Biological treatment of the organic fibre from the autoclaving of municipal solid wastes; preliminary results.

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Abstract

Commingled municipal solid waste (MSW) was autoclaved in the presence of saturated steam for 30 min at 145°C and 600 kPa. The organic fibre fraction from the autoclaved resulting material was examined for biodegradability. Aerobic and anaerobic tests were carried out to characterise the fibre in terms of biodegradation potential, which was moderate (biogas production potential of 251 ± 22 l [biogas] kg^{-1} [total solids (TS)] and dynamic respiration index of 1575 ± 116 mg [O_2] kg^{-1} [TS] h^{-1}). Manual and chemical characterisations were also performed to organic fibre. Following this characterisation, a laboratory-scale thermophilic anaerobic digestion process and a pilot-scale composting process were carried out to determine the possibilities of these biological treatments. In the anaerobic digestion process the biogas yield values obtained were within 0.15-0.21 m^3 [biogas] kg^{-1} [volatile solids (VS)] with an organic loading rate of 3 kg [VS] m^{-3} d^{-1}. However, it was difficult to reach the steady state in the anaerobic thermophilic process for the different organic loads tested. Further experiments are necessary to determine the optimal biogas production and performance under these conditions. The composting process performed correctly and the final material was stable (dynamic respiration index of 504 ± 74 mg [O_2] kg^{-1} [TS] h^{-1}) and with good properties for its application to soil regarding heavy metal contents that corresponding to class B compost, with the exception of some metals that corresponded to class A.

Keywords: anaerobic digestion; autoclaving; biodegradability; composting; municipal solid waste; organic fibre.

Nomenclature

DRI	dynamic respiration index
FAS	air filled porosity (or free air space)
FID	flame ionisation detector
GB_{21}	biogas production at 21 days
MBT	mechanical-biological treatment
MSW	municipal solid waste
OFMSW	organic fraction of municipal solid waste
OLR	organic loading rate
OUR	oxygen uptake rate
SS-OFMSW	source-separated organic fraction of municipal solid waste
TCD	thermal conductivity detector
TEM	transmission electron microscopy
TKN	total Kjeldahl nitrogen
TOC	total organic carbon
TS	total solids
VFA	volatile fatty acids
VS	volatile solids

1. Introduction

Today, landfill represents the most common way of disposing of municipal solid waste (MSW) (He et al., 2005). However, the adverse effects of waste landfill on the environment, such as the production of methane, odours from volatile organic compounds and leachate, the presence of vectors (insects, rodents and birds), public health hazards and plant toxicity have all been indicated as negative effects of this practice (Thorneloe and Pacey, 1994). To reduce biodegradable waste landfill the introduction of the European Council Directive 99/31/EC (European Commission, 1999) points to the development and implementation of new strategies for waste management in Europe. The objective of this Directive is to prevent, or mitigate, the negative environmental effects of disposing of organic waste in landfill by introducing stringent technical requirements for waste and landfills. Thus, the compliance of this Directive as well as the fact that new landfill sites are becoming difficult to obtain because of the lack of available land and the opposition from the residents living near the proposed sites, has diverted much of the organic fraction of municipal solid waste (OFMSW) to other purposes.

One of the emerging technologies to treat MSW and reduce its material going to landfill is autoclaving. Pilot tests on the autoclaving of MSW were conducted in the 1980s and in the late 1990s research was intensified (Ding et al., 1997; Otabbong and Barbolina, 1998). The main features of this treatment for recovering the value of municipal waste have already been described (Papadimitriou, 2007). Autoclaving is a hydrothermal process that takes place in a moist environment with high pressures. The heating of the reactor requires the injection of saturated steam, so that the residue is eventually autoclaved.

The effect of the treatment and its subsequent mechanical separation system is that approximately 80% of the initial volume that can be separated for recycling (Papadimitriou, 2007). At the same time, the sterilisation of pathogens, the loss of fluids, the compaction of plastics, and the disintegration of labels on glass bottles, food packaging and cans is achieved. Also, all incoming biodegradable fractions are collected together in a single organic fibre fraction, which has been recently studied for biodegradability under composting and anaerobic digestion conditions (Trémier, 2006; Stentiford, 2010).

However, the autoclaving process can be applied directly to mixed MSW in areas where source separation collection is not implemented. It may also be a good solution to treat the rejected fraction from the mechanical-biological treatment (MBT) plants. This rejected flow mainly corresponds to the fraction refused in the first mechanical pretreatment with a characterisation similar to the MSW. The post-treatment of this MBT residual flow through an autoclaving process may maximise the recycled ratio (glass, plastic, metal and biodegradables) of MBT plants. However, there is still some lack of knowledge about the suitability of this technology for treating large amounts of MSW. The most important concern to be solved is the fate of the organic fibre obtained after autoclaving the MSW, which is the main constituent in the autoclaved material.

The general objective of this research was to determine the biodegradability of the organic fraction obtained from the full-scale process of autoclaving of unsorted MSW. Although several studies have been presented to explain the characteristics and results of MSW autoclaving, there are few works on the anaerobic and aerobic biodegradability of organic fibre from MSW autoclaving.

2. Materials and Methods

2.1. Autoclaving process

An autoclaving process was carried out in a full-scale reactor with a capacity of 35 m^3, processing approximately 10-15 tonnes of unsorted MSW in a continuous mode of operation to avoid the problem of heterogeneity found in this kind of wastes. Working conditions were 600 kPa and 145ºC with a hydraulic retention time of 30 minutes. Organic fibre was obtained from the mechanical separation of this fraction from the rest of materials (glass, plastics, metals and stones) with a 10 mm sieving process and it was a highly homogeneous fibrous material as confirmed by transmission electron microscopy (TEM) images obtained with a JEOL electron microscope (model 1010, IZASA, Alcobendas, Spain) operating at an accelerating voltage of 15 kV (Fig. 1). This organic fraction represents 55% of the input material (in weight). Samples of about 50 kg of organic fibre and the starting MSW were used for analysis.

2.2. Anaerobic biodegradability batch assays

Batch assays were performed in triplicate in order to evaluate the biogas potential of the organic fibre under anaerobic conditions. Anaerobic batch tests were based on Field et al. (1988), adapted according to Ferrer et al. (2004) and taking into account some recommendations from Angelidaki et al. (2009), which states some of the basic principles to consider in biogas potential tests, such as the unification of methodologies, units, inoculum, etc. Batch reactors were commercial aluminium bottles with a volume of 1000 ml and with a modified lid to include a manual valve for biogas measures. Organic fibre was used as obtained, but MSW was previously ground to 20 mm using an industrial shredder. Before each batch, the reactor was filled up with the organic fibre and the corresponding inoculum (final total working volume 600 ml, Total

Solids (TS) content 3.5% on wet basis). This inoculum was obtained from a full-scale mesophilic anaerobic digester and mixed with the organic fibre in ratio 1:1 on dry matter basis (d.m.b.) (no inhibition was observed with this ratio). Then, the bottles were flushed with nitrogen to remove air and afterwards incubated at 37 °C for 21 days (GB_{21}). Biogas production was measured according to the pressure increase in the headspace by means of an SMC pressure switch manometer (model ZSE 30, SMC Corporation, Barcelona, Spain) (100 kPa, 5% accuracy). Biogas samples were taken periodically to analyse the methane content by gas chromatography. GB_{21} values were obtained from triplicates and expressed as average values with standard deviation. Complete details of this standardised procedure can be found elsewhere (Federal Government of Germany, 2001; Ponsá et al., 2011a; Ponsá et al., 2011b).

2.3. Continuous anaerobic laboratory reactor: experimental set-up and procedure

Inoculum for the laboratory-scale anaerobic reactor was obtained from a MBT plant located in Barcelona, Spain, from the recirculation of its thermophilic anaerobic reactor. Total Solids (TS) and Volatile Solids (VS) contents were 21.66 % of TS (wet basis) and 42.3 % of VS (TS basis).

Source-separated OFMSW (SS-OFMSW) for the start-up period of the laboratory-scale anaerobic digester was obtained from a MBT plant located in Montcada i Reixac, Barcelona, Spain. TS and VS contents were 37.0 % of TS (wet basis) and 70.2 % of VS (TS basis), respectively. Total organic carbon (TOC) percentage was 45% (w/w, dry basis) and total Kjeldahl nitrogen (TKN) was 3.2% (w/w, dry basis). This SS-OFMSW was diluted with tap water to reach a final concentration of 7% of TS. The reactor had been operating under these conditions for more than two years (Martín et al., 2010) and the feed was changed to the organic fibre.

The continuous anaerobic digestion process was carried out in a 5 l glass jacketed reactor coupled to a thermostatic bath that maintained the temperature under thermophilic conditions. These conditions were selected as previous experiments under mesophilic conditions showed neither stable nor high biogas production in continuous mode when compared to raw SS-OFMSW mesophilic anaerobic digestion (data not shown). The biogas channel, the feeding inlet pipe and the extracting and/or sampling outlet pipe were located in the stainless steel lid of the reactor. The reactor was fed once a day 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 pipe, and then, immediately, the feeding mixture was added through the inlet channel. Automatic stirring at 60 rpm was established as 20 min every 2 h and programmed through a commercial controller (model IKA-Works RW 20.n, Staufen, Germany). The biogas produced was volumetrically measured on line by water displacement, using an electric counter connected to a sensor level (Martín et al., 2010).

The criteria to determine the steady average values for each period were established as follows: the variations observed in volatile fatty acids (VFA), biogas yield, VS and TS reduction percentages should be lower than 10%. This corresponds to a more than three hydraulic residence times, except during the star-up period, which was changed after the VFA concentration was below inhibition, values (Angelidaki et al., 2009).

2.4. Respirometric tests

These tests are carried out to determine the specific oxygen consumption of organic samples. The procedure established in this study for the determination and calculation of the dynamic respiration index (DRI) is based on the previous works by Adani et al. (2004) and Barrena et al. (2005). No inoculum was used with aerobic tests according to the previous methodologies. A detailed description of the analytical procedure can be found in Ponsá et al. (2009) and Ponsá et al. (2010). DRI values were obtained from triplicates and expressed as average values with standard deviation.

2.5. Composting pilot reactor

Composting experiments were carried out at pilot scale, using an adiabatic cylindrical reactor with an operating volume of 50 l, which was filled with approximately 25 kg of organic fibre and 15 kg of bulking agent (wood chips).

The reactor walls were thermally isolated with polyurethane foam in order to avoid heat losses. A perforated plate was fitted into the bottom of the reactor to support the material and to optimize the airflow circulation. Two apertures were situated in the cover of the reactor: one used to conduct exhaust gases to an oxygen sensor and another one used to insert the Pt-100 sensor for measuring temperature (Design Instruments, Barcelona, Spain). At the bottom of the reactor there are two apertures: one used to introduce the compressed air and another one to remove leachate, if necessary.

The reactor was connected to a PC for the data acquisition and control using LabView 8.6 software (National Instruments, TX, USA). Temperature and oxygen sensors were connected to the data acquisition system (Puyuelo et al., 2010). Aeration was controlled through the oxygen uptake rate (OUR). The objective of the controller was to obtain an automatic airflow regulation in order to achieve the maximum measure of the biological activity without oxygen limitations. Complete details about this control, based on instantaneous OUR, can be found in Puyuelo et al. (2010).

2.7. Analytical methods and monitoring parameters

TS and VS were determined according to standard methods (APHA, 1999). Cellulose was determined according to the classical method by Soest and Wine (1968).

Alkalinity (measured as the concentration of $CaCO_3$ in g l^{-1}) was determined by titrating with H_2SO_4 0.5 M to pH 5.75 and 4.3. For VFA determination samples were previously centrifuged (30 min, 13500 rpm), filtered (0.45 μm) and then mixed (1/1, v/v) with a 0.2% pivalic acid solution as an internal standard. VFA (acetic, propionic, butyric, isovaleric and n-valeric acids) were determined by gas chromatography in a Hewlett Packard chromatograph (model HP 5890, Agilent Technologies, Barcelona, Spain) equipped with a flame ionisation detector (FID) and a Teknocroma (25% NPGA, 2% H_3PO_4) 2.7 m x 1/8" column. Nitrogen was the carrier gas at 230 kPa, and the oven, injector and detector temperatures were 130, 250 and 260°C, respectively. A total sample volume of 1 μl was used for chromatography. Total VFA concentration was expressed as grams of acetic acid per litre, which was the main compound found in VFA (most of the time, it was the only detected acid). The detection range was from 0.5 to 8 g [acetic acid] l^{-1}.

Methane and carbon dioxide content in the biogas were also analysed by means of a Hewlett Packard Chromatograph (HP 5890) equipped with a thermal conductivity detector (TCD) and a 3 m x 1/8" column (model Supelco Porapack Q, Supelco, Barcelona, Spain). Helium was the carrier gas at 338 kPa, and the oven, injector and detector temperatures were 70, 150 and 180°C, respectively. A total sample volume of 100 μl was used for chromatography (Pagans et al., 2007; Ponsá et al., 2011a).

Air filled porosity (FAS) in the composting reactor was measured using a self-made constant volume air pycnometer connected to the reactor. The method is carried out according to the description of Ruggieri et al. (2009).

3. Results and discussion

3.1. Organic fibre characterisation

3.1.1. Physicochemical characterisation

Table 1 shows the manual characterisation of the initial MSW and the final organic fibre obtained. During the autoclaving process paper and textile fibres deteriorate and are collected together with the organic fibre. As observed in Table 1, the organic fibre percentage after sieving the inert fractions (glass, plastic and metal) increases considerably as the paper and textile fractions are incorporated to this fraction by the result of the autoclaving process.

Also, during the autoclaving process, paints from cans and other packages are dissolved. This could be the cause of the slightly high heavy metal content found in organic fibre (Table 2). However, the values were not significantly higher than those found in mixed MSW in Spain (Huerta-Pujol et al., 2011a). A general mass balance of the autoclaving process with the main input and output flows of energy and materials are presented in Fig. 2.

Table 3 shows the characterisation of the organic fibre on basic parameters such as dry matter, pH, electrical conductivity, nitrogen, phosphorus and potassium contents. The values are similar to those found in the source-separated OFMSW (Ruggieri et al., 2008). Regarding the Kjeldahl nitrogen content of the organic fibre, it is in the low range when compared to source-separated OFMSW, which is usually between 2% and 3% (Ruggieri et al., 2008), whereas ammonia nitrogen values are within the typical range found in the OFMSW (0.02% to 0.2%) (Pognani et al., 2010).

Important components that were studied in the raw waste were fibres. During the autoclaving process, cellulose in the initial waste was reduced from 49% (d.m.b.) to 23% (d.m.b.) in the organic fibre, showing a significant hydrolysis under these conditions, hemicellulose content was low both in the initial waste (1.01%, d.m.b.) and the organic fibre (1.95%, d.m.b) and, as expected, lignin content significantly increased (from 11% to 31%, d.m.b.). These data show the different behaviour of fibres under autoclaving conditions and their resistance to chemical hydrolysis.

3.1.2. Biodegradability of the organic fibre

To characterise the biodegradability of organic fibres, the dynamic respiration index (DRI) and the specific anaerobic biodegradability assay (GB_{21}) were determined (Table 4). Both parameters are extensively used and accepted to determine the aerobic and anaerobic biodegradability, respectively (Ponsá et al., 2010). In the case of the input waste, the values obtained were lower than the typical values obtained for source-separated OFMSW (3500-5000 mg $[O_2]$ kg^{-1} [TS] h^{-1}), but close to the values observed with mixed MSW (1500-2500 mg $[O_2]$ kg^{-1} [TS] h^{-1}) (Barrena et al., 2011; Ponsá et al., 2011b). However, from the values presented in Table 4 and considering the inherent error of these methodologies, it can be concluded that the autoclaving of MSW has little effect on both the aerobic and anaerobic biodegradability of the material, although the values obtained in both cases were in the lower range of the OFMSW biodegradability values (Barrena et al., 2011). It is also interesting to note that no inoculum is used in the respiration tests; however, the organic fibre from autoclaving (which is apparently sterilised) does not present any delay in the activation of the biological activity, with similar values than those found in raw MSW (Barrena et al., 2011). It can be hypothesised that the strong autoclaving conditions are not able to deactivate the complex microbial autochthonous communities present in MSW.

Regarding the batch anaerobic tests (Table 4), the results obtained with organic fibre followed the same trend than those reported for DRI, with the highest values obtained for the OFMSW and a slightly lower value for the organic fibre when compared with unsorted MSW (Table 4). Recently, it has been reported that both aerobic and anaerobic biodegradability tests correlated well with the same type of wastes, although some deviations can be observed (Ponsá et al., 2008; Barrena et al., 2009). In some methodologies, where an inoculum is used for aerobic and anaerobic tests, both indices correlated well (Wagland et al., 2009).

3.2. Anaerobic digestion of the organic fibre

The thermophilic anaerobic digester was operated for a total time of 12 months where three experimental periods can be defined (Fig. 3). Start-up (Period I) lasted 80 days, in which the reactor was fed with diluted SS-OFMSW (TS = 40 g l^{-1}, VS = 35 g l^{-1}) and the TS content in the reactor was within 60-70 g l^{-1}. On the 22nd day the SS-OFMSW was changed for the autoclaved organic fibre and the organic loading rate (OLR) was increased from 1.6 kg [VS] m^{-3} d^{-1} to 4.4 kg [VS] m^{-3} d^{-1} during the rest of the experimental period to acclimatise the microbial communities to the new feedstock.

The second period (130 days, Period II) is characterised to try to reach a steady state with the final OLR of Period I. The TS content in the reactor was within 50-60 g l^{-1}. However, this steady state was not reached, probably because the OLR value was excessively high. Stentiford (2010) concluded that there was a general trend towards less stable operating conditions as the loading rate is increased, specially under thermophilic conditions (Ferrer et al., 2010). Thus, the digester was within stable limits at a loading rate of 3 kg [VS] m^{-3} d^{-1}, but there was general deterioration at higher loading rates. Finally, a third operation period (Period III, until the end of experiment) was started when the OLR was readjusted to 3 kg [VS] m^{-3} d^{-1} until the end of the experiment. The TS content in the reactor for this final period was within 60-70 g l^{-1}. The complete characterisation of these three periods is shown in the Table 5 and presented in Fig. 3.

Biogas yield values were lower than those found in similar experiments with non-autoclaved SS-OFMSW, which are around 60% of VS removal and 0.24 l [CH_4] g^{-1} [VS] (Martín et al., 2010). However, the values are similar to other experiments with autoclaved organic matter, which are within 30-50% VS removal (Stentiford, 2010) and 0.15-0.18 l [CH_4] g^{-1} [VS] (Papadimitriou, 2007). This low anaerobic biodegradability might be caused by the presence of plastics melted with the organic matter that makes this organic matter less available to the anaerobic microorganisms. Additionally, some studies have confirmed that the presence of plastics in the feed might interfere with biodegradability, although in this case the presence of plastics attached to the organic fibre could not be confirmed (Fig.e 1). Banks (2008) found evidence that plastic autoclaved together with newsprint could have an inhibitory effect on the anaerobic activity of the fibre produced by autoclaving.

Another hypothesis to consider could be the Maillard and caramelisation reactions (Papadimitriou, 2010). Maillard reactions involve primarily the reaction of reducing sugars and amino-compounds (e.g. amino acids and proteins) to produce mainly soluble but also insoluble polymers, particularly at high temperatures, low water activity, and pH higher than 4.5. In this study, reducing sugars could have been produced from the hydrolysis of cellulose (Papadimitriou, 2010). These reactions can product compounds that are not easily biodegradable under anaerobic conditions (Delgenès et al., 2003; Stuckey and McCarty, 1984).

3.3. Composting of the organic fibre

The composting reactor was operated during 20 days (Fig. 4). Organic fibre was mixed with wood chips as bulking agent to ensure a minimum value of air filled porosity of 60% prior to the experiment (Ruggieri et al., 2009), since in previous experiments a delay in the start-up of the composting process was detected, when the porosity of the organic fibre (30%) was not adjusted. These wood chips were obtained from the recirculated bulking agent of a full-scale composting plant. As shown in Fig. 4, the maximum value of temperature was 75ºC and it was obtained at the first day of process time. The biological activity measured as OUR also increased in the first stage of the process. This OUR control ensures that no oxygen limitation occurs (Fig. 4). The process was stable at 75ºC for 5 days approximately since during this period a high availability of the easy biodegradable compounds is assumed (Gea et al., 2004). It was also observed that temperature was maintained at high values for a large period of time even though the biological activity decreased. This behaviour has been observed in other lab-scale composting processes (Puyuelo et al., 2010) and, obviously, at full-scale composting piles (Barrena, 2006). Temperature slowly decreased to 70ºC and afterwards a drop to 60ºC was observed. Temperature was stabilised again for 13 days followed by a considerable decreasing period to 40ºC. At this point the low airflow needed indicates the end of the microbiological activity, as it can be observed in the low values of OUR (Fig. 4). In summary, the composting process was properly developed and no sign of delays in the aerobic biological activity could be observed when using a bulking agent to adjust a proper value of porosity.

3.4. Characteristics of compost from organic fibre

The main characteristics of the final product obtained from the composting process of the organic fibre are show in the Table 6. The values corresponding to the regulation in Spain for compost (Ministerio de la Presidencia, 2005) are also presented for comparison. The results show a great reduction of the DRI value, which means a complete stabilisation of the organic matter from the fibre. Moreover, the rest of parameters are within the normal values found for compost of the OFMSW (Ruggieri et al., 2008; Colón et al., 2010). The exception is found for several heavy metals such as lead (54 mg kg^{-1}), which is slightly over the limit for compost class A and especially copper and zinc (148 and 387 g kg^{-1}, respectively). The levels of these metals would classify this compost as class B, although the limits for these metals in class B are far from those found in compost from organic fibre (limits for class B compost: zinc: 500 mg kg^{-1}; copper: 300 mg kg^{-1}; lead: 150 mg kg^{-1}).

4. Conclusions

As a general conclusion, it can be stated that the organic fibre obtained in the autoclaving process can be further biodegraded under anaerobic or aerobic conditions. Preliminary experiments suggest that the organic fibre can be successfully composted obtaining a stable product that corresponds to class B compost. Also, the organic fibre can be anaerobically digested although the biogas yield and the VS removal were lower than those obtained from the anaerobic digestion of the source-separated OFMSW. Further research is necessary to confirm these results, especially in terms of scale-up of the anaerobic digestion process and its performance under different operating conditions.

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Tables

Table 1. Manual characterization of the starting mixed municipal solid waste (MSW) and the obtained organic fibre. Results are presented as weight percentages. Weight losses during MSW characterisation (250 kg) were 5.2%.

	Organics* (%)	Glass (%)	Metals (%)	Plastic (%)	Textile (%)	Other (%)
MSW	61.42	4.85	2.65	16.12	3.01	6.74
Organic fibre**	93.75	1.53	0.2	3.68	0	0.25

* It includes kitchen and garden wastes and paper.

** Once separated after autoclaving.

Table 2. Heavy metal content of the unsorted MSW, OFMSW and organic fibre obtained from the autoclaving process. Values for MSW and the OFMSW are calculated from average values (Huerta-Pujol et al., 2011b). Spanish legislation for compost according to Ministerio de la Presidencia (2005).

Metal	Cd	Cr	Cr(VI)	Cu	Hg	Ni	Pb	Zn
Organic fibre (mg kg^{-1}, dry basis)	1.1	79	<0.5	79	<0.01	40	111	304
Unsorted MSW (mg kg^{-1}, dry basis)	1.1	31	0	110	<0.01	33	103	279
OFMSW (mg kg^{-1}, dry basis)	0.41	13	0	93	<0.01	13	26	253
Spanish legislation (Class A)	0.7	70	0	70	0.4	25	45	200
Spanish legislation (Class B)	2	250	0	300	1.5	90	150	500
Spanish legislation (Class C)	3	300	0	400	2.5	100	200	1000

Table 3. Chemical characterisation of the unsorted MSW, OFMSW and organic fibre obtained from the autoclaving process. Values for MSW and the OFMSW are calculated from average values (Huerta-Pujol et al., 2011b).

Parameter	Dry matter (%, w.b.) *	pH	Electrical Conductivity (μS cm^{-1})	N Kjeldahl (%, d.b.)**	N-NH_3 (%, d.b.)	P (%, d.b.)	K (%, d.b.)
Organic fibre	46.0	5.65	3.94	2.14	0.10	0.58	0.47
Unsorted MSW	63.2	6.87	2.48	1.70	0.12	0.44	0.56
OFMSW	20.4	5.62	2.58	2.53	0.07	0.58	1.14

* wet basis

** dry basis

Table 4. Biodegradability assays (VS, volatile solids content, GB_{21} and Dynamic respiration Index, DRI, based on total solids, TS) for organic fibre and unsorted municipal solid waste (MSW).

	VS content (% on TS basis)	GB_{21} (l [biogas] kg^{-1} [TS])	DRI (mg [O_2] kg^{-1} [TS] h^{-1})
MSW	70.2	313 ± 21	1322 ± 113
Organic fibre	76.9	251 ± 22	1575 ± 116
OFMSW	79.6	393 ± 7	3600 ± 110

Table 5. Characterisation of the three anaerobic digestion periods. Abbreviations: OLR: organic loading rate; HRT: hydraulic retention time; VS: volatile solids.

Parameter	**Units**	**Period I**	**Period II**	**Period III**
OLR	kg [VS] m^{-3} d^{-1}	1.6 - 4.4	4.4	3
HRT	d	16 - 80	16	23.7
pH	-	7.5	7.11	7.01
Biogas yield	l [biogas] g^{-1} [VS]	-	0.15	0.19
CH_4	%	-	60.5	56.1
Methane Yield	l [CH_4] g^{-1} [VS]	-	0.09	0.107
VS removal	%	-	28.9	25.8
Alkalinity	g [$CaCO_3$] l^{-1}	0.27	0.33	0.49
Total VFA	g [acetic acid] l^{-1}	<0.5	<0.5	<0.5

Table 6. Properties of the final compost obtained from the autoclaved organic fibre. Spanish legislation for compost according to Ministerio de la Presidencia (2005).

Parameter	**Compost from organic fibre**	**Spanish legislation (Class A/B/C for heavy metals)**
Dry matter content (%)	63.1	60-70
Organic matter content (%, dry basis)	77.6	>35
pH (1:5 w:v extract)	8.06	No value
Elec. conductivity (1:5 w:v extract, mS cm^{-1})	3.1	No value
Nitrogen (Kjeldahl) (%, dry basis)	2.86	No value
C/N ratio	14	<20
Respiration index (mg [O_2] kg^{-1} [TS] h^{-1})	504	No value
Bulk density (kg l^{-1})	0.35	No value
Air filled porosity (%)	53.8	No value
E.coli (CFU/g)	<20	<1000
Salmonella (presence/absence in 25 g)	absence	absence
Nickel (mg kg^{-1}, dry matter basis)	22	25/90/100
Lead (mg kg^{-1}, dry matter basis)	54	45/150/200
Copper (mg kg^{-1}, dry matter basis)	148	70/300/400
Zinc (mg kg^{-1}, dry matter basis)	387	200/500/1000
Mercury (mg kg^{-1}, dry matter basis)	0.13	0.4/1.5/2.5
Cadmium (mg kg^{-1}, dry matter basis)	0.5	0.7/2/3
Chromium (mg kg^{-1}, dry matter basis)	43	70/250/300
Chromium VI (mg kg^{-1}, dry matter basis)	Not detected	Not detected

Legends to Figures

Fig. 1. Transmission electron microscopy (TEM) images of the organic fiber. a) and b) correspond to different resolution.

Fig. 2. General mass balance of the autoclaving process with the main input and output flows of energy and materials (MSW: unsorted municipal solid waste; PET: polyethylene terephthalate). Calculation basis is 100 kg of municipal solid waste.

Fig. 3. Evolution of the three periods of the anaerobic digestion of organic fibre. Figure presents the biogas yield, OLR (organic loading rate) and VS (volatile solids) removal. All the parameters are presented as the average values during two weeks. Vertical lines correspond to the three periods of operation (I, II and III).

Fig. 4. Evolution of the composting process of organic fibre. On-line temperature, oxygen content and oxygen uptake rate (OUR) are presented.

Fig. 1

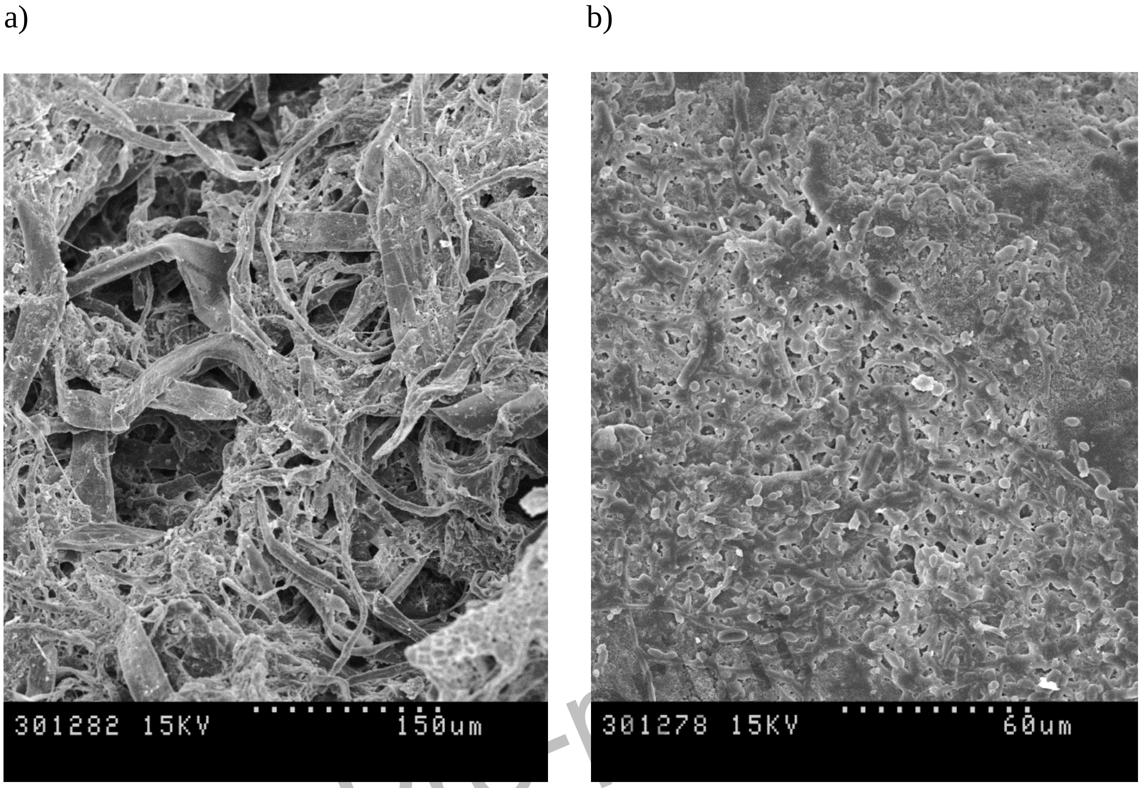


Fig. 2

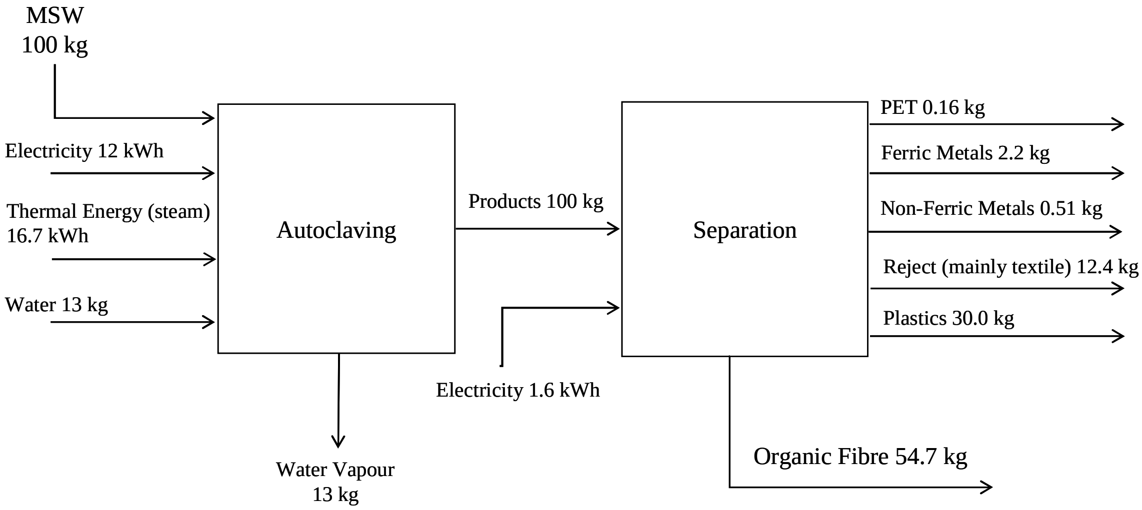
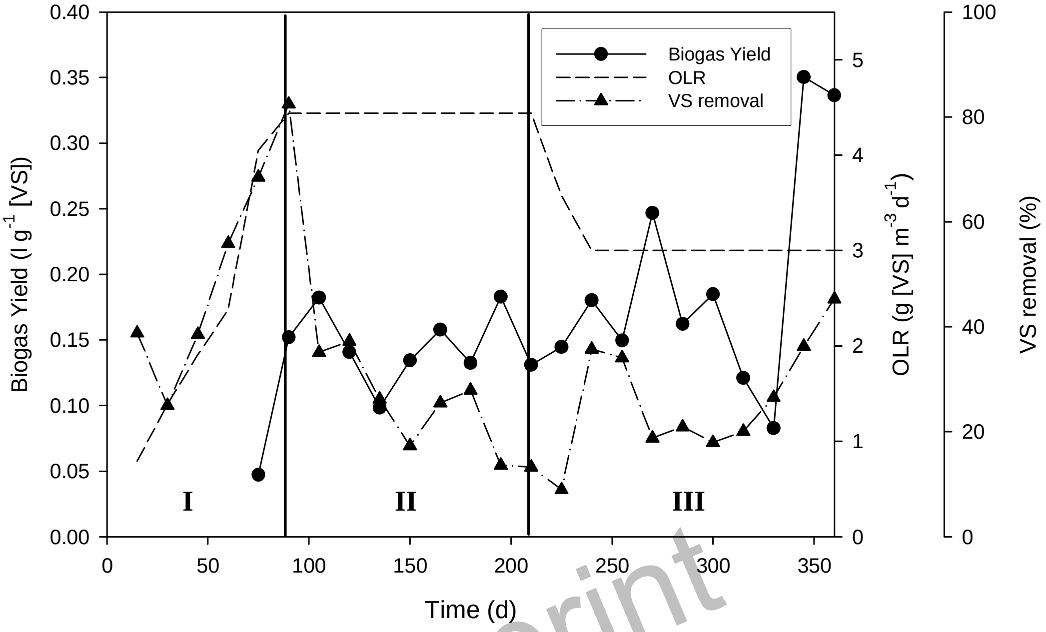
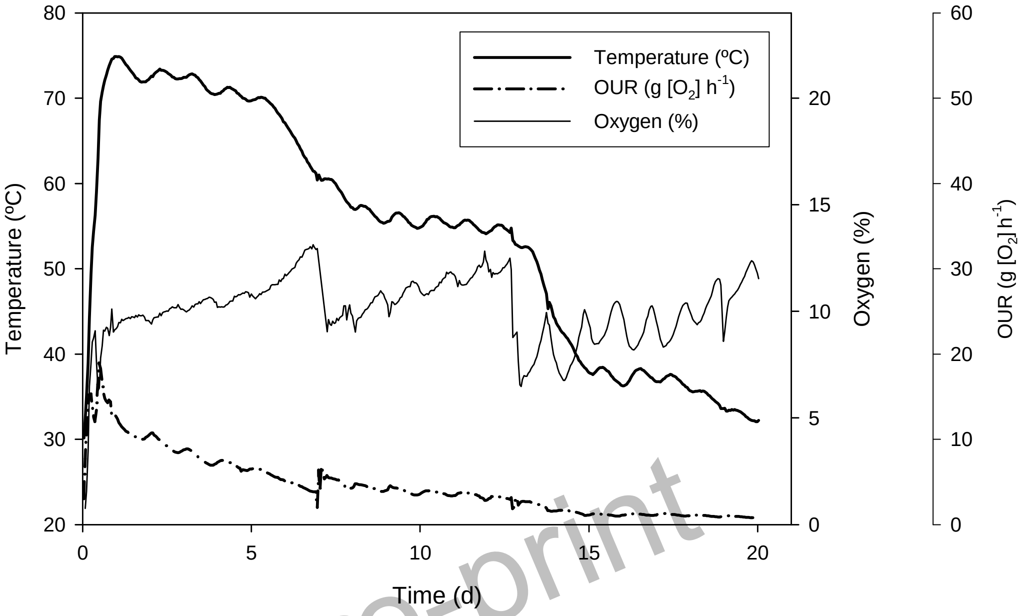

MSW
100 kg
Electricity 12 kWh
Thermal Energy (steam)
16.7 kWh
Water 13 kg
Autoclaving
Water Vapour
13 kg
Products 100 kg
Electricity 1.6 kWh
Separation
PET 0.16 kg
Ferric Metals 2.2 kg
Non-Ferric Metals 0.51 kg
Reject (mainly textile) 12.4 kg
Plastics 30.0 kg
Organic Fibre 54.7 kg

Fig. 3



Biogas Yield (l g^{-1} [VS])
0.00
0.05
0.10
0.15
0.20
0.25
0.30
0.35
0.40
OLR (g [VS] m^{-3} d^{-1})
0
1
2
3
4
5
VS removal (%)
0
20
40
60
80
100
Time (d)
0
50
100
150
200
250
300
350
I
II
III
Biogas Yield
OLR
VS removal

Fig. 4


Temperature (ºC)
OUR (g [O$_2$] h^{-1})
Oxygen (%)
Temperature (ºC)
Oxygen (%)
OUR (g [O$_2$] h^{-1})
Time (d)
80
70
60
50
40
30
20
0
5
10
15
20
60
50
40
30
20
10