinetic constant are presented only for orientation purposes, as the lack of fit is very significant (Figures 2a, 2b and 2c)). Values of these constants are compared with those obtained in an another study carried out in a one phase system operated at thermophilic conditions and using MS-OFMSW. In this case, the appearance of TVFA was very low (substrate was also

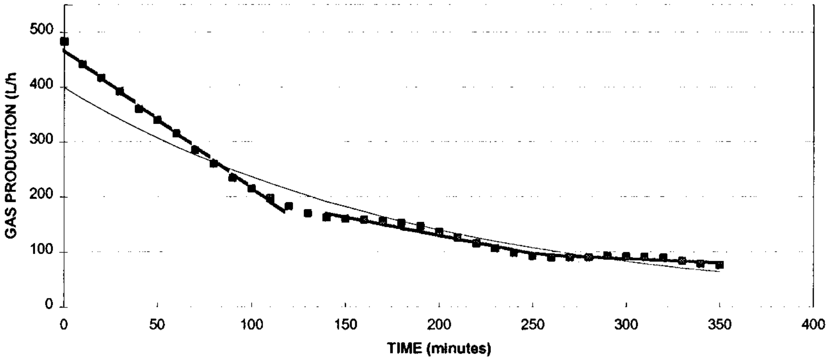

Figure 2a Profiles of gas production rate after digester feeding corresponding to the period 5A
Experimental points ☐; First order fit _____; Step diffusional fit - - - - -

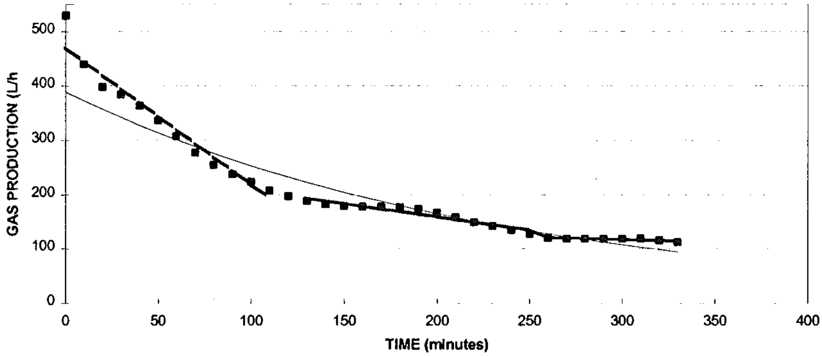

Figure 2b Profiles of gas production rate after digester feeding corresponding to the period 7B
Experimental points ☐; First order fit _____ ; Step diffusional fit - - - - -

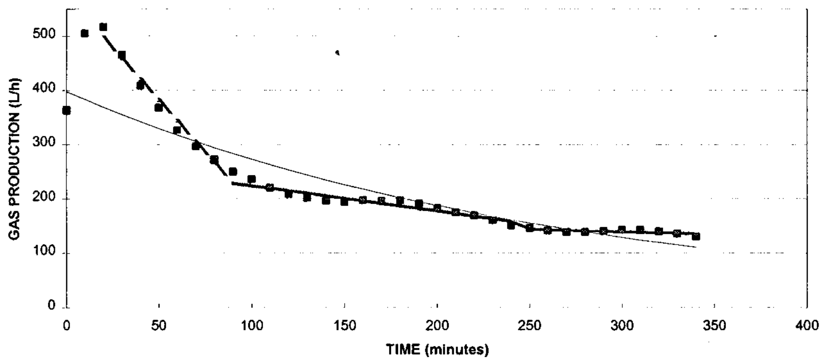

Figure 2c Profiles of gas production rate after digester feeding corresponding to the period 9C
Experimental points ☐; First order fit _____ ; Step diffusional fit - - - - -

different) and its degradation was hardly visible in the gas production profile. The degradation of the other two groups of compounds followed similar paths and the constants obtained are quite comparable (Cecchi *et al.*, 1997).

Table 6 Results of the fitting of the step diffusional and 1st order models

Model	**Step diffusional**			**1st order**
Constants	**k_1 (gC/m^{3}min^2)**	**k_2 (gC/m^{3}min^2)**	**k_3 (gC/m^{3}min^2)**	**K**
RUN 5A (Fig. 2a)	0.02235±0.00152	0.00591±0.00052	0.00093±0.00033	6.2
RUN 7B (Fig. 2b)	0.02236±0.00152	0.00435±0.00041	0.00081± 0.00025	4.5
RUN 9C (Fig. 2c)	0.03418±0.00226	0.0039 ±0.00039	0.00054± 0.00035	5.2
MS-OFMSW (thermophilic one-phase)	—	0.0033	0.00058	1.6

Conclusions

The main conclusions that can be drawn from the study carried out are as follows.

Good methanisation yields (specific gas production around 0.6 m^3/kgTVS) can be obtained in a two-phase system with a mesophilic temperature of the hydrolytic reactor and a thermophilic temperature in the methanogenic reactor and with an overall hydraulic retention time of around 12 days, treating the source selected OFMSW. A safe range of operating conditions in which the yields are similar are the following: HRT in the hydrolytic reactor 2–3 days (mesophilic temperature); HRT in the methanogenic reactor 8–9 days (thermophilic temperature). The increase of the temperature in the hydrolytic reactor up to the thermophilic levels apparently does not improve either the yields or the kinetics.

The quality of the feed strongly influences the system performance and even limits its utilization scope. The use of a two-phase system seems to be compulsory to anaerobically digest highly biodegradable wastes such as those coming from fruit and vegetable markets at thermophilic conditions. One-phase working in these conditions, did not operate successfully.

Kinetics of the process are represented by the step diffusional model.

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