Categorizing Raw Organic Material Biodegradability Via Respiration Activity Measurement: A Review

Raquel Barrena, Teresa Gea, Sergio Ponsá, Luz Ruggieri, Adriana Artola, Xavier Font and Antoni Sánchez*

Composting Research Group

Department of Chemical Engineering

Escola Tècnica Superior d'Enginyeria

Universitat Autònoma de Barcelona

Bellaterra (Cerdanyola, 08193-Barcelona, Spain)

* Corresponding author:

Dr. Antoni Sánchez

Phone: 34-935811019

Fax: 34-935812013

Email: antoni.sanchez@uab.cat

This is a pre-print of an article published by Taylor & Francis in Compost science and utilization on 2011.
Available online: http://www.tandfonline.com/doi/abs/10.1080/1065657X.2011.10736985
Article DOI 10.1080/1065657X.2011.10736985

Abstract

A massive characterization in terms of respiration activity for the most common types of organic solid wastes is presented in this compilation. Respiration activity for a solid waste is a crucial parameter to understand the behaviour of the waste in the environment and for waste management aspects such as the definition of a suitable biological treatment and the determination of the potential rate of microbial self-heating if organic wastes are to be used as solid recovered fuels. The respiration data compiled in this work are the result of five years of research focused on the determination of the biological activity of organic wastes. A compilation of respiration data found in the literature is also presented. The main groups of organic wastes analyzed are: municipal solid wastes (including mixed wastes and source-selected organic fraction), wastewater sludge (including digested and non-digested sludge from primary and secondary operations in municipal and industrial wastewater treatment plants), different types of manure (of different origin), other particular wastes (animal by-products, hair waste, fats, etc.) and some mixtures of different wastes. Results suggest that respiration activity can be used to classify the biodegradability of organic wastes into three main categories: i) highly biodegradable wastes (respiration activity higher than 5 mg O_2 g Organic Matter^{-1} h^{-1}), which includes source-selected organic fraction of municipal solid waste, non-digested municipal wastewater sludge and animal by-products; ii) moderately biodegradable wastes (respiration activity within 2 to 5 mg O_2 g Organic Matter^{-1} h^{-1}), including mixed municipal solid waste, digested municipal wastewater sludge and several types of manure; iii) wastes of low biodegradability (respiration activity lower than 2 mg O_2 g Organic Matter^{-1} h^{-1}), which includes few organic wastes such as some particular wastes from the food industry.

Keywords: Composting, Manure, Municipal solid wastes, Organic solid wastes, Respiration activity, Wastewater sludge.

Introduction

Current legislation on solid waste treatment and disposal has highlighted the importance of recycling and recovery of solid wastes a s a sustainable management practice instead of traditional incineration or landfilling. In fact, the European Landfill Directive (99/31/EC) sets targets for the reduction of biodegradable waste sent to landfill as 75% of the 1995 level by 2010, 50% of the 1995 level by 2013 and 35% of the 1995 level by 2020. The alternatives for landfill and incineration are biological treatment, based on composting, anaerobic digestion or a combination of both treatments. In any case, the level of biological activity for a given organic waste is necessary to define the operations used for biodegradation jointly with the stability of the final material, which can be the focus of future regulations (European Commission, 2001) and it is already in force in several European countries (Favoino, 2006; Federal Government of Germany, 2001; Godley *et al*., 2005).

Another application of the determination of biological activity is the measure of potential rate of microbial self-heating if organic wastes are to be used as solid recovered fuels (SRF). A method based on respiration activity has been published recently at European level (European Committee for Standardization, 2007). In this case, respiration activity is used to measure the microbial activity, as it acts as a primer causing the waste temperature to increase until autoxidation and the self-combustion processes takes place. Spontaneous combustion can occur when SRF from municipal solid waste or biomasses are stored and/or transported. The potential self-heating of SRF can be indirectly measured by the respiration index, which determines the extent to which easily biodegradable organic matter of a SRF has decomposed. Therefore, the respiration activity identifies the actual point reached in the decomposition process and represents a gradation on a scale of values, which thus enables a comparison of potential self-heating.

Although there is no consensus for a universal measurement of biological activity in solid wastes, tests based on the respiration activity have gained popularity in the last years as a measurement of the real activity of a given waste. Biological activity measurements (both under aerobic and anaerobic conditions) have been widely used in literature as a measure of biodegradable organic matter content or stability (in the case of final products). In this sense, aerobic respirometric techniques (often referred as OUR: Oxygen Uptake Rate) and methanogenic activity assays have been proposed (Adani *et al*., 2004; Barrena *et al*., 2006a; Hansen *et al*., 2004; Ianotti *et al*., 1993; Lasaridi & Stentiford, 1998; Ligthart & Nieman, 2002; Scaglia *et al*., 2000; Tremier *et al*., 2005). Also, some comparisons among the proposed methods have been made (Adani *et al*., 2003; Adani *et al*., 2006; Gea *et al*., 2004). Furthermore, a number of standards have been already proposed (ASTM, 1996; Cooper, 2005; The US Department of Agriculture and the US Composting Council, 2001). In spite of the amount and quality of the work considered, the variety of methods and the dispersion of the respiration data in the literature makes it very difficult to compare data and decide the required conditions for a biological treatment. For instance, in aerobic treatment (composting) respiration index can be used to estimate the oxygen requirements to fulfil biodegradation (Barrena *et al*., 2006b), whereas for anaerobic treatment, aerobic respiration activity can be successfully correlated with the potential biogas production (Cossu & Raga, 2008; Ponsá *et al*., 2008).

Our research group has a long experience in the determination of respiration activity of several organic wastes, such as municipal solid wastes coming from different collection systems (Barrena *et al*., 2006c; Gea *et al*., 2004), several types of wastewater sludge from municipal and industrial wastewater treatment plants (Barrena *et al*., 2005; Gea *et al*., 2005a; Gea *et al*., 2005b; Gea *et al*., 2007a; Gea *et al*., 2007b) and other wastes (Barrena *et al*., 2007). In addition, respiration activity has been determined with organic wastes amended with other complementary co-substrates (Ruggieri *et al*., 2008). This work has created a large database of respiration activity for organic wastes.

The aim of the present study is therefore to provide and discuss data on respiration activity for a large number of organic wastes, which are intended to be biologically treated. Most of the information used has been obtained over five years of respiration activity determinations, whereas the rest has been obtained from published results. Only respiration indices obtained with solid waste materials have been considered. Respirometry in liquid suspension has not been included in this review. The authors have proposed several activity categories based on the respiration indices calculated for a wide range of waste materials.

Materials and methods

Organic wastes

Organic wastes from several sources were used in this work. Respiration data from the experiences carried over five years have been gathered in this compilation. A brief explanation about the wastes origin is presented in Table 1. For convenience, organic wastes have been grouped in four main categories: municipal solid wastes (including mixed wastes (MSW) and source-selected organic fraction (OFMSW)), wastewater sludge (including digested and non-digested sludge from primary and secondary operations), manure (of different origin), bulking agents and other wastes.

Sampling of organic wastes

Parameters were determined in the laboratory after extracting a representative solid sample of the material obtained from several waste treatment plants in Spain. For this purpose, four subsamples of about 5 L were extracted from a waste pile of at least 250 kg and mixed. The total volume of sample (about 20 L) was manually mixed and a final volume of 2 L (1 kg) was used to carry out the respiration analysis.

Respiration index (RI)

Respiration index (RI) was determined using a static respirometer based on the model previously described by Ianotti *et al*. (1993) and following the modifications and recommendations given by the The U.S. Department of Agriculture and The U.S. Composting Council (2001). The experimental respirometer was described in a previous publication (Barrena *et al*., 2005). Values of RI were determined at 37ºC and are expressed as mg of oxygen consumed per g of organic matter and per hour (mg O_2 g OM^{-1} h^{-1}) and are always presented as an average of three replicates.

Literature data was consulted to obtain respiration activity of several types of organic wastes using several methodologies. All data was standardized to mg of oxygen consumed per g of organic matter and per hour as units of respiration activity, as discussed later.

Routine analytical methods

Moisture and organic matter (OM, in dry matter basis) were determined according to the standard procedures (The U.S. Department of Agriculture and The U.S. Composting Council, 2001). OM is often referred to in the literature as volatile solids (VS). OM and VS content are equivalent for the purpose of this work.

Results and discussion

Table 1 presents the levels of respiration activity for different organic wastes analyzed. The data is presented in the form of average respiration activity (where n is the number of samples analyzed) and maximum and minimum values of respiration. All values are expressed in mg of oxygen consumed per g of organic matter and per hour (mg O_2 g OM^{-1} h^{-1}). Table 2 presents a compilation of respiration activity data presented in the literature. As some of the published values are expressed in different units, two hypotheses have been considered to estimate the respiration activity in the same units as Table 1 to enable data comparison:

1) When respiration data in literature was expressed as CO_2 produced instead of O_2 consumed, it was assumed that 1 mol of CO_2 was produced from 1 mol of O_2 consumed, as this is the typical value of respiration quotient found in composting experiences (Gea *et al*., 2004).
2) When respiration data in literature was expressed on a dry matter basis, the value was transformed to organic matter basis considering the organic matter content.
3) It was assumed that the volatile solids content (respiration data was reported in these units in some references) was equivalent to organic matter content (both analytical tests are identical).

Table 3 summarizes the conversion factors used to obtain comparable respiration units.

Levels of respiration in different organic wastes

Municipal solid wastes

In general, respiration activity of MSW is high when compared to other organic wastes. Also, MSW respiration activity shows a high deviation when obtained from different origins. As organic materials in MSW are mainly composed of kitchen rejects and garden wastes, it seems evident that MSW presents a different composition according to population habits, food consumption models, types of edification, etc.

An interesting aspect on MSW respiration activity is the remarkable difference between MSW and the OFMSW. According to Table 1, the OFMSW respiration activity (average value of 5.81 mg O_2 g OM^{-1} h^{-1}) is practically twice the value found for mixed MSW (average value of 3.25 mg O_2 g OM^{-1} h^{-1}). This difference is even higher when the OFMSW comes from source-selected collection systems instead of being mechanically separated at the treatment facility. In this case, remaining mixed MSW is poor in organic materials (Ponsá *et al*., 2008). In fact, the RI_{max} values of respiration data for the OFMSW in Table 1 and 2 are obtained for source-selected OFMSW, whereas RI_{min} values of respiration data for mixed MSW are obtained for mixed MSW where a separate collection system for organic matter is implemented. As the success of source-selection systems is often measured from the level of impurities found in the OFMSW, this level can also have a direct effect on respiration activity of the source-selected fraction and the rest of mixed MSW. This is of special importance for the design of waste treatment plants based on biological operations, for instance, composting plants designed for source-selected OFMSW and Mechanical-Biological Plants (MBT) for the treatment of mixed MSW, since these plants must fulfil some stability requirements for final materials (compost or stabilized waste), which are based on respiration activity (Adani *et al*., 2006; Cossu & Raga, 2008; European Commission, 2001; Federal Government of Germany, 2001; Godley *et al*., 2005; Ponsá *et al*., 2008). In addition, it should be noted that MSW includes a high amount of volatile non-biodegradable materials such as plastics, which are computed in the total organic matter analysis.

Wastewater sludge

Most of the respiration data published for wastewater sludge relates to municipal wastewater, although some data on sludge coming from industrial sectors can also be found

(Table 2). In relation to this material, the presence of anaerobic digestion in the wastewater treatment plant must be carefully considered to interpret correctly the respiration data obtained (Table 1). It is evident that anaerobic digestion is responsible for the biodegradation of labile organic matter and, in consequence, produces a significant decrease in the respiration activity of wastewater sludge (from an average value of 7.01 mg O_2 g OM^{-1} h^{-1} for non-digested sludge to 2.56 mg O_2 g OM^{-1} h^{-1} for digested sludge). This means that the reduction of respiration activity due to anaerobic digestion of sludge is in the range of 60-70%. Recent results obtained by Ponsá *et al*. (2008) have reported similar values of reduction of respiration index for MSW (53% reduction) and source-selected OFMSW (69% reduction) when treated by anaerobic digestion. In addition to this point, it is also interesting to observe that the level of distribution found in respiration activity for non-digested sludge is significantly higher than that of digested sludge. This is due to the fact that non-digested sludge is a label applied to sludge obtained by different types of wastewater treatment (centrifugation, filtration, thickening) and different origins (primary, secondary and mixtures of both), whereas digested sludge is inherently more homogeneous. In any case, the initial sludge respiration activity must be again considered in the design of a composting plant, in crucial aspects such as the level of aeration required and the temperature profile obtained, which is directly related to the material potential metabolic activity (Barrena *et al*., 2006b; Manios *et al*., 2006). At the same time, it is important to consider the bulking agent respiration index together with the sludge, since this material is often considered inert and its respiration activity neglected.

Other wastewater sludge data coming from several industrial sectors are presented in Table 2. Among them, sludge from the food industry presents, as expected, levels of respiration activity similar to that of non-digested municipal wastewater sludge. However, in some cases, the information about the sludge origin and the previous treatments is unknown, which makes comparison impossible. Finally, it is worthwhile to mention that some data on respiration activity of sludge coming from physico-chemical operations without biological treatment (mainly filtration) have been found (Table 2, de Guardia *et al*., 2008). The activity levels for this type of sludge are in the range of 1.74 to 3.26 mg O_2 g OM^{-1} h^{-1} (average value of 2.55 mg O_2 g OM^{-1} h^{-1}), which are very similar to those found for anaerobically digested sludge. Unfortunately, as biological operations are dominant in wastewater treatment, there are insufficient data in the literature to extract significant conclusions about the respiration of physico-chemical sludge.

Manure

Although some high levels of respiration activity can be found for manure (Table 1 and 2), the general trend observed for the most common types of manure found in the literature (cow and pig manure) corresponded to a moderately active material in terms of respiration activity, far from the levels obtained for raw materials such as the OFMSW and non-digested wastewater sludge. Other types of manure such as horse or turkey manure also presented moderate levels of activity (around 2 mg O_2 g OM^{-1} h^{-1}). Although manure can be considered a non-treated waste, it is usually stored in livestock facilities for some time as a part of its management. This point should be considered since it has been reported that relatively short times of storage can reduce significantly the biological activity of pig manure (Bonmatí & Flotats, 2003). According to these data, composting of these wastes is feasible, but information on the respiration activity of each specific waste should be available. Finally, it must be pointed that some respiration data related to liquid fractions of manure (typically in form of diluted pig slurries) have not been included in Table 2. The respiration activity found for these fractions are typically below 0.2 mg O_2 g OM^{-1} h^{-1} (Tiquia, 2005).

Bulking agents and carbonaceous amendments

The group of bulking agents should be particularly mentioned. These materials are often used in composting processes to provide the adequate porosity and/or to adjust the moisture level of a given waste (Haug, 1993). Typically, their participation as co-substrates in the biological process is often considered as negligible. Although this can be true for inert or near-inert bulking agents (Gea *et al*., 2003), it must be pointed that some bulking agents (as shown in Tables 1 and 2) can have a considerable respiration activity and a significant degradation can then occur (Das *et al*., 2003; Eftoda & McCartney, 2004). Again, this point should be carefully considered in the design and operation of composting plants.

Other wastes and mixtures

Data on respiration activity of several minor groups of organic wastes coming from the food industry have been determined or are available from the literature. Two particular wastes have been studied in detail. Animal by-products from slaughterhouses (hair, bones, skin, etc. not intented for human consumption) have been recently studied (Table 1) in our laboratory. As expected, these wastes exhibited a high respiration activity (average value of 5.26 mg O_2 g OM^{-1} h^{-1}). This is of special interest for composting plant managers, since these materials must be exposed to 70ºC for 1 hour in order to achieve a complete sanitation to fulfil the European regulations (European Commission, 2002). According to the high respiration activity shown, it is evident that ensuring proper and controlled conditions for animal by-products composting, these materials are expected to self-heat to the required sanitation conditions, avoiding any additional thermal treatment.

A group that has received some attention is that of wastes coming from olive oil manufacturing (Table 2). These materials can be found in different forms (wastewater sludge, olive press cake and some mixtures) and the levels of respiration activity are medium to high, which contributes to an active composting process resulting in the detoxification of these wastes measured in terms of polyphenols removal (Zenjari *et al*., 2007; McNamara *et al*., 2008).

Other very specific wastes studied in our laboratory were hair wastes coming from de-hairing of cow skins for leather production and mushroom production wastes (Table 1). Their respiration activity can be considered as medium for hair wastes (they are mainly constituted of hydrolyzed protein as described in Barrena *et al*., 2007) and low for mushroom wastes (they consist of partially decomposed manure to favour mushroom growth), which is in accordance to the waste production process.

Finally, some literature values of respiration activity can be found for mixed wastes, where at least two co-substrates are composted (Table 2). As co-composting can be considered an emerging technology for the improvement of the process due to the inherent benefits related to the adjustment of the physico-chemical mixture properties (C/N ratio, porosity or moisture content), it is evident that the knowledge of the biological activity of proposed mixtures should be the focus of further studies on respiration activity of organic wastes, especially when it has been shown that the respiration activity of a mixture cannot be estimated from the individual values of each waste (Barrena *et al*., 2007; Gea *et al*., 2007b; Ruggieri *et al*., 2008).

Proposal for an activity index based on respiration activity

Figure 1 presents the summary of available respiration data including our experiments and literature values. As can be observed, respiration activity can be used to classify the biodegradability of organic wastes into three main categories: i) highly biodegradable wastes (respiration activity higher than 5 mg O_2 g OM^{-1} h^{-1}), which includes source-selected organic fraction of municipal solid waste, non-digested municipal wastewater sludge and animal by-products; ii) moderately biodegradable wastes (respiration activity within 2 to 5 mg O_2 g OM^{-1} h^{-1}), including mixed municipal solid waste, digested municipal wastewater sludge and several types of manure; iii) wastes of low biodegradability (respiration activity lower than 2 mg O_2 g OM^{-1} h^{-1}), which includes few organic wastes such as some types of manure and some particular wastes from the food industry. These categories have been represented in Figure 1, where the final proposal to classify the biodegradability of organic wastes is presented. This is to the authors' knowledge, the first attempt to classify the biodegradability of a large number of representative typologies of organic solid wastes. In conclusion, this classification can be very useful for the study, operation and design of organic waste treatment plants based on biological processes, as well as in the determination of the potential rate of microbial self-heating if organic wastes are to be used as solid recovered fuels.

Conclusions

Several conclusions can be obtained from this work:

1) Many authors have studied respiration indices to estimate the biological activity in organic solid wastes and stated that these methodologies as the most suitable parameters to do it. There are abundant data in literature on respiration activity of several organic wastes, although the methodology proposed for its determination is diverse.

2) The average levels of respiration activity ranged from 7 mg O_2 g OM^{-1} h^{-1} for non-digested municipal wastewater sludge to less than 2 mg O_2 g OM^{-1} h^{-1} for several

industrial organic wastes and bulking agents. Maximum reported value of respiration activity is 14.8 mg O_2 g OM^{-1} h^{-1} for non-digested wastewater sludge.

3) According to the data obtained and compiled, organic wastes can be quantitatively classified into different categories according to their biological activity, which is of special relevance when a biological treatment is proposed.

4) Values of respiration activity provide information about the potential biodegradability of organic wastes and the stage of biodegradation in a biological process. They are also necessary for the comparison of organic wastes as a complement of physical and chemical properties.

Acknowledgements

Financial support was provided by the Spanish *Ministerio de Ciencia e Innovación* (Project CTM2009-14073-C02-01).

References

Adani, F., Scatigna, L., Genevini, P. 2000. Biostabilization of mechanically separated municipal solid waste fraction. Waste Manage. Res. 18, 471-477.

Adani, F., Lozzi, P., Genevini, P. 2001. Determination of biological stability by oxygen uptake on municipal solid waste and derived products. *Compost Sci. Util.*, 9: 163-178.

Adani, F., Baido, D., Calcaterra, E., Genevini, P. 2002. The influence of biomass temperature on biostabilization-biodrying of municipal solid waste. *Biores. Technol*., 83: 173-179.

Adani, F., Gigliotti, G., Valentini, F., Laraida, R. 2003. Respiration index determination: a comparative study of different methods. *Compost Sci. Util*., 11: 144-151.

Adani, F., Confalonieri, R., Tambone, F. 2004. Dynamic respiration index as a descriptor of the biological stability of organic wastes. *J. Environ. Qual*., 33: 1866-1876.

Adani, F., Ubbiali, C., Genevini, P. 2006. The determination of biological stability of composts using the Dynamic Respiration Index: The results of experience after two years. *Waste Manage*., 26: 41-48.

Ahn, H.K., Richard, T.L., Glanville, T.D. 2008. Optimum moisture levels for biodegradation of mortality composting envelope materials. *Waste Manage*., 28: 1411-1416.

ASTM, 1996. Standard Test Method for Determining the Stability of Compost by Measuring of Oxygen Consumption. American Society for Testing and Materials, D5975-96.

Baffi, C., Dell'Abate, M.T., Nassisi, A., Silva, S., Benedetti, A., Genevini, P.L., Adani, F. 2007. Determination of biological stability in compost: A comparison of methodologies. *Soil Biol. Biochem*., 39: 1284-1293.

Barrena, R., Vázquez, F., Gordillo, M.A., Gea, M.T., Sánchez, A. 2005. Respirometric Assays at Fixed and Process Temperatures to Monitor Composting Process. *Biores. Technol*., 96: 1153-1159.

Barrena, R., Vázquez, F., Sánchez, A. 2006a. The Use of Respiration Indices in the Composting Process: A Review. *Waste Manage. Res*., 24: 37-47.

Barrena, R., Cánovas, C., Sánchez, A. 2006b. Prediction of temperature and thermal inertia effect in the maturation stage and stockpiling of a large composting mass. *Waste Manage*., 26: 953-959.

Barrena, R., Pagans, E., Faltys, G., Sánchez, A. 2006c. Effect of inoculation dosing on the composting of source-selected organic fraction of municipal solid wastes. *J. Chem. Technol. Biotechnol*., 81: 420-425.

Barrena, R., Pagans, E., Artola, A., Vázquez, F., Sánchez, A. 2007. Co-composting of hair waste from the tanning industry with de-inking and municipal wastewater sludges. *Biodegradation*., 18: 257-268.

Berthe, L., Druilhe, C., Massiani, C., Tremier, A., De Guardia, A. 2006. Respirometry to follow the decline of biodegradability and stabilisation of organic matter during a composting treatment. In: Kraft, E., Bidlingmaier, W., Bertoldi, M., Diaz, L.F., Barth, J., (Eds.), Proceedings of 5th International Conference ORBIT 2006, Weimar, pp. 271-278.

Berthe, L., Druilhe, C., Massiani, C., Tremier, A., de Guardia, A. 2007. Coupling a respirometer and a pycnometer to study the biodegradability of solid organic wastes during composting. *Biosystems Eng*., 97: 75-88.

Bonmatí, A., Flotats, X. 2003. Air stripping of ammonia from pig slurry: characterisation and feasibility as a pre-or post-treatment to mesophilic anaerobic digestion. *Waste Manage*., 23: 261-272.

Cooper, B.J. 2005. Stability (Biodegradability) Horizontal-7 WP4. Energy Research Center of the Netherlands. URL: http://www.ecn.nl/docs/society/horizontal/hor_desk_7_stability.pdf

Cossu, R., Raga, R. 2008. Test methods for assessing the biological stability of biodegradable waste. *Waste Manage*., 28: 381-388.

Cronje, A.L., Turner, C., Williams, A.G., Barker, A.J., Guy, S. 2004. The respiration rate of composting pig manure. *Compost Sci. Util*. 12: 119-129.

Das, K.C., Tollner, E.W., Eiteman, M.A. 2003. Comparison of synthetic and natural bulking agents in food waste composting. *Compost Sci. Util*., 11: 27-35.

De Guardia, A., Petiot, C., Rogeau, D. 2008. Influence of aeration rate and biodegradability fractionation on composting kinetics. *Waste Manage*., 28: 73-84.

Eftoda, G., McCartney, D. 2004. Determining the critical bulking agent requirement for municipal biosolids composting. *Compost Sci. Util*., 12: 208-218.

European Commission, 2001. Working document. Biological treatment of biowaste. 2nd draft. URL: http://www.compost.it/www/pubblicazioni_on_line/biod.pdf

European Commission, 2002. Regulation (EC) No 1774/2002 of the European Parliament and of the Council of 3 October 2002 laying down health rules concerning animal by-products not intended for human consumption. Official Journal L 273, 10/10/2002 P. 0001-0095.

European Committee for Standardization, 2007. Solid recovered fuels - Determination of potential rate of microbial self heating using the real dynamic respiration index. Document CEN/TS 15590, Brussels.

Favoino, E. 2006. The EU legislation and the requirements following for national organic waste management strategies and policies. First Baltic Biowaste Conference, European Compost Network/Organic Recovery and Biological Treatment association. URL: http://www.recestonia.ee/ecn/presentations/2%20Enzo%20Favoino.pdf

Federal Government of Germany. German Federal Ministry for the Environment, Nature Conservation and Nuclear Safety. Ordinance on environmentally compatible storage of waste from human settlements and on biological waste-treatment facilities of 20 February 2001. URL: http://www.bmu.de/english/publication/current/publ/5263.php

Galli, E., Pasetti, L., Fiorelli, F., Tomati, U. 1997. Olive-mill wastewater composting: microbiological aspects. *Waste Manage. Res*., 15: 323-330.

Gea, M.T., Artola, A., Sánchez, A. 2003. Application of Experimental Design Technique to the Optimization of Bench-scale Composting Conditions of Municipal Raw Sludge. *Compost Sci. Util*., 11: 321-329.

Gea, M.T., Barrena, R., Artola, A., Sánchez, A. 2004. Monitoring the Biological Activity of the Composting Process: Oxygen Uptake Rate (OUR), Respirometric Index (RI) and Respiratory Quotient (RQ). *Biotechnol. Bioeng*., 88: 520-527.

Gea, M.T., Artola, A., Sánchez, A. 2005a. Composting of De-inking Sludge from the Recycled Paper Manufacturing Industry. *Biores. Technol*., 96: 1161-1167.

Gea, T., Artola, A., Sort, X., Sánchez, A. 2005b. Composting of Residuals Produced in the Catalan Wine Industry. *Compost Sci. Util*., 13: 168-174.

Gea, M.T., Barrena, R., Artola, A., Sánchez, A. 2007a. Optimal Bulking Agent Particle Size and Usage for Heat Retention and Disinfection in Domestic Wastewater Sludge Composting. *Waste Manage*., 27: 1108-1116.

Gea, M.T., Ferrer, P., Alvaro, G., Valero, F., Artola, A., Sánchez, A. 2007b. Co-composting of sewage sludge:fats mixtures and characteristics of the lipases involved. *Biochem. Eng. J*., 33: 275-283.

Godley, A., Muller, W., Frederickson, J., Barker, H. 2005. Comparison of the SRI and DR4 biodegradation test methods for assessing the biodegradability of untreated and MBT treated municipal solid waste. In: Kühle-Weidemeier, M, (Ed.). International Symposium MBT 2005/Internationale Tagung MBA 2005. Cuvillier Verlag, Germany, pp. 548-559.

Hansen, T.L., Schmidt, J.E., Angelidaki, I., Marca, E., Jansen, J.L.C., Mosbæk, H., Christensen, T.H. 2004. Method for determination of methane potentials of solid organic waste. *Waste Manage*., 24: 393-400.

Haug, R.T. 1993. The practical handbook of compost engineering. Lewis Publishers, Boca Raton.

Iannotti, D.A., Pang, T., Toth, B.L., Elwell, D.L., Keener, H.M., Hoitink, H.A.J. 1993. A quantitative respirometric method for monitoring compost stability. *Compost Sci. Util*., 1: 52-65.

Lasaridi, K.E., Papadimitriou, E.K., Balis, C. 1996. Development and demonstration of a thermogradient respirometer. *Compost Sci. Util*., 4: 53-61.

Lasaridi, K.E., Stentiford, E.I. 1998. A simple respirometric technique for assessing compost stability. *Wat. Res*., 32: 3717-3723.

Lasaridi, K.E., Stentiford, E.I., Evans, T. 2000. Windrow composting of wastewater biosolids: process performance and product stability assessment. *Wat. Sci. Technol*., 42: 217-226.

Li, X., Zhang, R., Pang, Y. 2008. Characteristics of dairy manure composting with rice straw. *Biores. Technol*., 99: 359-367.

Liang, C., Das, K.C., McClendon, R.W. 2003. The influence of temperature and moisture contents regimes on the aerobic microbial activity of a biosolids composting blend. *Biores. Technol*., 86: 131-137.

Ligthart, J., Nieman, H. 2002. Proceedings of the Workshop on Harmonisation of Anaerobic Biodegradation, Activity and Inhibition Assays. EUR 20535 EN, European Commission Joint Research Centre.

Liwarska-Bizukojc, E., Ledakowicz, S. 2003. Estimation of viable biomass in aerobic biodegradation processes of organic fraction of municipal solid waste (MSW). *J. Biotechnol*., 101: 165-172.

Malinska, K.A., Richard, T.L. 2006. The impact of physical properties and compacting on biodegradation kinetics during composting. In: Kraft, E., Bidlingmaier, W., Bertoldi, M., Diaz, L.F., Barth, J., (Eds.), Proceedings of 5th International Conference ORBIT 2006, Weimar, pp. 125-132.

Manios, T., Maniadakis, K., Kalogeraki, M., Mari, E., Stratakis, E., Terzakis, S., Boytzakis, P., Naziridis, Y., Zampetakis, L. 2006. Efforts to explain and control the prolonged thermophilic period in two-phase olive oil mill sludge composting. *Biodegradation*., 17: 285-292.

Mari, I., Ehaliotis, C., Kotsou, M., Balis, C., Georgakakis, D. 2003. Respiration profiles in monitoring the composting of by-products from the olive oil agro-industry. *Biores. Technol*., 87: 331-336.

Martel, J.L., Huyard, A., Allain, M., Tremier, A. 2006. Industrial application of a new respirometric test to different sludge and organic waste mixtures to be composted. In: Kraft, E., Bidlingmaier, W., Bertoldi, M., Diaz, L.F., Barth, J., (Eds.), Proceedings of 5th International Conference ORBIT 2006, Weimar, pp. 223-232.

McNamara, C.J., Anastasiou, C.C., O'Flaherty, V., Mitchell, R. 2008. Bioremediation of olive mill wastewater. *Int. Biodeter. Biodegr*., 61: 127-134.

Miyatake, F., Iwabuchi, K. 2006. Effect of compost temperature on oxygen uptake rate, specific growth rate and enzymatic activity of microorganisms in dairy cattle manure. *Biores. Technol.*, 97: 961-965.

Papadimitriou, E.K., Balis, C. 1996. Comparative study of parameters to evaluate and monitor the rate of a composting process. *Compost Sci. Util.*, 4: 52-61.

Palestky, W.T, Young, J.C. 1995. Stability measurement of biosolids compost by aerobic respirometry. *Compost Sci. Util.*, 3: 16-24.

Petruska, J.A., Mullins, D.E., Young, R.W., Collins, E.R.Jr. 1985. A benchtop system for evaluation of pesticide disposal by composting. *Nuclear Chem. Waste Manage.*, 5: 177-182.

Ponsá, P., Gea, T., Alerm, L., Cerezo, J., Sánchez, A. 2008. Comparison of aerobic and anaerobic stability indices through a MSW biological treatment process. *Waste Manage.*, 28: 2735-2742.

Ramirez, J.C., Cowan, R., Strom, P.F. 2006. Respirometric analysis to assess stability of compost and modeling of composting kinetics. In: Kraft, E., Bidlingmaier, W., Bertoldi, M., Diaz, L.F., Barth, J., (Eds.), Proceedings of 5th International Conference ORBIT 2006, Weimar, pp. 289-300.

Ruggieri, L., Gea, T., Artola, A., Sánchez, A. 2008. Influence of co-substrates of different biochemical composition on raw sludge co-composting. *Biodegradation.*, 19: 403-415.

Scaglia, B., Tambone, F., Genevini, P.L., Adani, F. 2000. Respiration index determination: Dynamic and static approaches. *Compost Sci. Util.*, 8: 90-98.

Scaglia, B., Erriquens, F.G., Gigliotti, G., Taccari, M., Ciani, M., Genevini, P., Adani, F. 2007. Precision determination for the specific oxygen uptake rate (SOUR) method used for biological stability evaluation of compost and biostabilized products. *Biores. Technol.*, 98: 706-713.

Stegmann, R., Lotter, S., King, L., Hopping, W.D. 1993. Fat of an absorbent gelling material for hygiene paper products in landfill and composting. *Waste Manage. Res.*, 11: 155-170.

Tiquia, S.M. 2005. Microbiological parameters as indicators of compost maturity. *J. Appl. Microbiol.*, 99: 816-828.

Tremier, A., de Guardia, A., Massiani, C., Paul, E., Martel, J.L. 2005. A respirometric method for characterising the organic composition and biodegradation kinetics and the temperature influence on the biodegradation kinetics, for a mixture of sludge and bulking agent to be co-composted. *Biores. Technol.*, 96: 169-180.

The U.S. Department of Agriculture and the U.S. Composting Council. 2001. Test methods for the examination of composting and compost, Edaphos International, Houston.

VanderGheynst, J.S., Gosset, J.M., Walker, L.P. 1997. High-solids aerobic decomposition: pilot-scale reactor development and experimentation. *Process Biochem.*, 32: 361-375.

Xi, B., Zhang, G., Liu, H. 2005. Process kinetics of inoculation composting of municipal solid waste. *J. Hazard. Mater.*, 124: 165-172.

Zenjari, B., El Hajjouji, H., Ait Baddi, G., Bailly, J.R., Revel, J.C., Nejmeddine, A. Hafidi, M. 2006. Eliminating toxic compounds by composting olive mill wastewater–straw mixtures. *J. Hazard. Mat.*, 138: 433-437.

Tables

TABLE 1: Levels of respiration activity obtained for the different wastes analyzed (n is the number of samples analyzed, RI_{av} is the average respiration activity, RI_{max} is the maximum respiration activity and RI_{min} is the minimum respiration activity).

Waste description	Respiration activity (RI) ($mg\ O_2\ g\ OM^{-1}\ h^{-1}$)			
	n	RI_{av}	RI_{max}	RI_{min}
Mixed municipal solid wastes	6	3.25	5.14	1.89
Organic fraction of municipal solid waste	9	5.81	9.22	3.82
Non-digested municipal wastewater sludge	5	7.01	8.10	5.01
Digested municipal wastewater sludge	5	2.56	3.73	1.64
Pig manure	7	2.70	3.12	1.99
Cow manure	6	2.65	3.77	2.20
Animal by-products	5	5.26	6.51	2.42
Hair wastes	3	2.46	3.22	1.72
Mushroom production wastes	7	1.60	2.20	1.11
Bulking agents	9	0.90	2.07	0.21

TABLE 2: Levels of respiration activity data previously reported in literature.

Waste description*	Respiration activity ($mg\ O_2\ g\ OM^{-1}\ h^{-1}$)**	Reference	Temperature***
Municipal Solid Waste (mixed and organic fraction)			
Mixed MSW	2.2	Adani *et al*., 2000	Process Temperature
Mixed MSW	1.75 - 2.00	Adani *et al*., 2003	Process Temperature
Mixed MSW and sawdust	7.0	Xi *et al*., 2005	Process Temperature
Source-selected OFMSW	3.5	Adani *et al*., 2002	Process Temperature
Source-selected OFMSW	3.8	Adani *et al*., 2001	Process Temperature
Mechanically separated OFMSW	3.26 - 5.15	Adani *et al*., 2003	Process Temperature
Mechanically separated OFMSW	2.45	Adani *et al*., 2004	Process Temperature
Mechanically separated OFMSW	8.58	Scaglia *et al*., 2007	Process Temperature
Mechanically separated OFMSW	2.17	Scaglia *et al*., 2000	Process Temperature
OFMSW and green waste	0.97 - 1.50	Adani, 2004	Process Temperature
OFMSW and green waste	1.61	Scaglia *et al*., 2000	Process Temperature
OFMSW and wood wastes	3.6	Scaglia *et al*., 2000	Process Temperature
Household wastes and pine bark	10.2	Berthe *et al*., 2007	35 ºC

Waste description*	Respiration activity ($mg\ O_2\ g\ OM^{-1}\ h^{-1}$)**	Reference	Temperature
Municipal Solid Waste (mixed and organic fraction)			
Household and lignocellulosic waste	9.0	Scaglia *et al*., 2007	Process Temperature
Synthetic food waste	1.8	VanderGheynst *et al*., 1997	Procees Temperature
Synthetic food waste	3.6	Liwarska-Bizukojc *et al*., 2003	37ºC
Wastewater treatment sludge			
Urban wastewater sludge	2.0	Lasaridi *et al*., 2000	30ºC
Urban wastewater sludge	5.8	Palestky and Young, 1995	35ºC
Urban digested wastewater sludge	1.2	VanderGheynst *et al*., 1997	Process Temperature
Secondary sewage sludge and straw	1.5	Lasaridi and Stentiford, 1998	30ºC
Urban dewatered sludge and wood wastes	5.4	Martel *et al*., 2006	40ºC
Urban dewatered sludge and wood wastes	4.2	Martel *et al*., 2006	40ºC
Urban dewatered sludge and wood wastes	3.1	Martel *et al*., 2006	40ºC
Urban dewatered sludge and wood wastes	4.6	Martel *et al*., 2006	40ºC
Urban dewatered sludge and wood wastes	4.0	Martel *et al*., 2006	40ºC
Urban wastewater sludge and sawdust	2.8 - 2.4	Liang *et al*., 2003	36ºC - 43ºC

Waste description*	Respiration activity ($mg\ O_2\ g\ OM^{-1}\ h^{-1}$)**	Reference	Temperature
	Wastewater treatment sludge		
Urban wastewater sludge and pine barks	14.8	Berthe *et al*., 2006	35ºC
Urban wastewater sludge and pine barks	6.4	Berthe *et al*., 2007	35ºC
Urban wastewater sludge and straw	3.25	Lasaridi *et al*., 2000	30ºC
Sludge (agro food industry) and pine barks	5.5	Berthe *et al*., 2007	35ºC
Sludge (food industry) and pine barks	2.0 - 2.6	Tremier *et al*., 2005	37-39ºC
Physico-chemical sludge and wood chips	0.89 - 3.26	de Guardia *et al*., 2008	Process Temperature
	Manure		
Pig manure and straw	9.6	Cronje *et al*., 2004	Process Temperature
Dairy cattle manure	5.0	Miyatake and Iwabuchi, 2006	Process Temperature
Cow manure and sawdust	1.92	Petruska *et al*., 1985	40ºC
Dairy manure and rice straw	2.3	Li *et al*., 2008	Process Temperature
Horse manure and cranberry fruit	1.62	Ramirez *et al*., 2006	25ºC
Turkey litter	2.08	Ahn *et al*., 2008	30ºC
Beef manure	1.13	Ahn *et al*., 2008	30ºC

Waste description*	Respiration activity ($mg\ O_2\ g\ OM^{-1}\ h^{-1}$)**	Reference	Temperature
Olive wastes and wastewater sludge			
Olive tree leaves and olive press cake	1.0 – 1.7	Papadimitriou and Balis, 1996	49 ºC
Olive press cake and olive mill wastewater	1.82 - 3.01	Mari *et al*., 2003	35ºC - 48,5ºC
Olive mill wastewater and olive press cake	0.7 - 1.7	Lasaridi *et al*., 1996	36ºC - 57ºC
Olive press cake and olive wastewater	1.98 - 3.78	Mari *et al*., 2003	35ºC - 48,5ºC
Bulking agents and carbonaceous amendments			
Alfalfa hay	3.96	Ahn *et al*., 2008	30ºC
Silage	3.08	Ahn *et al*., 2008	30ºC
Oat straw	1.46	Ahn *et al*., 2008	30ºC
Corn stalks	0.42	Ahn *et al*., 2008	30ºC
Leaves	0.75	Ahn *et al*., 2008	30ºC
Soybean straw	0.92	Ahn *et al*., 2008	30ºC
Wheat straw	0.92	Ahn *et al*., 2008	30ºC
Saw dust	0.15	Ahn *et al*., 2008	30ºC

Waste description*	Respiration activity ($mg\ O_2\ g\ OM^{-1}\ h^{-1}$)**	Reference	Temperature
	Bulking agents and carbonaceous amendments		
Soil compost blend	0.17	Ahn *et al*., 2008	30ºC
Wood shaving	0.06	Ahn *et al*., 2008	30ºC
	Mixed wastes		
Municipal solid wastes and poultry manure	2.0	Iannotti *et al*., 1993	37ºC
Advance life support organic wastes mixture	1.1	Ramirez *et al*., 2006	25ºC
Municipal sludge/animal residue/compost	1.09	Scaglia *et al*., 2007	Process Temperature
Shredded MSW and diapers	10.06	Stegmann *et al*., 1993	Process Temperature
Apple pomade and wood chips	0.75	Malinska and Richard, 2006	30ºC
Compost and chicken-dung	5.0	Baffi *et al*., 2007	Process Temperature

* Codification used: OFMSW: Organic Fraction of Municipal Solid Waste; MSW: Municipal Solid Waste. ** When several data is available, the range of respiration data is presented. *** Process temperature is the temperature profile the material spontaneously develops during respirometry due to self-heating in absence of temperature control.

TABLE 3: Unit conversion table for respiration indices.

Unit†	Multiply by*	To obtain
mg CO_2 g OM^{-1} h^{-1}	32/44	mg O_2 g OM^{-1} h^{-1}
mg O_2 g DM^{-1} h^{-1}	1/OM	
mg O_2 kg OM^{-1} h^{-1}	0.001	
mmol O_2 kg DM^{-1} h^{-1}	32/OM	

† DM: dry matter; * OM: organic matter fraction of the waste analyzed, on dry basis (g OM/g DM).

Captions to Figures

Figure 1: Distribution of respiration activity data for the different wastes analyzed. The average and maximum and minimum values are presented. Number of available data is presented in brackets.

Figure 1: Barrena *et al*.