Hydrolysis and thermophilic anaerobic digestion of sewage sludge and organic fraction of municipal solid waste

A. Del Borghi, A. Converti, E. Palazzi, M. Del Borghi

Abstract An attempt is presented and discussed to adapt a well-known process successfully employed in the U.S.A. for the simultaneous treatment of the organic fraction of municipal solid waste (MSWOF) and sewage sludge to the particular situation of water works in Italy. It consists of preliminary domestic grinding of MSWOF, its discharge into the sewer, screening, and final digestion of the resulting residue together with sewage sludge. In order to avoid extension work of the present activated sludge sections necessary to face the organic load increase, a fine screening is necessary, while the efficiency of anaerobic digestion can be improved by shifting the system from mesophilic (37 °C) to thermophilic (55 °C) conditions. The effects of thermal, chemical, and biological pretreatments of both MSWOF and sewage sludge on methane, carbon dioxide, and biogas productions are investigated either separately or jointly. During these pretreatments, volatile suspended solid (VSS) concentration remarkably decreased while soluble chemical oxygen demand (COD) increased as the result of the progressive hydrolysis of the polymeric materials present in the feed. Finally, the kinetic parameters of the hydrolysis of these materials are estimated and compared in order to provide useful information on the factors limiting the anaerobic digestion as well as to suggest the best way to carry out the process on a large scale.

List of symbols

Symbol	Units	Description
a	$dm^{3n} \, g_{VSS}^{-n}$	parameter in Eq. (1)
COD	$g_{COD} \, dm^{-3}$	concentration of the organic substances
K_s	$g_{VSS} \, dm^{-3}$	saturation constant of Monod-type equation
n		dimensionless parameter of Eq. (1)
OLR	$g_{COD} \, dm^{-3} \, d^{-1}$	organic loading rate
r	d^{-1}	specific rate of VSS removal
SS	$g_{SS} \, dm^{-3}$	suspended solids concentration
t	d	time
T	$°C$	temperature
TS	$g_{TS} \, dm^{-3}$	total solids concentration
VS	$g_{VS} \, dm^{-3}$	volatile solids concentration
VSS	$g_{VSS} \, dm^{-3}$	volatile suspended solids concentration
v^o_{COD}	$dm^3 \, g_{COD}^{-1}$	biogas production per unit mass of fed COD
v^r_{COD}	$dm^3 \, g_{COD}^{-1}$	biogas production per unit mass of removed COD
v^o_{VS}	$dm^3 \, g_{VS}^{-1}$	biogas production per unit mass of fed VS
v^r_{VS}	$dm^3 \, g_{VS}^{-1}$	biogas production per unit mass of removed VS
X	$g_{VSS} \, dm^{-3}$	biomass concentration

Greek letters

η		removal yield
τ	d	residence time

Subscripts

f	final value
max	maximum value
0	starting value
s	soluble
t	total

Abbreviations

COD	chemical oxygen demand
MSWOF	organic fraction of municipal solid waste
SS	suspended solids
TS	total solids
VS	volatile solids
VSS	volatile suspended solids

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1 Introduction

The simultaneous anaerobic digestion of hydrolysed mixtures of sewage sludge and MSWOF can be considered as an excellent alternative to dumping, composting, incinerating of household waste or to simple fermentation processes, being addressed to both energy recovery and environmental protection.

It has been demonstrated that digester performances are highly sensitive to the quality of the feed. For example, the biodegradation kinetic constant for the source-selected MSWOF is about 5–10 times larger than that for fresh mechanically-selected MSWOF, while the ultimate biogas yield is 2.5 times larger [1].

Since the performance of anaerobic digestion of both sludge and MSWOF proves to strictly depend also on the efficiency of pretreatments, a comparative examination of different pretreatment procedures has been done by various researchers. The bioconversion of lignocellulosic materials (wood, plants, crop residues) to methane is hindered by their relative resistance to enzymatic hydrolysis. Efforts to maximise the rate and yield of methane production can be categorised into four general areas: a) physico-thermochemical pretreatment of lignocellulosic residues to increase their susceptibility to enzyme action [2–5]; b) addition of trace nutrient to accelerate the fermentation [6, 7]; c) optimisation of the C/N ratio in mixed organic residues [8, 9]; and d) development of thermophilic and multireactor systems [10].

Physico-thermochemical pretreatment has been reported to reduce the substrate refractory nature of lignocellulosics by converting the highly resistant crystalline structure of cellulose to amorphous cellulose, or by disrupting the lignin crosslinks, which accelerates diffusion of the hydrolytic enzymes and increases the surface area available for enzymatic attack [4, 11].

Some studies indicate that chemical pretreatments with alkaline or acidic compounds ensure the most significant benefits [12–14]. In particular, the alkaline hydrolysis is the cheapest and most effective chemical method currently available in terms of solubilisation capacity [15, 16]. An alkali concentration of 4.0 g dm^{-3} seems to represent the optimum for the hydrolysis of MSWOF and sludge mixture; in fact, the rate of solubilisation increases as alkaline dosage increases up to a NaOH concentration threshold of 7.0 g dm^{-3}, beyond which polymerisation and gelification of the mixture take place, thus making the complete hydrolysis of organic matter unfeasible [14]. Also the methane yield and methanogenesis rate of a subsequent digestion step were strongly influenced by NaOH concentration. Finally, first order kinetics were demonstrated to describe at best the alkaline hydrolysis reaction mechanism.

The innovation introduced in this study consists in a high temperature-alkaline pretreatment followed by bacterial hydrolysis, in order to enhance the solubilisation of the organic polymers contained in a mixture of ground MSWOF and primary and secondary sludge. When this technique is used to digest mixtures from discharge of the organic fraction of the household waste to the collection system, the increased organic content of the feed would need to enlarge both the pre-existing activated sludge section and the digester. As suggested in this study, a possible alternative to this expensive solution is to screen more effectively the wastewater enriched with MSWOF, thus avoiding activated sludge overload, and to adapt the heterogeneous population present in the digester to thermophilic (55 °C) conditions.

These pretreatments, breaking the polymeric chains to give more easily degradable monomers, are able to improve biogas production through a reduction of inert solids content as well as an increase in the concentration of organic substances in the feed (soluble COD).

2
The proposed process

The solid waste and sewage sludge produced in urban areas are generally treated in different plants: the sludge from biological oxidation plants is often anaerobically digested while the municipal solid waste is dumped or incinerated. The simultaneous digestion of MSWOF together with sewage sludge under mesophilic conditions is regularly used in several countries, including the U.S.A. This process is routinely performed conveying the MSWOF, after rough screening, to the wastewater treatment plant where it is partially treated. The resulting mixture of screened material and sewage sludge containing most of the organic fraction of household waste is then submitted to digestion. However, this additional supply of organic substances into the digester would require to apply higher residence times or, alternatively, to enlarge the reactor volume, or to add additional digesters. The only alternative which would allow to use the pre-existing plants without any substantial modification is to carry out the digestion under thermophilic conditions, provided they ensure a remarkable efficiency improvement.

The proposed methodology includes a preliminary domestic classification and grinding of MSWOF in the sinks, their discharge together with wastewater into the sewer system, subsequent fine screening, mixing with primary and secondary sludge and with previously ground commercial waste. Before the thermophilic digestion, the mixture is submitted to a high temperature-alkaline pretreatment and successive bacterial hydrolysis for optimal solubilisation of the organic substances (Fig. 1). Finally a biogas and a stabilised product, useful as organic soil amendant or directly disposable in landfills without risk of putrefaction, is obtained.

3
Materials and methods

3.1
Experimental set-up

Experiments were carried out using two 1-dm^3 glass tanks as hydrolytic reactors, both filled with 50% (dry basis) of primary and secondary sludge from the municipal wastewater treatment plant of Punta Vagno (Genoa) and with 50% of MSWOF, which was made up of fruits and vegetables adequately ground and mixed to form a homogeneous slurry.

Digestion tests were carried out simultaneously using 3-dm^3 and 2-dm^3 glass tank digesters nearly completely submerged in water baths at controlled temperature.

3.2
Feed preparation

The average compositions of both sludge and MSWOF, listed in Table 1, were selected from the data available in the literature for municipal productions and compositions of both household waste and primary and secondary sludge. Furthermore, it has been supposed that all the equivalent population served by the hypothetical plant
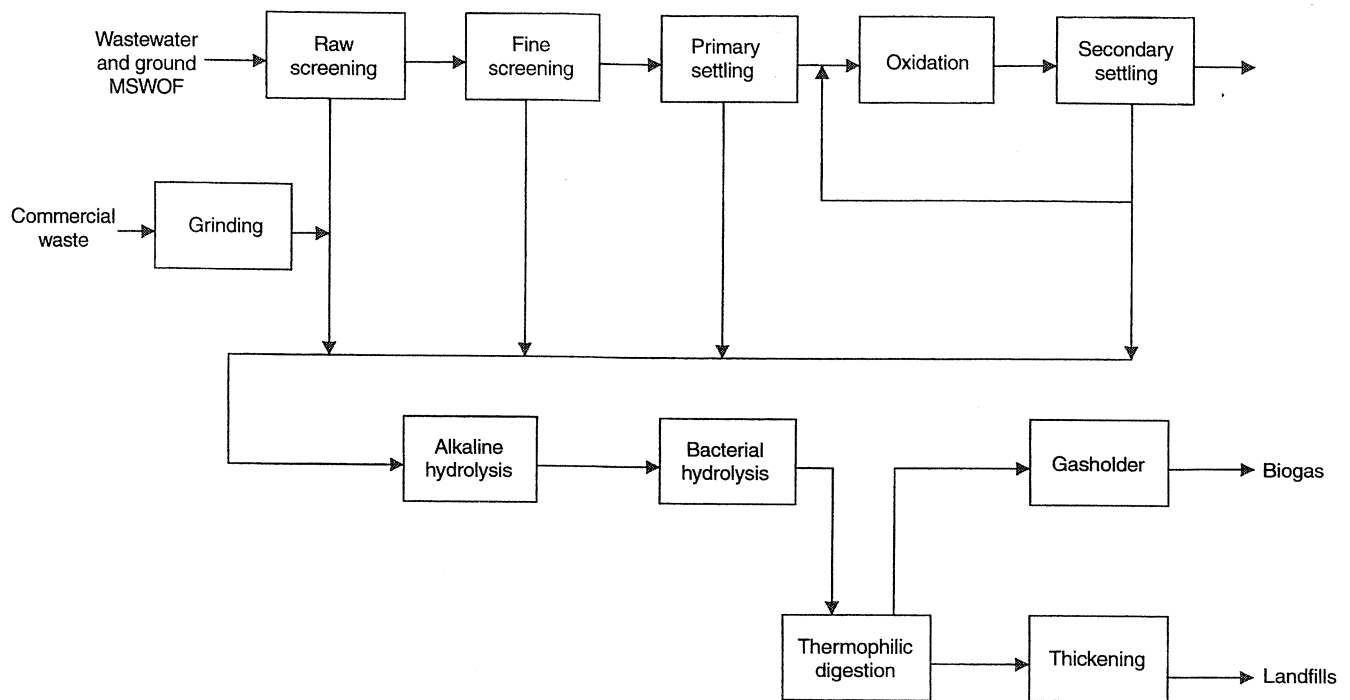
Fig. 1. Schematic diagram of the process proposed for the simultaneous treatment of the organic fraction of municipal solid waste and sewage sludge

should have the possibility to discharge the MSWOF directly into the sewer system.

Two different suspensions were used as feeds for anaerobic digestion. They were prepared by mixing ground MSWOF and sludge and diluting the resulting mixture with tap water up to total solid (TS) concentrations of about 2% and 6% by weight, respectively. The former quite low TS concentration was supposed to ensure the maximum yield of hydrolysis of the organic mixtures, while the latter simulates the usual solid content of the feed for sewage sludge digesters. The average compositions of both feeds are reported in Table 2.

Table 1. Characterisation of sludge and MSWOF

Parameter	Sludge	MSWOF
TS (g_{TS} dm^{-3})	49.2	145.9
SS (g_{SS} dm^{-3})	43.5	113.8
VS (g_{VS} dm^{-3})	39.0	132.0
Organic content (g_{COD} $g_{dry\ solids}^{-1}$)	2.75	10.2

Table 2. Average compositions of the feeds for the thermophilic anaerobic digestion

Parameter	2% mixture	6% mixture
TS (g_{TS} dm^{-3})	21.0	62.4
SS (g_{SS} dm^{-3})	18.2	54.9
VS (g_{VS} dm^{-3})	16.8	47.8
VSS (g_{VSS} dm^{-3})	14.0	46.3
Soluble COD (g_{COD} dm^{-3})	6.0	15.0

3.3
Feed pretreatments

The following batch tests of hydrolysis of the feed were carried out to evaluate the efficiency of each pretreatment procedure on the performance of the successive anaerobic digestion:

A) bacterial hydrolysis;
B) chemical hydrolysis, heat treatment, and bacterial hydrolysis;
C) heat treatment and bacterial hydrolysis;
D) chemical hydrolysis and bacterial hydrolysis.

Heat treatment was performed by autoclaving the mixtures at 110 °C for 20 minutes, chemical hydrolysis by adding NaOH up to a concentration of 4.0 g dm^{-3} [14], and bacterial hydrolysis at 25 °C and pH 7.0 by inoculating the mixtures with 1.0 g dm^{-3} of selected hydrolytic bacteria. Samples were collected, at regular time intervals, both before and after each physical or chemical pretreatment.

Standard methods were used for COD, TS, volatile solids (VS), suspended solids (SS), and VSS determinations [17]. These parameters were followed to evaluate the effectiveness of the hydrolysis of the organic polymeric materials contained in the mixture.

3.4
Hydrolytic bacteria

The consortium of hydrolytic bacteria used in this work was kindly supplied by Manitoba Italia, Nova Milanese, Italy. It was isolated from activated sludge and showed the average composition listed in Table 3.

556

Table 3. Average composition of the heterogeneous population employed for bacterial hydrolysis of the feeds

Bacteria	Percentage (%)
Bacillus cereus	38.0
Arthrobacter sp.	9.5
Bacillus polymyxa	52.4
Micrococcus sp.	0.15

3.5
Anaerobic digestion tests

The possible performance improvement of fed-batch thermophilic digestion consequent to feed hydrolysis has been evaluated through a set of anaerobic digestion tests carried out by feeding the digester with 6% hydrolysed mixture. A parallel blank test was also performed using the same mixture not subjected to any pretreatment.

The fed-batch tests were carried out sampling every 24 h and substituting the sampled volume with an equivalent amount of fresh feed. The organic loading rate (OLR) has been increased from 0.56 to 5.0 g_{COD} dm^{-3} d^{-1} by feeding the digesters with fixed volumes of solutions having increasing organic content. The start-up phase for each selected organic load was followed by daily measurements of methane, carbon dioxide, and total biogas productions. Mixed liquor was analysed after reaching steady state conditions.

4
Results and discussion

4.1
Hydrolysis tests

Comparative examination of the pretreatments of MSWOF and sludge mixtures, previously called A, B, C and D, shows that the combination of high temperature, alkaline hydrolysis, and bacterial hydrolysis ensures the most significant benefits in terms of VSS solubilisation. In particular, while the concentration of VSS did not vary significantly during thermal and chemical pretreatments (from 14.0 to 13.6 g_{VSS} dm^{-3} for 2% mixture and from 46.3 to 44.0 g_{VSS} dm^{-3} for 6% mixture), the results of Fig. 2 show that a remarkable decrease took place during the subsequent bacterial hydrolysis. At the same time, sharp increases in soluble COD were observed during both thermal and chemical treatments (from 6 to 10 g_{COD} dm^{-3} for 2% mixture and from 15 to 18 g_{COD} dm^{-3} for 6% mixture) and the subsequent bacterial hydrolysis (Fig. 3).

As regards 6% mixture, similar results have been obtained in terms of percentages of VSS removal and soluble COD increase, while TS and total COD kept practically constant during the bacterial hydrolysis. This was probably due to a slow bacterial growth that partially offset the liquefaction of polymeric solids.

The above results have then been used in a kinetic study to investigate the mechanism of the mixture hydrolysis. To this purpose, VSS removal rate has been expressed by the equation:

$$-\frac{d(VSS)}{dt} = (1 - e^{-a(VSS)^n}) \frac{X \cdot r_{max} \cdot VSS}{K_S + VSS} . \qquad (1)$$
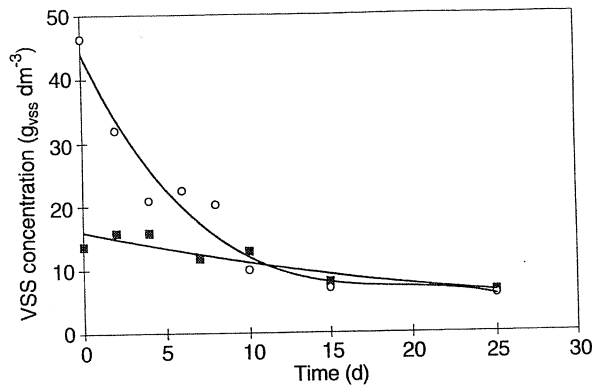

Fig. 2. Effect of bacterial hydrolysis on VSS concentration of 2% (■) and 6% (○) mixtures of MSWOF and sewage sludge

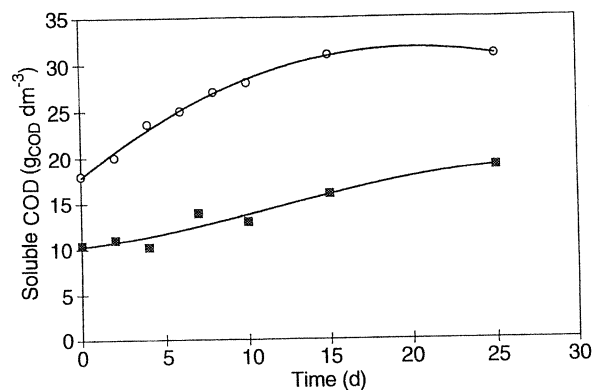**Fig. 3.** Effect of bacterial hydrolysis on soluble COD of 2% (■) and 6% (○) mixtures of MSWOF and sewage sludge

When VSS $\ll K_S$, Eq. (1) can be simplified as follows:

$$-\frac{d(VSS)}{dt} = a \frac{X \cdot r_{max} \cdot VSS^{n+1}}{K_S} , \qquad (2)$$

while, for large values of VSS, it turns into the Monod-type expression:

$$-\frac{d(VSS)}{dt} = \frac{X \cdot r_{max} \cdot VSS}{K_S + VSS} . \qquad (3)$$

From the behaviour of the rate of VSS removal, plotted in Fig. 4 versus VSS concentration, the values listed in Table 4 have been estimated for the parameters appearing in Eq. (1) by linear regression. Analogous and complementary equations could be used to describe soluble COD release consequent to hydrolysis.

Various expressions have been proposed in the past to describe the hydrolysis kinetics of organic solids. Often, they resemble Eq. (3), which is valid for single substrates or for synthetic mixtures of substrates; sometimes, mainly in the case of complex substrates, they are similar to Eq. (2) [18].

The VSS content of the feeds used in this work is the result of the simultaneous presence of two different groups of substrates, the former consisting of scarcely biodegradable substrates (i.e. lignin and cellulose) [19], while the latter being a mixture of simple carbon sources.
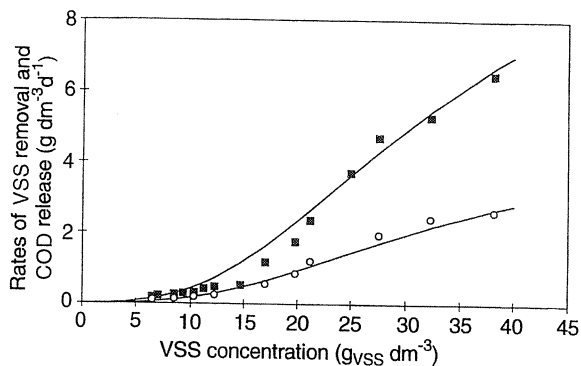
Fig. 4. Behaviours of the rates of VSS removal (■) and soluble COD release (○) versus VSS concentration

Table 4. Values of the kinetic parameters of Eq. (1) estimated by linear regression from the experimental data

Parameter	Value
a ($\mathrm{dm}^{3n}\ \mathrm{g_{VSS}}^{-n}$)	0.0015
n (–)	2
$X \cdot r_{max}$ ($\mathrm{g_{VSS}\ dm^{-3}\ d^{-1}}$)	15
K_s ($\mathrm{g_{VSS}\ dm^{-3}}$)	38
Mean Square error	0.087

As well known, the mechanism of utilisation of the substrates by bacterial cells can be described by a sequence of three steps: a) contact of a cell with a substrate molecule, b) transport of the molecules into the cell, and c) substrate utilisation. It is obvious that, in presence of large molecules or sterically incompatible molecules or highly crystalline molecules, which cannot be easily transported into the cells, a further step of hydrolysis by esoenzymes should have to be considered.

The curves describing the solubilisation rates versus actual concentration in Fig. 4 suggest the presence of different types of substrates in the mixture of MSWOF and sludge, leading to the following situation: at high substrate concentration, at which the removal rate is high and follows a Monod-type behaviour, only the group of single substrates is hydrolysed; the solubilisation rate progressively decreases as far as the group of complex lignocellulosics becomes the prevailing fraction in the mixture.

4.2
Anaerobic digestion tests

The start-up phase, preceding the pseudo-steady state achievement, was followed in terms of methane, carbon dioxide, and total biogas productions.

The main results of anaerobic fermentations, in terms of biogas volume daily produced per unit reactor volume, are illustrated in Figs. 5 and 6 for the non-hydrolysed and the pre-hydrolysed feeds, respectively. First of all, in agreement with the observations of Cecchi et al. [10], pseudo-steady state conditions, measured by biogas production, were achieved more slowly at higher rather than at lower organic load. In addition, according to Converti et al. [20], the pseudo-steady state achievement was
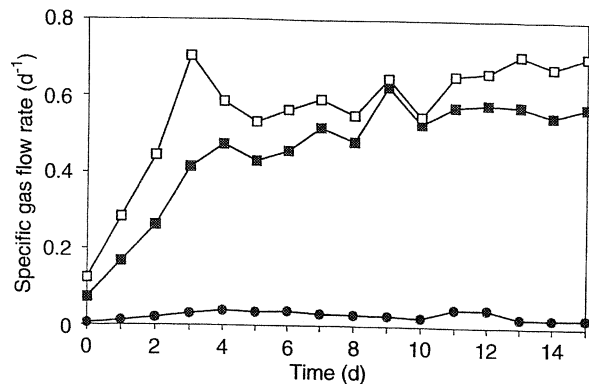

Fig. 5. Behaviours of the specific gas flow rates during the start-up of fed batch fermentation of non-hydrolysed mixture of MSWOF and sewage sludge. ORL = 4.0 $\mathrm{g_{COD}\ dm^{-3}\ d^{-1}}$. Components: (■) CH_4; (□) CO_2; (●) N_2
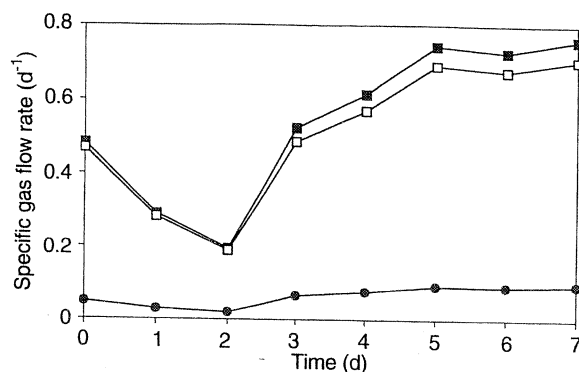

Fig. 6. Behaviours of the specific gas flow rates during the start-up of fed batch fermentation of pre-hydrolysed mixture of MSWOF and sewage sludge. ORL = 3.75 $\mathrm{g_{COD}\ dm^{-3}\ d^{-1}}$. Components: (■) CH_4; (□) CO_2; (●) N_2

strongly accelerated when hydrolysed mixtures were used instead of untreated feeds.

A comparison between the results of biogas production obtained under pseudo-steady state conditions at different starting levels of organic substances with or without the hydrolysis pretreatments shows that:

● the specific biogas production from the hydrolysed mixture is constantly about 20% higher than that from the untreated one (Fig. 7);

● the volume of biogas produced per unit mass of the hydrolysed mixture is constantly higher than the respective values obtained for non-hydrolysed feed. In particular, it is about 100% higher at low organic load and 30% higher at values of this parameter usually employed for anaerobic digestion (Fig. 8).

In addition, the steady state values of co-digestion of non-hydrolysed and pre-hydrolysed mixtures of MSWOF and sludge, gathered in Tables 5 and 6 respectively, show that final SS and VSS levels are actually lower for the hydrolysed mixture than for the untreated one. The VS/TS ratio at the end of the digestion of the hydrolysed mixture is higher than in the feed because of the additional VS contribution due to biomass growth in the digester. However, this phenomenon is not observed for the non-
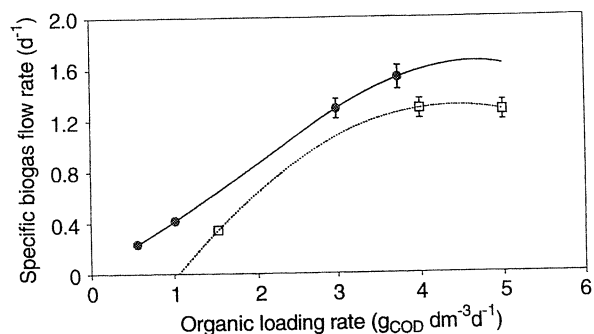
Fig. 7. Dependence of the specific biogas flow rate at steady state on the organic load. Feeds: (●) hydrolysed and (□) non-hydrolysed mixtures of MSWOF and sewage sludge
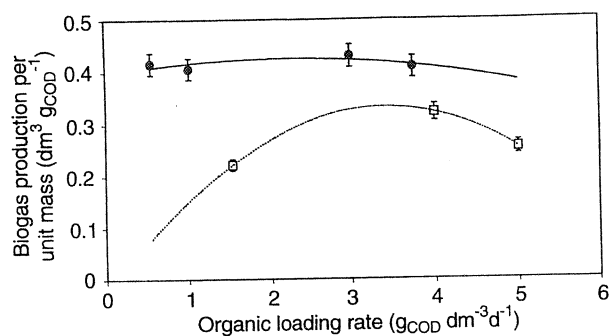

Fig. 8. Influence of the organic load on the specific biogas production per unit mass. Feeds: (●) hydrolysed and (□) non-hydrolysed mixtures of MSWOF and sewage sludge

C. mesophilic digestion of the organic fraction of source-sorted municipal solid wastes [1];

D. mesophilic digestion of MSWOF (50%) and sewage sludge (50%) [1];

E. mesophilic digestion of pre-hydrolysed agricultural waste and sewage sludge [20];

F. thermophilic digestion of MSWOF (50%) and sewage sludge (50%) (this work);

G. thermophilic digestion of pre-hydrolysed MSWOF (50%) and sewage sludge (50%) (this work).

As expected, the residence times of thermophilic processes can be quite lower than those of mesophilic ones. At the same time, the increase in temperature allows to work at loads of both COD and VS remarkably higher than those usually employed in traditional mesophilic digestion.

The specific biogas production, that strictly depends on the organic loading rate, is generally higher for MSWOF and sludge mixtures than for sludge. The unsatisfactory value observed for process E can be ascribed to some extent to a relevant fraction of suspended non digestible ligninic particles, not completely hydrolysed by the caustic treatment. Other possible inhibitions could arise from the formation of furfural during cellulose hydrolysis and the release of phenolic compounds during lignin hydrolysis. This phenomenon has not been evidenced in process G, which is characterised by both chemical and bacterial pre-hydrolysis; so the specific production of biogas has been particularly high, also due to the low VS/COD ratio of the feed, as a consequence of liquefaction of great part of solid organic matter. The lower methane content suggests, on the other hand, some carbon loss during the hydrolysis.

Although, the total volatile solids reduction in the digester is comparable for all processes tested for MSWOF digestion, if one takes into account the complete process (hydrolysis plus digestion), the yield of VS reduction observed for process G is much higher (83.7%) than for the others.

The volatile solids amount in the digester is very low in comparison with the other digestion processes and the

hydrolysed mixture because of its higher starting VS content.

A performance comparison of the proposed process with the results of anaerobic digestion of different feeds is presented in Table 7. To this purpose, the following digestion processes have been selected:

A. mesophilic digestion of sewage sludge [10];
B. thermophilic digestion of sewage sludge [10];

Table 5. Results of the thermophilic anaerobic digestion of a non-hydrolysed mixture of MSWOF and sludge

OLR (g_{COD} dm^{-3} d^{-1})	1.53			4.00			5.00		
	t_0	t_f	η	t_0	t_f	η	t_0	t_f	η
TS (g_{TS} dm^{-3})	21.0	7.9	0.62	62.4	16.3	0.74	62.4	25.6	0.59
SS (g_{SS} dm^{-3})	18.2	4.4	0.76	54.9	12.2	0.78	54.9	21.0	0.62
VS (g_{VS} dm^{-3})	16.8	4.7	0.72	47.8	11.7	0.75	47.8	17.2	0.64
VSS (g_{VSS} dm^{-3})	14.0	3.4	75.8	46.3	9.5	79.6	46.3	14.9	67.8
COD_t (g_{COD} dm^{-3})	23.0	11.5	0.50	60.0	30.0	0.50	60.0	27.0	0.55
COD_s (g_{COD} dm^{-3})	6.0	1.2	80.0	15.0	3.1	79.2	15.0	4.0	73.3
VS/TS (g_{VS} g_{TS}^{-1})	0.8	0.60	–	0.74	0.71	–	0.76	0.67	–
v_{VS}^o (dm^3 g_{VS}^{-1})		0.202			0.402			0.365	
v_{COD}^o (dm^3 g_{COD}^{-1})		0.222			0.322			0.254	
v_{VS}^r (dm^3 g_{VS}^{-1})		0.423			0.532			0.498	
v_{COD}^r (dm^3 g_{COD}^{-1})		0.442			0.858			0.765	

t_0 = starting value
t_f = final value
η = removal yield

Table 6. Results of the thermophilic anaerobic digestion of a pre-hydrolysed mixture of MSWOF and sludge

OLR (g_{COD} dm^{-3} d^{-1})	0.56			1.02			3.00			3.75		
	t_0	t_f	η	t_0	t_f	η	t_0	t_f	η	t_0	t_f	η
TS (g_{TS} dm^{-3})	9.3	3.9	0.58	16.8	6.7	0.60	42.4	12.7	0.70	42.4	13.6	0.68
SS (g_{SS} dm^{-3})	3.5	1.0	0.70	6.3	1.6	0.74	25.0	6.2	0.75	25.0	5.7	0.77
VS (g_{VS} dm^{-3})	4.0	1.8	0.56	7.4	3.2	0.56	20.9	8.0	0.62	20.9	7.7	0.63
VSS (g_{VSS} dm^{-3})	2.4	0.72	0.70	4.4	1.2	0.73	15.7	4.1	0.74	15.7	3.9	0.75
COD$_t$ (g_{COD} dm^{-3})	8.4	3.5	0.58	15.3	6.1	0.60	45.0	17.5	0.61	45.0	18.0	0.60
COD$_S$ (g_{COD} dm^{-3})	4.7	0.95	0.80	8.6	1.7	0.80	16.9	3.2	0.81	16.9	3.4	0.80
VS/TS (g_{VS} g_{TS}^{-1})	0.48	0.46	–	0.43	0.48	–	0.49	0.62	–	0.49	0.57	–
v_{COD}^o (dm^3 g_{COD}^{-1})		0.416			0.406			0.430			0.409	
v_{COD}^r (dm^3 g_{COD}^{-1})		0.716			0.675			0.701			0.681	

t_0 = starting value
t_f = final value
η = removal yield

Table 7. Performance comparison of the anaerobic digestion of various feeds under different conditions

Digestion process	A	B	C	D	E	F	G
VS load (g_{VS} dm^{-3} d^{-1})	1.6	4.8	4.2	2.8	3.4	4	1.73
Organic load (g_{COD} dm^{-3} d^{-1})	–	–	–	–	–	5	3.75
T (°C)	37	55.5	35	35	35	55	55
Residence time (d)	14.4	11.6	13.6	14.5	20	12	12
TS in the feed (g_{TS} dm^{-3})	31	84.4	64.8	57	151	62.4	42.4
VS in the feed (g_{VS} dm^{-3})	21	55	57.1	40	125	47.8	21
VS/TS in the feed (g_{VS} g_{TS}^{-1})	0.68	0.65	–	0.7	0.85	0.76	0.49
VS/TS in the digested sludge (g_{VS} g_{TS}^{-1})	0.51	0.56	–	0.47	0.81	0.67	0.57
VS removal yield (%)	26.6	–	67	57	–	64	63
VS in the reactor (g_{VS} dm^{-3})	18.6	36.6	–	17.4	–	17	7.7
Specific biogas production (dm^3 g_{VS}^{-1})	0.3	0.19	0.62	0.6	0.12	0.36	0.87
CH$_4$ content (%)	62	65.4	62.5	60	45	50	46

A = mesophilic digestion of sewage sludge [10]; B = thermophilic digestion of sewage sludge [10]; C = mesophilic digestion of the organic fraction of source-sorted municipal solid wastes [1]; D = mesophilic digestion of MSWOF (50%) and sewage sludge (50%) [1]; E = mesophilic digestion of pre-hydrolysed agricultural waste and sewage sludge [20]; F = thermophilic digestion of MSWOF (50%) and sewage sludge (50%) (this work); G = thermophilic digestion of pre-hydrolysed MSWOF (50%) and sewage sludge (50%) (this work)

final amount of sludge to be disposed of is about one half that of the same process without hydrolysis.

5
Conclusions

After a preliminary grinding, the organic fraction of municipal solid wastes has been mixed with sludge from municipal wastewater treatment plant, in proportion simulating the disposal of MSWOF through the sinks and the sewer system. Successively, this mixture has been hydrolysed by thermal, chemical, and biological treatment.

During these treatments, the content of volatile suspended solids decreased, while soluble COD, that represents the organic fraction which can actually be solubilised, increased. The kinetic analysis of the biological hydrolysis has been simulated by a simple model successfully employed in the past to describe the degradation of mixtures of both simple and complex substrates.

The hydrolysed mixture was then used as feed for a thermophilic digester. In order to establish how much this hydrolytic pre-treatment could make the anaerobic digestion easier, a non-hydrolysed mixture of MSWOF (50%) and sludge (50%) was also tested.

Hydrolysis allowed an improved availability of organic substances, but the methane percentage of biogas is less (49%) than the usual values (60%), probably due to some carbon consumption during the bacterial hydrolysis.

Nevertheless, the most important result which can be ascribed to hydrolysis of the feed is the very low total and volatile solids concentrations in the digester, which could allow us to convert the mesophilic reactors employed to digest the sewage sludge into thermophilic ones, capable of treating mixtures of MSWOF and sludge without considerable plant changes. In this circumstance, the MSWOF could be sorted directly at the source, thus simplifying the problem of urban solid waste disposal.

Future research will simulate the complete process, taking into account the experimental kinetic equations in order to evaluate the process performance and to estimate the related costs.

References

1. Mata-Alvarez, J.; Cecchi, F.; Pavan, P.; Llabres, P.: The performances of digesters treating the organic fraction of municipal solid wastes differently sorted. Biological Wastes 33 (1990) 181–199

60

2. Fan, L.T.; Gharpuray, M.M.; Lee Y.-H.: Evaluation of pretreatments of enzymatic conversion of agricultural residues. Biotechnol. Bioeng. Symp. 11 (1981) 29–45

3. Han, Y.W.; Timpa, J.; Ciegler, A.; Courtney, J.; Curry, W.F.; Lambremont, E.N.: γ-Ray-induced degradation of lignocellulosic materials. Biotechnol. Bioeng. 23 (1981) 2525–2535

4. Ryu, D.D.Y.; Lee, S.B.; Tassinari, T.; Macy, C.: Effect of compression milling on cellulose structure and on enzymatic hydrolysis kinetics. Biotechnol. Bioeng. 24 (1982) 1047–1067

5. McCarty, P.L.; Young, L.Y.; Colberg, P.J.; Baugh, K.; Bachmann, A.; Beard, V.; Hehn, D.: Autohydrolysis of organic residues to increase biodegradability to methane. Paper presented at the SERI Biomass Program Review Meeting, Washington, DC, June 23–25, 1982

6. Grohmann, K.; Himmel, M.: Hemicellulases as a pretreatment tool for anaerobic digestion. Paper presented at the SERI Biomass Program Review Meeting, Washington, DC, June 23–25, 1982

7. Speece, R.E.; Parkin, G.F.: Nutritional stimulation of methane fermentation. Paper presented at the SERI Biomass Program Review Meeting, Washington, DC, June 23–25, 1982

8. Ghosh, S.; Henry, M.P.; Klass, D.L.: Bioconversion of water hyacinth-coastal Bermuda grass-MSW-sludge blends to methane. Biotechnol. Bioeng. Symp. 10 (1980) 163–187

9. Hashimoto, A.G.: Conversion of straw-manure mixtures to methane at mesophilic and thermophilic temperatures. Biotechnol. Bioeng. 25 (1983) 185–200

10. Cecchi, F.; Pavan, P.; Musacco, A.; Mata-Alvarez, J.; Sans, C.; Ballin, E.: Comparison between thermophilic and mesophilic anaerobic digestion of sewage sludge coming from urban wastewater treatment plants. Ingegneria Sanitaria-Ambientale 40 (1992) 25–32

11. Gracheck, S.J., Rivers, D.B.; Woodford, L.C.; Giddings, K.E.; Emert, G.H.: Pretreatment of lignocellulosics to support cellulase production using Trichoderma reesei QM 9414. Biotechnol. Bioeng. Symp. 11 (1981) 47–65

12. Strickland, R.C.; Beck, M.J.: Effective pretreatment alternatives for the production of ethanol from hemicellulosic hardwood hydrolyzates. Paper presented at 9th Symp. on Energy from Biomass and Wood Wastes, Lake Buena Vista, FL, 28 Jan.-1 Feb., 1985, 1–22

13. Perego, P.; Converti, A.; Zilli, M.; Del Borghi, M.: Acid hemicellulose hydrolysates: physical treatments and continuous immobilized-cell fermentations. Bioproc. Eng. 10 (1994) 35–41

14. Novelli, A.; Ottonello, F.; Converti, A.; Lodi, A.; Rovatti, M.; Del Borghi, M.: Alkaline hydrolysis for the treatment of the organic fraction of municipal solid wastes and sludges. Chem. Biochem. Eng. Q. 9 (1995) 195–199

15. Baccay, R.A.; Hashimoto, A.G.: Acidogenic and methanogenic fermentation of causticized straw. Biotechnol. Bioeng. 26 (1984) 885–891

16. Mukherjie, S.R.; Levine, A.D.: Chemical solubilization of particulate organics as a pretreatment approach. Wat. Sci. Technol. 25 (1992) 2289–2292

17. A.P.H.A.: Standard Methods for the examination of water and wastewater; 16th edn.; APHA, AWWA, WPCF. Washington, D.C., 1985

18. Del Borghi, M.; Palazzi, E.; Ferraiolo, G.: The role of kinetic phenomena on the design of a rotating biological surface. Experimental application to straw paper wastewater treatment. La Chimica e l'Industria 59 (1977) 77–82

19. Baver, A.J.: Effect of lignin on the in vitro digestibility of wood pulp. J. Anim. Sci., 37 (1973) 768

20. Converti, A.; Drago, F.; Ghiazza, G.; Macchiavello, A.; Del Borghi, M.: Co-digestion of municipal sewage sludges and pre-hydrolysed woody agricultural wastes. J. Chem. Tech. Biotechnol. 69 (1997) 231–239