Waste Management 55 (2016) 49–60

Contents lists available at ScienceDirect

Waste Management

journal homepage: www.elsevier.com/locate/wasman

Treatment of mechanically sorted organic waste by bioreactor landfill: Experimental results and preliminary comparative impact assessment with biostabilization and conventional landfill

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ARTICLE INFO

Article history:
Received 26 October 2015
Revised 10 February 2016
Accepted 18 March 2016
Available online 26 March 2016

Keywords:
Bioreactor landfill
Dynamic respiration index
Landfill gas
Life cycle analysis
Mechanically sorted organic fraction
Methane

ABSTRACT

Treatment and disposal of the mechanically sorted organic fraction (MSOF) of municipal solid waste using a full-scale hybrid bioreactor landfill was experimentally analyzed. A preliminary life cycle assessment was used to compare the hybrid bioreactor landfill with the conventional scheme based on aerobic biostabilization plus landfill. The main findings showed that hybrid bioreactor landfill was able to achieve a dynamic respiration index (DRI) < 1000 $mgO_2/(kgVS\ h)$ in 20 weeks, on average. Landfill gas (LFG) generation with CH_4 concentration >55% v/v started within 140 days from MSOF disposal, allowing prompt energy recovery and higher collection efficiency. With the exception of fresh water eutrophication with the bioreactor scenario there was a reduction of the impact categories by about 30% compared to the conventional scheme. Such environmental improvement was mainly a consequence of the reduction of direct and indirect emissions from conventional aerobic biostabilization and of the lower amount of gaseous loses from the bioreactor landfill.

1. Introduction

One of the main criticisms of the whole waste management chain is still the need for landfilling for final disposal of material resulting from recycling, recovery and treatment operations. The main concerns are the environmental impact due to liquid and gaseous emissions generated mainly by the biodegradable fraction of the disposed waste, health risks and soil use. As reported by the European Environmental Agency (EEA, 2011), in 2011, landfill gas (LFG) in the EU-15 (Desideri et al., 2003) accounted for about 3% of the whole anthropogenic greenhouse gas (GHG) emissions. Among the gaseous emissions from landfill, methane and dinitrogen oxides, generated by the aerobic/anaerobic spontaneous degradation of waste, have global warming potentials of about 20 and 300 times higher than CO_2, respectively (Hischier et al., 2010). For a further reduction of the environmental impact, the Council Directive (99/31/EC) on Landfill imposes a mandatory stepwise reduction of the amount of biodegradable waste landfilled with respect to the MSW generated in 1995, by 25%, 50% and 65%, respectively, by 2006, 2009 and 2016. In Italy the fraction of MSW landfilled in 2013 was about 37% (ISPRA, 2014). For the EU28 this figure, referring to the same year, was about 35%, even if for Eastern European States it was 60% up to 90%.

An efficient solution for diverting such waste from landfill is by source segregation aimed at recovery operations by organic fertilizer/soil improvement production. Currently in the EU28 about 50% of the whole generated organic fraction (OF) of MSW is source segregated and recovered by composting. The remaining fractions are generally collected, commingled with residual MSW (RMSW). Incineration of RMSW, an efficient strategy both for energy recovery and mass and biological reactivity reduction, currently treats about 24% of the waste generated in the EU28. Otherwise, incineration costs are significantly affected by scale factor and its social acceptance is still low in several EU areas.

Another widespread and viable solution for reducing the amount of landfilled biodegradable waste is by Mechanical Biological Treatment (MBT) (Di Maria, 2012). MBT consists in converting RMSW via mechanical and biological processes aimed mainly at stabilizing the biologically degradable components. In these facilities the RMSW undergoes mechanical processing, such as shredding, screening and metal sorting, in order to separate the OF from the other recyclable materials and components with higher calorific value. The Mechanically Sorted OF (MSOF) is then

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http://dx.doi.org/10.1016/j.wasman.2016.03.033
0956-053X/

biologically processed (Frike et al., 2005; Nguyen et al., 2007) to reduce its reactivity and mass before disposal. The other sorted fractions can be exploited for further recovery aims, including energy recovery, or at least landfilled. In compliance with Italian legislation (Decreto Ministeriale, 2010), one of the limits imposed for RMSW disposal in landfill is a residual biological reactivity level, measured by the dynamic respiration index (DRI) $\leqslant$ 1000 mgO_2/(kgVS h) (Di Maria and Micale, 2014). As reported by De Gioannis et al. (2009) MBT can reduce GHG emissions from landfill up to 90%. Benefits concerning reduction of long-term emissions from landfill by MBT were also reported by Frike et al. (2005) and Binner and Zach (1999). Reduction of environmental impact due to composting was also reported by Abduli et al. (2011) in a life cycle analysis (LCA) of waste management in Teheran. On the other hand, even if MBT is suitable for RMSW pre-treatment, some criticisms have been highlighted: a rather high energetic consumption, from 30 kW h/tonne to 50 kW h/tonne (Di Maria et al., 2015); indirect (*i.e.* energy consumption, maintenance) and direct GHG emissions from bio-stabilization (*e.g.* N_2O, NH_3, VOC, CO, H_2S) (Beyolt et al., 2015; Hischier et al., 2010; Valerio, 2010). The high level of indirect and direct GHG emissions from aerobic treatment of biological waste was also reported by Takata et al. (2013) for urban areas in Japan. In this case aerobic treatment was charged with an energy input of 115 kW h/Mg. Maulini-Duran et al. (2013) reported from 0.01 kg/Mg to 19.37 kg/Mg of direct GHG emissions generated by composting biosolids. Martinez-Blanco et al. (2010) reported 0.034 kg/Mg and 0.092 kg/Mg, respectively, of methane and nitrous oxide from composting the OF of solid waste. In the same study VOCs and NH_3 emissions were 1.21 kg/Mg and 0.11 kg/Mg, respectively. Furthermore, in a previous study, Di Maria et al. (2013a) demonstrated that for a landfill equipped with LFG energy recovery, excessive bio-stabilization of RMSW could lead to a reduction in global environmental benefits. This was a consequence of the relevant increase mainly in indirect emissions (*i.e.* energy consumption) of biostabilization and consequent reduction of the benefits (*i.e.* avoidance of fossil fuels) due to the reduction in the amount of LFG generated/recovered. On the basis of these findings, performing the bio-stabilization phase of the MSOF directly in the landfill using MBT could be a possible improvement for waste management systems. This requires construction and management strategies able to enhance the aerobic/anaerobic biological processes already occurring in conventional landfills. This goal can be achieved by managing landfills in bioreactor mode. Bioreactor landfills can be operated in anaerobic (Di Maria et al., 2013b; Pohland and Kim, 1999), aerobic (Bilgili et al., 2012) and semi-anaerobic (Cossu et al., 2003) conditions, but the main difference from conventional landfills is moisture control performed by leachate recirculation. Moisture control is a key parameter for enhancing the biodegradation process. Several studies have been proposed in the literature concerning both lab-scale and full-scale analysis of bioreactor landfills. Benson et al. (2007) reported the results of operating five full-scale landfills showing the increase in the amount of gas generated and the reduction in leachate pollutant concentration for recirculated landfill compared to the conventional one. Xie et al. (2015) and Di Maria et al. (2013b) demonstrated the adsorption of heavy metals by MSW by leachate recirculation. Nikitina et al. (2015), Slezak et al. (2015) and Warith (2002) investigated the biodegradation of waste in lab- and full-scale tests. In a comparative life cycle assessment (LCA) of landfill technologies, Manard et al. (2004) reported a lower impact due to bioreactor landfill compared to the conventional one. Modelling six landfilling technologies in a LCA perspective Manfredi and Christensen (2009) reported that bioreactor landfill can shorten the time frame that emissions lead to environmental impact. All the results obtained indicate the positive effects of leachate recirculation. With the exception of Di Maria et al. (2013b), the majority of the studies available in the literature concern bioreactor landfills for RMSW disposal. Hence, there is a lack of information on how bioreactor landfills perform for the treatment of the MSOF with respect to the traditional scheme based on MBT and conventional landfill.

For this aim, a full-scale hybrid bioreactor landfill for the MSOF generated in a waste management district of central Italy was monitored for two years. The main parameters such as LFG and the DRI of the MSOF were experimentally measured. Experimental data were also used for performing a preliminary comparative LCA between the scenario adopting MBT and conventional landfill and the scenario in which the MSOF was treated by the hybrid bioreactor landfill.

2. Material and methods

2.1. Experimental setup

In the hybrid bioreactor landfill the MSOF was positioned in successive layers, without compaction, for the construction of physically separated biocells, 6 m in height with an average volume of about 8000 m^3 (Fig. 1). Hybrid conditions in the bioreactor landfill were achieved by enhancing the initial aerobic phase, based on the natural circulation of air in the waste body due to the temperature difference with the external environment. Transition to anaerobic conditions occurred gradually in the underlying layers as a consequence of the increased thickness of waste caused by the continuous disposal of waste. Each biocell was equipped with a leachate collection pipe network and four vertical wells were constructed during MSOF positioning using a 1 m diameter metallic grid filled with coarse gravel. For enhancing air circulation also in successive layers during biocell construction, each well was connected with three horizontal trenches, forming an angle of 120° from one another. Trenches consisting of a 1 m^2 section, 15 m long, filled with coarse gravel, were constructed in layers 2 m and 4 m from the cell bottom. During the anaerobic phase this system was used for LFG collection. A semi-closed leachate recirculation system was also constructed for each cell. The leachate collected by the draining pipes was stored in a tank equipped with an overflow system. The recirculation network was constructed with perforated HDPE pipes positioned about 0.5 m under the waste mass in gravel trenches at a distance of about 2 m from one another and fed with the leachate stored in the tank by a temporized pump. An important aspect investigated was the development of aerobic and anaerobic phases inside the mass of the disposed waste. Considering the full-scale application, this aspect was followed by monitoring two main parameters: temperature; gas composition. Since aerobic processes are highly exothermic the rapidity of the increase in the temperatures and the level achieved during the first weeks from waste disposal indicate how the aeration process was efficient. Over longer periods, quite high temperature levels can be maintained due to the insulating effect of the successive layers of waste making the temperature at which biological processes occur no longer significant. In this phase useful information can be obtained from knowing the composition of the gas generated inside the waste mass (*e.g.* O_2, CH_4, CO_2). For these reasons the first biocell was equipped with temperature and gas probes (Fig. 2). Sixteen gas sampling probes and 16 temperature probes (Lorenzoni, IKE Pt100 Φ 5 mm, AISI 316) were positioned inside the waste mass during the biocell construction. The probes and the gas sampling systems were positioned on the same layers at two different levels from the cell bottom: 2 m; 4 m. Both temperature probes and gas sampling systems were connected with cables and 12 mm diameter pipes, respectively, directly outside the waste