In search of a reliable technique for the determination of the biological stability of the organic matter in the mechanical-biological treated waste

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Abstract

The biological stability determines the extent to which readily biodegradable organic matter has decomposed. In this work, a massive estimation of indices suitable for the measurement of biological stability of the organic matter content in solid waste samples has been carried out. Samples from different stages in a Mechanical-Biological Treatment (MBT) plant treating municipal solid wastes (MSW) were selected as examples of different stages of organic matter stability in waste biological treatment.

Aerobic indices based on respiration techniques properly reflected the process of organic matter biodegradation. Static and dynamic respirometry showed similar values in terms of aerobic biological activity (expressed as Oxygen Uptake Rate, OUR), whereas cumulative oxygen consumption was a reliable method to express the biological stability of organic matter in solid samples. Methods based on OUR and cumulative oxygen consumption were positively correlated. Anaerobic methods based on biogas production (BP) tests also reflected well the degree of biological stability, although significant differences were found in solid and liquid BP assays. A significant correlation was found between cumulative oxygen consumption and ultimate biogas production.

The results obtained in this study can be a basis for the quantitative measurement of the efficiency in the stabilization of organic matter in waste treatment plants, including MBT plants, anaerobic digestion of MSW and composting plants.

Keywords: Biogas, Composting, Mechanical-Biological Treatment Plant, Municipal Solid Wastes, Respirometry, Waste Treatment.

Notation

AT_4: Cumulative oxygen consumption during 4 days (g O_2/kg DM)

BOD: Biochemical Oxygen Demand (g O_2/L)

BP_{LF}: Biogas Production, liquid sample, final (L/kg DM)

BP_{L21}: Biogas Production, liquid sample, 21 days (L/kg DM)

BP_{SF}: Biogas Production, solid sample, final (L/kg DM)

BP_{S21}: Biogas Production, solid sample, 21 days (L/kg DM)

COD: Chemical Oxygen Demand (g O_2/L)

DM: Dry Matter (%)

DOC: Dissolved Organic Carbon (g C/L)

DRI_i: Dynamic Respiration Index, instantaneous (g O_2 kg DM^{-1} h^{-1})

DRI_{24h}: Dynamic Respiration Index, average of maximum values during 24 h (g O_2 kg DM^{-1} h^{-1})

DRI_{max}: Dynamic Respiration Index, absolute maximum (g O_2 kg DM^{-1} h^{-1})

VS: Volatile Solids (%, Dry Matter basis)

SRI: Static Respiration Index (g O_2 kg DM^{-1} h^{-1})

TOC: Total Organic Carbon (%, Dry Matter basis)

1. Introduction

The growing environmental awareness reflected in the last legislative documents (European Commission, 2001; 2003) has lead to an increasing number of treatment plants designed for treating different organic wastes with the aim to avoid or reduce landfilling of non-stable organic materials. The bulk municipal solid waste stream (MSW, which can contain a range of 40-60% of organic materials) and the source-selected organic fraction of municipal solid waste (OFMSW, with an organic content over 80%) have deserved special attention from the European authorities. As a result, MSW and OFMSW are being treated in a large number of different facilities such as mechanical-biological treatment (MBT), anaerobic digestion (often called "methanization") and composting plants. The main objectives of these plants is to reduce the content of the biodegradable organic matter in order to reduce the impacts of waste (e.g., odor production, self-heating and self combustion, biogas production, leachate and pathogen re-growth) when landfilled. Low impact means high biological stability of the organic matter as this parameter correlates well with waste impacts (Muller et al., 1998).

A current definition of biological stability was proposed by Lasaridi and Stentiford (1996), i.e, biological stability determines the extent to which readily biodegradable organic matter has decomposed. It identifies the actual point reached in the decomposition process and represents a gradation on a recognized scale of values, which thus enables comparison of the process of decomposition.

If the treatment efficiency of these plants is to be evaluated then a representative measure of the biological stability, must be used. This measure would permit the evaluation of current

working plants, the improvement of the biological treatment process, the design of optimized facilities and the potential impact of the final products.

Traditionally total organic matter content (OM) measured as volatile solids (VS) has been used to monitor the evolution of composting processes (Komilis and Ham, 2003). However, when VS content is used in MSW streams, it results in an overestimation of its biodegradable organic matter content because of the presence of non-biodegradable volatile materials such as plastics which are not biodegradable under the normal operating conditions found in MBT, anaerobic digestion or composting plants. Moreover VS content depends by raw material and, as it is a quantitative parameter and not qualitative it does not represent a correct measure of the waste impact. Other related measures such as total organic carbon (TOC) (Ros et al., 2006) or dissolved organic carbon (DOC) (Fontanive et al., 2004) have been used, also, for this purpose, but they suffer of the same problem indicated for VS.

A research on the development of analytical methods or indices to be used as a measure of the biological stability in solid materials is at present being carried out (Adani et al., 2003; Cooper, 2005; Barrena et al., 2006a). This is not the case of the wastewater field, where a standard and accepted method for the determination of readily biodegradable organic matter exists: the Biochemical Oxygen Demand (BOD). However, in the solid waste treatment, there is no a consensus within the research community. At this moment, some assays have been developed, under aerobic (Scaglia et al., 2000; Adani et al., 2001; Adani et al., 2004a; Barrena et al., 2005) and anaerobic conditions (Ligthart and Nieman, 2002; Hansen et al., 2004). These assays are usually based on respirometric techniques (static and dynamic) and methanogenic activity assays.

The developed tests have been used for different purposes such as the monitoring of a biological treatment process of organic wastes or the characterization of the biological stability of the final product obtained (Adani et al., 2004b; Sugni et al., 2005; Adani et al., 2006; Barrena et al., 2006b). Also oxygen uptake rate (OUR) has been used to estimate the production term in the resolution of energy and mass balances for process modelling (Richard et al., 2002; Barrena et al., 2006c; Komilis, 2006).

At present, some standards have been already proposed (ASTM, 1996; U.S. Department of Agriculture and U.S. Composting Council, 2001; Cooper, 2005). Some of these methods have been also considered in the European legislation drafts (European Commission, 2001) and adopted in national regulations by some European countries such as Germany (Federal Government of Germany, 2001), Italy (Favoino, 2006), Spain (ARC, 2006) or England and Wales (Godley et al., 2005).

Table 1 shows the test conditions for some of the national standards defined for biological stability determination under aerobic and anaerobic conditions. As can be observed, the methodologies proposed differ in many key aspects such as the use of an inoculum, the amount of sample to be used, the water content, the assay temperature (mesophilic or thermophilic) or the test duration. Moreover, even the expression of the results (oxygen uptake rate or cumulative consumption) and the units (dry or organic matter basis) are different among the test published.

Although some authors present partial comparisons between static and dynamic respirometric approaches or some correlations between indices used for biodegradable organic matter determination (Adani et al., 2003; Gea et al., 2004; Barrena et al., 2005), this is, to our knowledge, the first study where a massive comparison of indices and methods is

carried out. The objectives of this research are therefore: i) to study the suitability of the methods proposed by different authors or institutions for the determination of the biological stability in samples from a MBT plant, which were obtained at different stages of their biodegradation; ii) to compare the two main groups of methods proposed (aerobic and anaerobic), iii) to determine the correlations among the methods studied and iv) to determine the efficiency of the treatment of biodegradable organic matter in the MBT studied, based on some selected indices.

2. Materials and Methods

2.1 Materials

Samples were obtained from a Mechanical-Biological Treatment (MBT) plant that treats MSW. Samples were collected during October-November 2005 at the following days of the biological treatment process: 0 (initial sample), 32, 42 and 63 (final sample). Analytical methods were carried out on a representative sample (20 kg) obtained by mixing 9 increments of about 2 kg each, took from different points through the material.

2.2. Mechanical-Biological treatment plant

The MBT plant studied is located in the province of Umbria (Italy). Non-selected MSW were mechanically pre-treated by a sieve with a cut-off of 50 mm. The fraction of material with a size smaller than 50 mm (40 % of the total income) was biologically treated using an aerobic process. This process consisted of an aerated (specific air-flow supplied was of 10 $m^3\ h^{-1}\ Mg^{-1}$ wet weight) and turned windrow (turning and watering occurred twice a week),

which is typically used in composting systems. The normal operation of the plant is a biological process of 45 days to obtain a stabilized product prior to landfilling according to local regulations (dynamic respiration index below 1 g O_2 kg OM^{-1} h^{-1}). In the results presented, the biological process was extended to 63 days for the purpose of this study. A schematic diagram of the MBT plant is shown in Figure 1.

2.3. Expression of biological indices

As it has been commented in Table 1, biological indices are both expressed in two bases: dry matter (DM) and volatile solids (VS). In this work, the basis selected for the expression and comparison of the studied indices has been dry matter. This selection is based on the presence in MSW of significant amounts of non-biodegradable volatile matter (e.g. plastics), which is accounted in the volatile solids determination obtained by combustion of the sample.

2.4. Aerobic methods

2.4.1. Dynamic methods

The Dynamic Respiration Index (in general, DRI) was measured using the method suggested by Adani et al. (2001; 2004a; 2004b), which is determined in a 20-L adiabatic respirometric reactor (Costech International, Cernusco S.N., Italy; DiProVe, Milan, Italy). The respirometer consists of an insulated container (the respirometric reactor), a control cabinet, an air supply system, a personal computer and a biofilter. A Clark-type temperature compensation electrode and a differential-pressure electronic transmitter ensured both oxygen and airflow measurements every 10 s. The instantaneous data were then sent to in-

house developed software for DRI calculation. An extensive description of the scientific apparatus was previously reported by Adani et al. (2001).

The oxygen uptake rate obtained under dynamic conditions was determined by measuring the difference in oxygen concentration (mL/L) between the inlet and outlet air flow that had passed through the biomass. The Instantaneous Dynamic Respiration Index (DRI_i) was then calculated as:

$$DRI_i(g\ O_2\ kg^{-1}\ DM\ h^{-1}) = \frac{Q \cdot \Delta O_2 \cdot 31.98}{1000 Vg \cdot X_{DM}} \qquad (1)$$

where DRI_i is the instantaneous DRI, Q (L/h) the airflow, ΔO_2 (mL/L) the difference in oxygen concentration in the inlet and outlet air flow of the reactor, 1000 is the conversion factor from mL to L, Vg (L/mol) the volume occupied by one mole of gas at inlet air temperature, 31.98 (g/mol) is the molecular weight of O_2, and X_{DM} (kg) the weight of dry total solids of the sample.

Tests were performed setting an O_2 concentration of 140 mL L^{-1} (14%) in the outlet airflow to ensure aerobic conditions during the entire DRI measurement, by means of a feed-back control that automatically adapted the airflow rate. Test lasted 96 h and during this time oxygen concentration and DRI measurements were recorded hourly. Each trial was made in one replicate, because of the large amount of representative sample used (10-15 kg), which is considered representative of the material (Adani et al., 2001).

The degree of biological stability measured by DRI was calculated using three methods representing different ways of expressing DRI from the value of DRI_i:

i) DRI_{24h}: the average value of 12 instantaneous respiration indices (DRI_i) obtained during the 24 h of the most intense biological activity (highest values of DRI_i).
ii) DRI_{max}: the instantaneous maximum respiration rate registered during the entire test.
iii) AT_4: the cumulative value of oxygen consumption recorded during 96 h (4 days). This value was obtained by numerical integration of DRI_i values obtained during 96 h.

2.4.2. Static method

Static Respiration Index (SRI) was determined using a static respirometer based on the model previously described by Ianotti et al. (1993) and according to the method described by Barrena et al. (2005). Briefly, the drop of oxygen content in a flask containing a waste representative sample (250 g) was monitored with an oxygen meter (Lutron 5510, Lutron, Taiwan) connected to a personal computer (RS232 communication protocol) with in-house developed software to register oxygen values. Assay temperature was fixed at 37ºC. Previously to the respirometric test, samples were adjusted to a moisture content of 50-60% and incubated during 18 h at this temperature. During incubation samples were continuously aerated with previously humidified air at the sample temperature. Once incubation was finished, air supply was stopped and drop of the O_2 level was recorded every 15 s for 90 min. In all the SRI determinations three replicates were used, being the standard deviation in the range of 10% (Barrena et al., 2005). After oxygen measurement, the total volume of free air space in each sample flask was determined. The SRI of the sample was calculated from the slope in a linear segment on the chart O_2 (%) versus time using:

$$\text{SRI}\,(\text{g } O_2 \text{ kg}^{-1} \text{ DM h}^{-1}) = \frac{V \cdot P \cdot 31.98 \cdot s \cdot 60}{R \cdot T \cdot X_{DM}} \qquad (2)$$

where V (L) is the volume of air in the flask, P (atm) the atmospheric pressure at elevation of measurement (atm), 31.98 (g/mol) the oxygen molecular weight, 60 the conversion factor from minutes to hours, s (mol O_2 mol^{-1} min^{-1}) the slope of the oxygen drop during the respiration test in O_2 percentage per minute divided by 100, R (0.08206 L atm mol^{-1} K^{-1}) the ideal gas constant, T (K) the temperature (37ºC), and X_{DM} (kg) the weight of dry total solids of the sample.

2.5. Anaerobic methods. Biogas production

2.5.1. Solid state

200 g of a wet representative waste sample were used in this test. Sample was mixed in a weight ratio 1:1 with an inoculum coming from the output of an industrial solid state anaerobic digester located in Barcelona (Spain). No water was added to this mixture.

The mixture was incubated in a water bath at 35ºC in a sealed aluminium bottle with a working volume of 1 L. Before each experiment, the bottles were purged with nitrogen gas to ensure anaerobic conditions. The bottle was provided with a ball valve connected to a pressure digital manometer, which allowed the determination of the biogas pressure. The bulk density of the mixture was determined in order to calculate the headspace volume of the bottles. During the test, the bottles were shaken once a day. The results on biogas production were obtained from the pressure in the bottle and the headspace volume. Excessive pressure in the bottle was released by purging the biogas produced (25-30 times during the experiment). Biogas composition was also routinely measured.

The tests were carried out in triplicate and the results obtained at 21 days (BP_{S21}) and at the end of the test when no significant biogas production was detected (BP_{SF}) are expressed as biogas volume (L) produced at normal conditions (T=273 K, P=1 bar) per kg of dry matter. A triplicate measure of the inoculum biogas production was carried out as a blank and deducted from the biogas production of the waste samples. None of the samples analysed presented acidification due to an excessive production of volatile fatty acids.

Biogas composition was analysed by gas chromatography (Perkin-Elmer AutoSystem XL Gas Chromatograph) with a thermal conductivity detector and using a column Hayesep 3m 1/8" 100/120. Volatile fatty acids (VFA) were determined by gas chromatography (Perkin-Elmer AutoSystem XL Gas Chromatograph) with a flame ionization detector (FID) and a column HP Innowax 30 m x 0.25 mm x 0.25 µm. The details of biogas and VFA analysis can be found elsewhere (Fernández et al., 2005).

2.5.2. Liquid state

The test is similar to that of the solid state and the results are expressed in the same units. The dried samples were ground mechanically until a diameter of about 1 mm was achieved (standard size). The samples that were 1 mm in size were inserted into 60 ml glass vials with a stopper equipped with a metal ring and a pierceable silicon septum and incubated in a thermostat bath at 35°C. 1 ml syringes were used for biogas sampling. Their pistons were lubricated with silicon fat to permit movement when even only slight pressure developed inside the vials. Upon closure nitrogen was insufflate continuously to guarantee

perfect anaerobiosis. One grams of sample (on DM basis) plus 1 gram (on DM basis) of inoculums (sludge) were inserted into all the vials and enough distilled water was added to achieve a DM content of 50 g kg^{-1} wet weight. Thereafter the quantitative production of biogas (expressed in mL) was measured and so was the relative composition by means of gas chromatography using a gas chromatograph (Carlo Erba MegaSeries 5300, Italy), with a Mega capillary column about 25 m long, with ∅ 0.32 mm and flame ionization detector (FID). The gas used as carrier was nitrogen at the pressure of 20 kPa, whereas the flame was fed with a 2:1 mixture of air and hydrogen (v/v), the temperatures for injector and FID were 150 e 350 °C, respectively, whereas the oven was maintained constant at 35 °C. Tests were carried out in triplicate within the research.

2.6. Analytical methods

Representative samples of the material from different locations of the pile processed were used to carry out all the analytical tests. Moisture (sometimes expressed as dry matter or total solids), volatile solids (VS), pH, total organic carbon (TOC) and dissolved organic carbon (DOC) were determined according to the standard procedures (APHA, 1998).

The biochemical oxygen demand (BOD_5) and the chemical oxygen demand (COD) were determined using waste elutes. Elutes were obtained by water-extraction of waste using distillate water (1:10 ratio solid liquid) for 24 hours under shaking (UNE-EN 12457-4:2002). Analyses were performed in triplicate.

3. Results and discussion

3.1. Physico-chemical parameters

In the characterization of samples from the MBT plant, the first step was to carry out the analysis of some selected chemical parameters related to the biodegradation process. The results are summarised in Table 2. Moisture content presented a significant decrease during the aerobic treatment of MSW, though moisture was added during the process. This is a typical behaviour that can be found in similar processes such as composting, since the increase of temperature to the thermophilic range implies water vaporization (Haug, 1993), in a phenomenon called "biodrying" (Sugni et al., 2005). In the case of the MBT plant studied, the material was in the range of 50-60ºC during approximately three weeks, which permitted both waste biodrying and sanitation. On the other hand, pH showed a progressive tendency to alkalinisation, which is also typical in composting processes because of ammonia generation (Haug, 1993).

The rest of chemical parameters studied (VS, COD, TOC and DOC) presented in Table 2 are directly related to the content of organic carbon present in waste samples. However, none of these methods is capable of discerning between biodegradable and non-biodegradable organic matter, since the principle of the methods is the material combustion or strong chemical oxidation. This fact poses important problems when the efficiency of biological treatments is to be evaluated in working plants or selected in the design of waste treatment plants. In the MBT studied, the reduction observed in the values of these parameters after the biological treatment is poor in all cases (Table 2), when compared to biological indices, as it will be discussed later. The reason in this case is probably the high content of non-biodegradable organic materials that are usually present in MSW streams (typically plastics), moreover chemical parameters do not take into account for qualitative

aspects of organic matter such as biological indicators. The results obtained in the MBT plant are similar to those found in composting processes (Gea et al, 2005). Other authors had previously found that COD did not show clear trends and did not allow any conclusions about compost stability (Lasaridi and Stentiford, 1998). In any case, it seems evident that these parameters should not be considered in the study of waste treatment plants based on biological process. This fact is also confirmed by the poor correlation found between biological and chemical methods (Table 4), which will be discussed later.

3.2. Aerobic indices

The results obtained in the study for different aerobic indices based on respirometric techniques are presented in Table 3. Among them, BOD_5 is universally used in the wastewater treatment field, whereas the rest of parameters (generically called respiration index) are commonly used in the composting field (Adani et al., 2003; Gea et al, 2004). The reduction results obtained for these indices showed a high efficiency of the biological treatment used in the MBT plant when compared to reductions calculated from chemical data (Table 2). The lowest reduction resulted for the BOD_5, which can be due to the use of a liquid extract of the waste, instead of using the waste itself, as it is done in respiration techniques. In fact, it was possible to estimate AT_4 values from BOD_5 values in Table 2 and considering the dry matter content of the samples (data not shown). The results of this estimation showed a good approximation of AT_4 values from BOD_5, except in the case of the initial sample, where the BOD_5 underestimated the AT_4 value. It is probable that this sample contented a significant amount of non-extractable biodegradable organic matter, which is not accounted in the BOD_5 test but is degraded in the AT_4 test, which uses the

solid sample. In the rest of the samples, as the biological process progresses, the biodegradable organic matter is in more soluble forms and, in consequence, extractable and measured in a BOD_5 test. In consequence, BOD_5 should not be used as a measure of the biological stability with fresh solid samples.

In relation to the use of respirometric techniques on solid state, the utilization of static or dynamic approaches, has been previously discussed, and the presence of a continuous air flow in dynamic systems favours the transport of oxygen to biomass and this results in DRI values higher than those of SRI (Scaglia et al., 2000). However, in the case of the samples studied, the differences between static and dynamic indices (DRI_{max} or DRI_{24h}) were minimal (Table 3) and the correlations among them were significant (Table 4). It is possible that the relatively high porosity found in MSW permitted an optimal oxygen diffusion that makes biological activity the rate limiting step even in static conditions. Nevertheless, it must be pointed that the system used for SRI determination has been previously optimized to minimize diffusion problems (put reference). In consequence, under these conditions, SRI can be an alternative to DRI methods to the study of MBT plants.

Other point that can be observed from Table 4 is the excellent correlations found between rate-based respiration indices (SRI, DRI_{max} and DRI_{24h}) and the cumulative oxygen consumption (AT_4). This fact is of special interest since cumulative consumption is used in some national regulations (Federal Government of Germany, 2001; Godley et al., 2005) or standard procedures (ASTM, 1996), probably due to the similarity with the BOD_5 test. Therefore, the use of SRI or DRI alternatively to AT_4 can permit to obtain stability data and to evaluate the efficiency of a MBT plant, in a shorter time (Adani et al., 2004a). According

to the aerobic biological indices, the reduction of biodegradable organic matter in the MBT plant studied is in the range of 70-80%, which is significantly higher than results obtained using chemical parameters only (Table 2 and 3).

3.3. Anaerobic indices

Anaerobic indices based on biogas or methane production have been used to monitor the biological treatment of solid wastes. However, their use is often limited to anaerobic digestion processes (Hansen et al., 2004; Fernández et al., 2005). In this work, two biogas production (BP) tests using solid and liquid conditions were assayed. For each sample, BP was measured at 21 days because some national regulations use the cumulative biogas production during 21 days as a requirement to consider a waste as stabilised (Federal Government of Germany, 2001). The ultimate biogas production was also determined.

The results obtained are presented in Table 5. It can be observed that BP followed an expected pattern according to the biological stability, however, there are significant differences between solid and liquid tests. Thus, BP carried out in suspended liquid state reflects properly the biological stability, with a final reduction in BP_L very similar to that obtained in aerobic respiration tests. The correlation between BP_L (both at 21 days and ultimate) and SRI, DRI_{24} and DRI_{max} is significant at $p<0.05$, whereas the significance between BP_L and AT_4 increases to $p<0.01$. These results demonstrate that anaerobic tests can be used to predict the stage of biodegradation of organic matter in solid waste samples. Also, as the biological process in the MBT plant studied is aerobic, these results can be interpreted in the sense that the organic matter biodegradation does not preferably affects aerobically biodegradable organic matter, because aerobic and anaerobic indices showed an

identical evolution profile. These results should be confirmed with other wastes and MBT plants configurations, including anaerobic digestion processes, where a different evolution of these indices may be expected if the anaerobic biodegradation affects preferably to a specific pool of anaerobically biodegradable organic matter. In any case, this is, to our knowledge, the first approximation to a quantitative determination of aerobically and anaerobically readly biodegradable fractions, i.e. biological stability, of organic matter in solid wastes.

Results of BP carried out using solid samples and inoculum are also shown in Table 5. The values of reduction of BP_S are significantly lower than those of BP_L. A possible hypothesis may be that anaerobic degradation in solid state was not complete. As no VFA were detected during the entire test, a possible explanation could be the difficulty in achieving a homogenous mixture to provide availability of substrate to microorganisms. This fact is more pronounced in the initial non-degraded sample, which presented a similar BP than that of 32-days sample (Table 5). In fact, there was no a statistically significant correlation between biogas production obtained at solid and liquid state (Table 4).

Nevertheless, from a practical point of view, an obvious drawback of the use of anaerobic methods is the long time necessary to complete the test. Even though a duration of 21 days of the anaerobic test is accepted, this value is far from aerobic tests (4 days at most for AT_4). Moreover, it must be pointed that other authors propose longer times to carry out methanogenic activity assays (Shin et al., 2001). In the present case, the ratio of biogas produced at 21 days vs ultimate BP is in the range of 55-80%. Although this type of correlations for anaerobic assays have not been found in literature, similar values are

obtained when comparing BOD_5 determined at five days and ultimate values in the field of aerobic wastewater treatment (Metcalf and Eddy, 2003).

3.4. Comparison between aerobic and anaerobic indices

As stated before, a complete correlation matrix among all the indices tested (chemical, aerobic and anaerobic) is presented in Table 4. Several useful conclusions can be extracted from Table 4. Firstly, there was a poor correlation between chemical and biological parameters, both aerobic and anaerobic. This fact demonstrates that the former should not be, in general, used for the study of waste treatment plants involving biological treatments.

On the other hand, the aerobic indices tested in this study, especially the group of respirometric indices, presented a high level of correlation among them, which clearly indicated that they can be used for the monitoring of biodegradation of organic wastes in MBT or related plants. Also, respirometric indices are strongly recommended when the overall efficiency of a waste treatment plant is to be evaluated.

Finally, it must be emphasized that anaerobic tests based on biogas production in liquid state also presented a high level of correlation with respiration tests. The ratio between cumulative ultimate biogas production (BP_{LF}) and cumulative oxygen consumption (AT_4) is 2.45 L biogas produced per gram of oxygen consumed, being this ratio practically constant during the entire aerobic process.

3.5. Future implementation of biodegradability indices in MBT plants

Today, there is an increasing growth of a solid waste treatment technology based on biological processes. However, the construction and operation of these new plants (MBT,

anaerobic or composting plants) has not been accompanied by a scientific knowledge of the engineering principles and the parameters to be followed to evaluate the efficiency of these facilities in the organic matter biodegradation. The use of indices based on biological properties of the samples to be studied (both aerobic and anaerobic) should be a starting point for the application of engineering and scientific criteria in the design of the future plants and the fulfilment of international requirements of stabilized solid wastes prior to landfilling.

4. Conclusions

From the results obtained it can be concluded that:

1) Aerobic indices based on respiration techniques and determined under different conditions are useful indicators of the biological stability. Respiration indices based on the rate of oxygen consumption or cumulative oxygen can be successfully used for the prediction of the biological stability in heterogeneous solid wastes.
2) Anaerobic methods based on biogas production correlated well with organic matter biodegradation, although significant differences were found in solid and liquid BP assays.
3) A significant correlation was found between cumulative oxygen consumption and ultimate biogas production, which indicated that both indices can be used to express the degree of biological stability and to monitor a MBT plant.
4) The results obtained in this research can be a basis for the quantitative measurement of the efficiency in the biodegradation of the readily organic matter, i.e. biological stability, in waste treatment plants, including MBT plants, anaerobic digestion of

MSW and composting plants. However, a general consensus (scientific and politic) is necessary to decide what indices are to be used to characterize these facilities.

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Tables

Table 1: Selection of parameters and conditions used in methods for the determination of biodegradable organic matter (OM: organic matter, DM: dry matter).

Reference	Inoculation	Amount of sample	Water Content	Temperature	Test duration	Results expression
Aerobic						
Adani et al., 2001	no	10-13 kg	75% water holding capacity	self-heated	< 4 days	mg O_2 kg VS^{-1} h^{-1}
ASTM, 1996	yes	500 g	50 %	58ºC	4 days expandable	mg O_2/g VS
Cooper, 2005	no	100 g	40 - 60 %	25ºC	7 days	mg CO_2 g DM^{-1} d^{-1}
Federal Government of Germany, 2001	no	40 g	saturation + empty filtration	20ºC	4 days + lag phase	mg O_2/g DM
Godley et al., 2005	yes	400 g	50%	35ºC	4 days	mg O_2/g DM or mg O_2/g VS
Anaerobic						
Federal Government of Germany, 2001	yes	50 g	50 g DM + 50 mL inoculum + 300 mL water	35ºC	21 days + lag phase	L/kg DM
Godley et al., 2005	yes	20 g	20 g OM + 50 mL inoculum + 200 mL solution	35ºC	100 days	L/kg OM

Table 2: Chemical parameters obtained in the samples from the MBT plant.

Sample	Moisture (%)	Volatile solids (%, DM basis)	pH	COD (g O_2/L)	Total Organic Carbon (%, DM basis)	Dissolved Organic Carbon (g C/L)
Initial (0 days)	48.1	50.4	6.78	5.72	26.1	2.01
32 days	37.1	44.1	7.05	6.47	23.6	2.27
42 days	28.7	45.8	7.32	4.02	20.1	1.65
Final (63 days)	17.4	47.8	8.34	3.56	19.7	1.39
Reduction (%)	-	-	-	37.8	24.5	30.8

Table 3: Results obtained for the different aerobic respiration indices on a dry matter basis.

Sample	BOD_5 ($g\ O_2\ L^{-1}$)	Static RI ($g\ O_2\ kg\ DM^{-1}\ h^{-1}$)	Dynamic RI (maximum) ($g\ O_2\ kg\ DM^{-1}\ h^{-1}$)	Dynamic RI (average 24 h) ($g\ O_2\ kg\ DM^{-1}\ h^{-1}$)	Cumulative AT_4 (4 days) ($g\ O_2/kg\ DM$)
Initial (0 days)	5.94	2.59	2.76	2.58	146
32 days	4.56	1.18	1.17	1.13	71.5
42 days	3.43	0.95	0.83	0.77	48.3
Final (63 days)	2.46	0.84	0.64	0.60	31.7
Reduction (%)	58.6	67.6	76.8	76.7	78.3

Table 4: Correlation matrix between chemical parameters and biodegradability (aerobic and anaerobic) indices. (Table it is not clear as it appear more a correlation matrix between all parameters than ……..(see title). Moreover what the number indicate ? Are they the regression coefficient ? I do not think so, please add this information, otherwise reader cannot understand the Table,)

	VS	COD	TOC	DOC	BOD	SRI	DRI_{max}	DRI_{24h}	AT_4	BP_{S21}	BP_{SF}	BP_{L21}	BP_{LF}
VS	1	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns
COD		1	2.18^{**}	ns	1.06^{*}	ns	ns	ns	ns	ns	ns	ns	ns
TOC			1	ns	0.48^{*}	ns	ns	ns	15.8^{*}	ns	ns	25.3^{*}	39.8^{*}
DOC				1	ns	ns	ns	ns	ns	ns	130^{*}	ns	ns
BOD					1	ns	ns	ns	32.3^{*}	ns	ns	52.2^{*}	80.2^{*}
SRI						1	1.19^{**}	1.11^{*}	61.4^{**}	ns	ns	93.8^{*}	150^{*}
DRI_{max}							1	0.93^{***}	52.0^{**}	ns	ns	80.0^{*}	127^{*}
DRI_{24h}								1	55.8^{**}	ns	ns	86.0^{*}	137^{*}
AT_4									1	ns	ns	1.56^{**}	2.45^{**}
BP_{S21}										1	2.00^{**}	ns	ns
BP_{S100}											1	ns	ns
BP_{L21}												1	1.56^{**}
BP_{LF}													1

***, **, *: significant at p<0.001, 0.01 and 0.05 respectively, ns; not significant

Table 5: Results obtained for the biogas production on a dry matter basis for solid and liquid phase. Biogas is expressed at 0ºC and 1 bar (normal conditions).

Sample	Biogas production (solid, 21 days) (L kg DM^{-1})	Biogas production (solid, final*) (L kg DM^{-1})	Biogas production (liquid, 21 days) (L kg DM^{-1})	CH_4 (%v/v)	Biogas production (liquid, final**) (L kg DM^{-1})	CH_4 (%v/v)
Initial (0 days)	110	172	238	66	352	64
32 days	109	185	139	64	187	57
42 days	83	112	92	72	100	57
Final (63 days)	57	76	55	74	78	74
Reduction (%)	48.2	55.8	76.9		77.8	

* end of biogas production was reached at 100 days

** end of biogas production was reached at 75 days for initial and 32-days sample and at 38 days for 42-days and final sample

Legends to Figures

Figure 1: Scheme of the Mechanical-Biological Treatment studied.

Fig. 1: Barrena et al.