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BIODEGRADABILITY DETERMINATION OF MUNICIPAL WASTE: AN EVALUATION OF METHODS

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SUMMARY: The Environment Agency is required to monitor the diversion of biodegradable municipal waste (BMW) from landfill. Reliable methods are needed to measure the biodegradability of municipal waste, both as mixed municipal waste and as individually separated fractions. An evaluation of several methods was carried out using a variety of organic materials typically found in municipal solid waste. The assessment considered biological and non-biological methods to determine which provides the best-fit surrogate measurement for relative waste biodegradability. The biological methods tested were: the aerobic specific oxygen uptake rate, dynamic respiration index tests, and the anaerobic biochemical methane potential test. The non-biological methods evaluated were: dry matter, loss on ignition, total organic carbon, total nitrogen, water extractable dissolved organic carbon, biological oxygen demand, chemical oxygen demand, lignin and cellulose content and cellulase hydrolysis. This paper also reviews how such tests can be used to measure the relative biodegradation of municipal waste and benchmark the relative diversion from landfill achieved by the pre-treatment of municipal waste in a mechanical biological treatment (MBT) process.

1. INTRODUCTION

The Landfill Directive 1999/31/EC (Council of the European Union 1999) set targets for member states to limit the current landfilling of biodegradable municipal waste (BMW). This is a significant waste stream; approximately 28 million tonnes of municipal solid waste (MSW) was produced in England in 2000/1, of which approximately 80% was landfilled. It is likely that initially, the biodegradable content of MSW will be deemed to be 68% in England and 62% in Wales. The amount of MSW generated is also increasing annually by ~3% each year.

Under the Waste and Emissions Trading (WET) Act 2003, DEFRA and the National Assembly Wales (NAW) will allocate annual allowances to each Waste Disposal Authority (WDAs) in England and Wales, and these will be reduced year on year. Each allowance will relate to one tonne of BMW, which can be landfilled by that authority. During the next year, the Landfill Allowances and Trading Schemes (LATS) Regulations will be published in England and the Landfill Allowances Scheme (LAS) Regulations will be published in Wales. Under these regulations, the Environment Agency will be responsible for monitoring the performance of WDAs to ensure that in each year they only landfill the amount of BMW for which they have allowances. The performance of each authority will be reported to DEFRA and NAW annually and to the European Commission for the years 2010, 2013 and 2020.

Some waste technologies produce outputs that may be landfilled, e.g. ash from an incinerator or treated waste from a mechanical biological treatment (MBT) process. To fulfil its monitoring role within the LATS/LAS regulations, the Environment Agency will need to assess the relative amount of BMW that has been removed by any treatment process. Additionally the criteria for acceptance of organic non-hazardous (treated) waste into landfills are to be set at the national level (European Commission 2002) and in the UK there is no means of assessing this at present.

The objective of this research project is to derive a means of assessing the biodegradable content of MSW that has been removed by treatment (and that which remains) prior to that waste being landfilled. This paper describes the results from an experimental evaluation of several methods identified in a review of organic waste characterization methods (Godley et al. 2003). The methods were used to characterize eleven different organic materials typically found in MSW (cellulose, newspaper, corrugated paper, vegetables, tinned meat, nappies, cotton sheets, wool, twigs, grass clippings and greenwaste compost). This paper also discusses the application of these methods for monitoring the reduction in biodegradability of MSW, which has been treated by MBT prior to landfilling.

2. EVALUATION OF METHODS

2.1 Non-biological methods

2.1.1 Gravimetric methods

Determination of the waste moisture and dry matter (DM) contents by drying at 105°C, and organic matter content by loss on ignition (LOI) at 550°C, is considered obligatory for waste characterization. The results (Table 1) indicate that the DM content of the wastes varies considerably and with the exception of compost the LOI was similar to the DM content. Like compost most MSW is likely to have a LOI content lower than the DM content and therefore consideration of whether to use DM and/or LOI for measuring waste mass is required.

2.1.2 Elemental composition

Total organic carbon (TOC) determination provides a cross-check of the LOI content, and is a waste acceptance criterion for landfill (Council of the European Union 2002).

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Total nitrogen (TN) determination is required for setting up some biological biodegradation tests. The results (Table 1) indicate that TOC content of the wastes is typical for organic materials and is between 36 to 55% (average 43%) of the LOI. The TN content varies considerably, with wastes composed mainly of cellulose (newspaper, corrugated paper) being virtually N free whilst wool (composed mainly of protein) has the highest N content.

Table 1. Dry matter (DM), Loss on ignition (LOI), total organic carbon (TOC) and total nitrogen (TN) contents of wastes

Waste sample	DM (%wet wt)	LOI (% DM)	TOC (%DM)	TN (%DM)
Cellulose	95.8	99.4	41.7	<0.20
Newspaper	90.8	92.8	44.1	<0.20
Corrugated paper	92.3	90	40.8	<0.20
Grass	18.9	86.4	31.4	2.24
Twigs	63.5	96.6	48.3	0.85
Vegetables	13.4	94.5	38.9	3.23
Meat	22.7	93.8	51.5	3.98
Cotton	97.2	99.3	52.9	0.29
Wool	93.9	94.9	31.9	10.90
Nappies	96.8	85.6	33.1	<0.20
Compost	62.5	31.8	9.8	0.78

2.2. Biological methods

Biological methods involve incubating the organic waste in the presence of micro-organisms that decompose the organic matter as a substrate for their growth. Tests may be carried out under anaerobic (methanogenic) or aerobic conditions and are monitored by measuring biogas production (CH_4 and CO_2) in anaerobic tests and either O_2 consumption or CO_2 production in aerobic tests.

2.2.1 Anaerobic biochemical methane potential (BMP)

This test measures waste biodegradability under anaerobic methanogenic conditions by measuring the amount of biogas, methane and carbon dioxide ($CH_4 + CO_2$) or specifically CH_4 produced. We evaluated a modified BMP test using 20 g LOI of waste in the test, and that was based on a Blue Book method (SCA 1977) for determining anaerobic degradability of sewage sludges. Tests were incubated until significant biogas production ceased, which for some wastes required incubation times of up to 120 days. The results (Table 2) show the differences in biogas production from the wastes, which we presume reflect differences in the relative biodegradabilities.

2.2.1 Aerobic waste biodegradation test methods

Several aerobic waste biodegradability test methods exist as well as different monitoring techniques and ways of expressing results. They can be categorized into three main method types; static respiration index (SRI), dynamic respiration index (DRI) and liquid systems such as the specific oxygen uptake rate (SOUR) method.

The SRI method is a closed solid-state technique and involves monitoring O_2 consumption by the reduction in air pressure of the vessel headspace after removal of evolved CO_2 by adsorption in an alkaline trap. The DRI method (e.g. ASTM 1996) is an open solid-state system involving passing air through the waste and monitoring the difference in either O_2 (consumed) or CO_2 (produced) between the inflow and out-flowing air. In general SRI methods give lower rates of O_2 consumption than DRI based methods (Adani et al. 2002). The SOUR test (Lasaridi and Stentiford 1998) involves homogenizing the waste in a water suspension, seeding with activated sludge, and monitoring the removal of dissolved oxygen (DO) from the liquid. The DO is intermittently replaced by sparging with air. This study evaluated the DRI and SOUR aerobic biodegradation tests.

2.2.2 Expression of aerobic biodegradation test results

Aerobic biodegradation results are usually reported as either the peak O_2 consumption rate (respiration index, RI), or the cumulative O_2 consumption over a set period (often described as the AT value). The draft biowaste working document (European Commission 2001) gives limits for biodegradability in both terms, i.e. a four day AT value (AT4) of 10 g O/kg DM and a respiration index of 1000 mg O/kg LOI.h. The ASTM standard method (ASTM 1996) reports results as the AT4 value in terms of g O/kg LOI. Therefore the unit (DM or LOI) describing the waste should be specified.

2.2.3 Results of DRI and SOUR method evaluation

The DRI tests were carried out at 35^{o}C over seven days using the greenwaste compost as microbial seed and an alkaline trap method for monitoring CO_2 production (ref std). Oxygen consumption was estimated by assuming a 1:1 molar ratio of CO_2 production to O_2 consumption. The DRI test results illustrated in Table 2 indicate that biodegradation was incomplete within the seven days incubation time; however a correlation between the completed BMP and DRI results is given in Figure 2.

Table 2. Comparison of results from anaerobic BMP and aerobic DRI and SOUR tests on selected organic wastes.

Waste sample	BMP Biogas	DRI AT4value	SOUR Peak rate	Percentage waste carbon mineralized (%)		
	(l /kg LOI)	(mg O_2?/kg LOI)	(mg O_2?/kg LOI.h)	BMP	DRI (96h)	SOUR (90h)
Cellulose	136	84900	20	16.9	7.59	0.07
Newspaper	76	76600	150	8.5	6.05	0.13
Corrugated paper	320	125000	660	37.8	10.3	1.83
Grass	225	119000	2880	33.1	12.3	16.30
Twigs	93	57100	13900	10	4.29	4.34
Vegetables	312	137000	24700	40.6	12.5	45.5
Meat	633	150000	12600	61.7	10.3	30.5
Cotton	26	12900	530	2.6	0.91	0.39

Wool	21	17000	90	3.4	1.90	0.42
Nappies	278	86100	240	38.5	8.35	0.16
Compost	24	26300	580	4	3.12	1.91

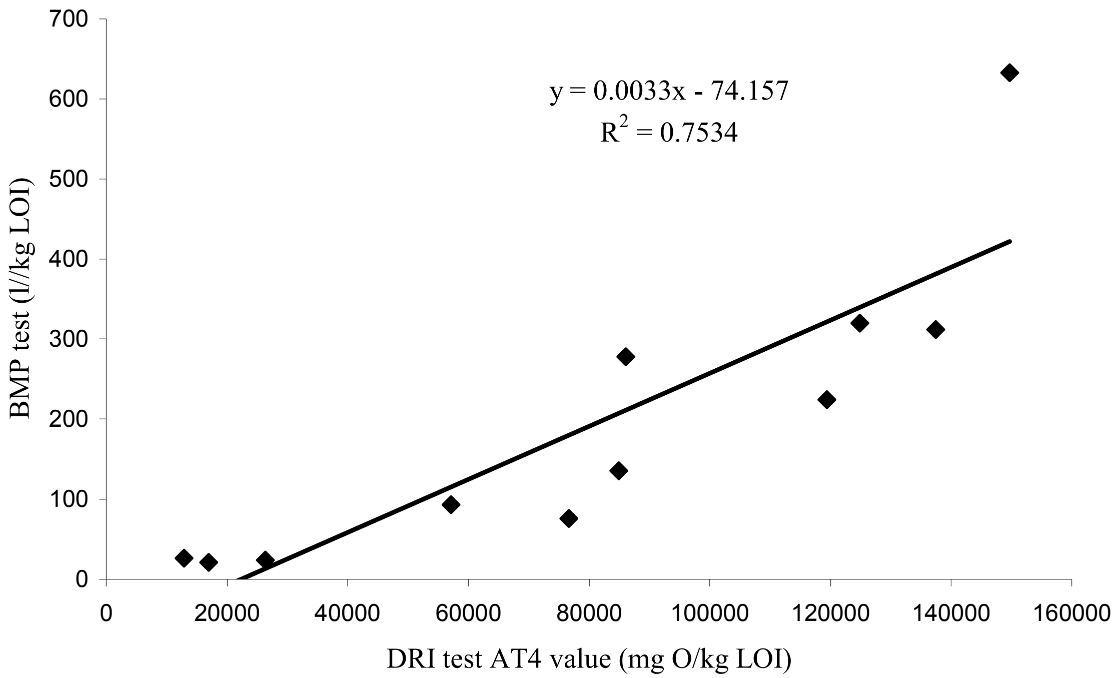

Figure 1. Correlation between the aerobic DRI (AT4 value) and the anaerobic BMP biological waste degradation tests

The SOUR results (Table 2) indicate that materials composed principally of polymeric materials e.g. cellulose, newspaper, corrugated paper, nappies, give low biodegradability results in the SOUR test compared with the BMP and DRI tests. This might reflect the microbial seed properties of the activated sludge, e.g. if it lacked sufficient cellulose degrading activity within the SOUR test time-scale. There is no apparent correlation between the SOUR and either the BMP or DRI test results.

2.3 Surrogate tests for biodegradability

Since biological tests are time consuming and costly it is desirable to have simpler, rapid and cheaper methods that may be a useful surrogate for biological tests.

2.3.1 Water extractable dissolved organic carbon (DOC), BOD and COD

The landfill waste acceptance criteria (Council of the European Union 2002) include limits on leachability determined using the compliance leaching test BS EN 12457 (CEN 2002). This test involves extracting the waste with water and then analyzing the eluate for leached components. In the UK the limit values for leachability at liquid to solid ratio 10 l/kg (L/S10) will apply. The extracted DOC and/or the ratio of the 5-day biological oxygen demand to chemical oxygen demand (BOD_5/COD ratio) of the extracted DOC, may reflect overall waste biodegradability (Binner *et al.* 1999, Cossu *et al.* 2001). Therefore the release of DOC, BOD_5 and COD were also determined at L/S10. The results (Table 3) show that the DOC is low in most wastes composed of polymeric materials e.g. cellulose, wool, cotton, newspaper and corrugated paper, and higher in materials composed of direct plant or animal matter e.g. vegetables, meat, twigs and grass. The BOD_5 is high and difficult to measure accurately in wastes with high extractable DOC, however for most wastes the BOD_5/COD ratios are within the range 0.2 – 0.8 suggesting that the extracted DOC is biodegradable. The BOD_5/COD ratio for compost is low (0.05) suggesting that the extracted DOC is much more recalcitrant as expected from a waste pre-treated in a biological process. We found no correlation between the DOC, BOD_5, COD, and the BOD_5/COD ratio and any of the biological tests (BMP, SOUR, DRI).

2.3.2 Cellulose and lignin content

The "cellulose" (sum of cellulose and hemicellulose) and lignin content can be determined by several acid detergent fibre (ADF) methods (Edwards 1973, Lewin *et al.* 1996) and the cellulose to lignin (C/L) ratio may correlate with the waste biodegradability (Barlaz et al. 1997, Eleazer et al. 1997, Stinson and Ham 1995). Test results (Table 3) indicate the cellulose and lignin contents vary although for most wastes the cellulose exceeds the lignin content. Compost, however, had less cellulose than lignin, which is expected as the biological treatment removes significant cellulose but leaves the lignin largely intact. Interestingly wool, which lacks cellulose and lignin, gives high apparent lignin values, thought to be due to its man-made plastic fibre content. Therefore, this test needs to be applied with caution. There is no correlation between the cellulose, lignin and C/L ratios and the biological degradation tests.

Table 3. Results of DOC, BOD_5, COD cellulose and lignin contents from leaching, cellulase hydrolysis, and acid detergent fibre (ADF) tests.

Waste	DOC mg C/kg DM		BOD_5 mg O/kg DM	COD mg O/kg DM	Cellulose % DM	Lignin %DM	C/L ratio
	Leaching test	Cellulase test	Leaching test	Leaching test	ADF test	ADF test	ADF test
Cellulose	1570	81200	1420	3690	83.4	4.2	19.9
Newspaper	1290	40470	1730	3680	54	16.9	3.2
Corr-paper	8410	76800	2090	22500	61.1	9.6	6.36
Grass	27700	65400	104000	134000	21.6	12.8	1.69
Twigs	25000	56200	55700	94900	45.9	13.1	3.5
Vegetables	13900	231100	369000	33100	17.8	6.1	2.92
Meat	7560	164000	150000	20400	8.4	5.5	1.53
Cotton	1540	9290	1330	4760	92.4	2.1	44
Wool	686	4890	485	2340	39.1	33.1	1.18
Nappies	17100	82500	10000	49500	74.3	27.9	2.66

Compost	2460	21220	259	5210	8.9	17.7	0.5

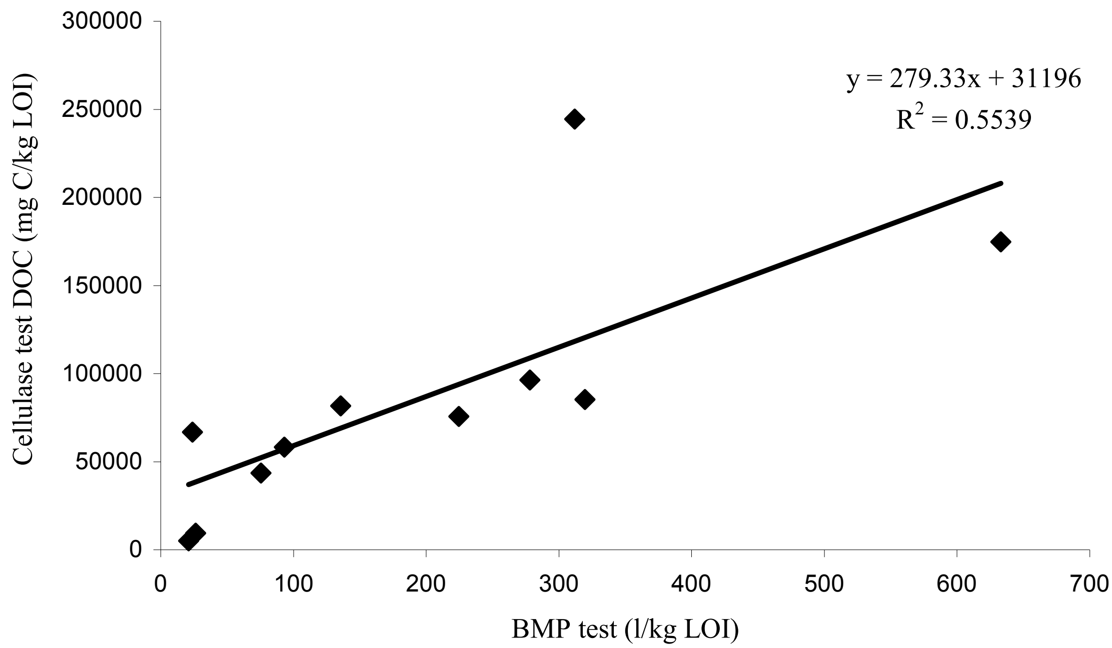

Figure 2. Correlation between the dissolved organic carbon (DOC) released by the cellulase hydrolysis test and the biogas production from the anaerobic BMP test.

2.3.3 Cellulase hydrolysis test

Cellulose and hemicelluloses are a major component of plant derived organic wastes. During decomposition of such wastes, microorganisms produce enzymes (cellulase and hemicellulases) to hydrolyse these polysaccharides into soluble sugars, which are then utilized by the microorganisms. The degree of waste hydrolysis achieved by enzymatic treatment with commercial cellulase and hemicellulase preparations might therefore correlate with biodegradability. Such a test (Rodriguez *et al*. 2001) is evaluated using a 24 hour incubation time and monitoring the production of DOC. The results (Table 3) show that for most wastes the DOC released from the enzymic hydrolysis test exceeds the DOC released from the leaching test, confirming the hydrolysis of waste polymers. The cellulase test results correlate quite well with the BMP (Figure 2) and DRI tests.

2.4 Monitoring MBT processes

This study indicates that the most useful tests are for DM, LOI, and TOC as measures of general waste composition, the BMP and DRI tests as biological biodegradability tests, and the cellulase hydrolysis test as a possible surrogate for biological methods. One of the main aims of the Landfill Directive is to significantly reduce the landfilling of biodegradable waste and thereby reduce the risk to the environment from fugitive methane emissions generated as landfill gas. Therefore it may be useful to consider the benefits from pre-treating municipal waste by MBT in terms of a reduction in the amount of landfill gas produced. Several possible approaches to monitoring the variety of MBT processes using the methods above might then be considered.

2.4.1 Estimation by total mass reduction.

The simplest approach to monitoring the relative reduction in biodegradability of municipal waste pre-treated in an MBT plant would be by measurement of the total wet mass reduction. However loss of mass due to moisture reduction alone would have no impact on the potential biogas production of the remaining organic matter.

2.4.2 Estimation by sampling and testing of waste streams

The amount of potential biogas production from the raw waste (B_{rw}) might be estimated from the LOI mass of the waste and its biodegradability (biogas production from BMP test or estimated from a correlated DRI or cellulase test), i.e. B_{rw} (m^3) = mass LOI (tonnes) x BMP (m^3/ t LOI). During the biological stage of an MBT plant it is expected that the biodegradability of the organic matter will decrease. Similar testing of the pre-treated waste prior to landfill allows an estimation of the potential biogas production from the pre-treated waste (B_{tw}). The percentage reduction in estimated potential biogas production from landfilling the pre-treated waste compared with the raw waste is then given by $(B_{rw}-B_{tw})/B_{rw}$ x100%. This might then be used to calculate the relative percentage of BMW diverted from landfill. This approach would require frequent waste sampling and analysis of the samples for LOI and biodegradability.

2.4.3 Estimation from monitoring process parameters

For most MBT processes the biological stage takes place within an in-vessel system. This may allow monitoring of inputs and outputs by on-line quality instruments. Some of these parameters are likely to reflect the relative degree of biodegradation and hence loss in LOI mass that can then be related to the loss in biodegradability (potential biogas production of the waste). A suitable parameter might be the CO_2 production as measured in the exhaust gas of an in-vessel system aerated by an air blower. In this case suitable calibration of the CO_2 monitoring system with waste LOI and biodegradability measurements would enable the calculation of the relative diversion of BMW from landfill using on-line process measurements.

2.4.4 Estimation by specific process understanding

In a sufficiently controlled and understood process system it should also be possible to provide an accurate prediction of the relative degree of biodegradation and loss in potential biogas production achieved by the process without the need for extensive monitoring. Such an approach would require calibration with a sampling and measurement scheme and identification of key parameters that demonstrate that the process has performed within agreed standards. Such monitoring might be based upon routine wet mass measurements, if it can be adequately demonstrated to the Environment Agency that the process operates and performs consistently to agreed standards.

3. CONCLUSIONS

This study has evaluated several methods for characterizing municipal organic wastes according to their relative biodegradable content. The study concludes that general waste characterization in terms of dry matter (DM) and organic matter (LOI) content is essential. In addition, TOC is also a useful measurement as it provides a cross-check of the organic content. The LOI and TOC tests do not characterize the relative biodegradability of the waste. However, such a measure is required in order for the Environment Agency to fulfil its monitoring role under the LATS and LAS regulations. The Environment Agency must be able to accurately monitor the reduction in relative biodegradability of MSW, which is pre-treated in a MBT plant prior to landfilling. The most promising biological tests we evaluated are the DRI and BMP methods and a cellulase enzymic hydrolysis method that may provide a rapid surrogate measure of relative biodegradability.

These tests can be used in several approaches in order to calculate the amount of BMW diverted from landfill during the pre-treatment of MSW in MBT processes prior to landfill. The general approach might be to estimate the reduction in potential landfill gas production that has been achieved by an MBT process and use this percentage reduction to calculate the BMW diverted from landfill. Several options are then possible for monitoring MBT processes, which perform consistently to agreed standards. Consistent achievement of agreed process performance standards may reduce the requirement for extensive sampling and testing of municipal waste samples.

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