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Lessons learned by modelling biogas production in an Italian state-of-the-art landfill active for 35 years

FOLINO A.[1], GENTILI E.[2], KOMILIS D.[3], CALABRO' P.S.[1,*]

[1]Department of Civil, Energy, Environmental and Materials Engineering, Università Mediterranea di Reggio Calabria, via Zehender – loc. Feo di Vito, 89122 Reggio Calabria, Italy.

[2] CMSA Cooperativa Muratori Sterratori e Affini, Via L. Ariosto 3, 51016 Montecatini Terme (PT), Italy.

[3] Department of Environmental Engineering, Democritus University of Thrace, Kimmeria Campus GR 671 00 Xanthi, Greece

*corresponding author:
e-mail: paolo.calabro@unirc.it

Abstract "Fossetto" landfill is in operation in the municipality of Monsummano Terme (Tuscany, Italy) since 1988, at its origin, it was used as a controlled landfill where mixed municipal solid waste, without any separate collection, was disposed of. Since 2003, a biogas recovery system is active, while a mechanical-biological treatment (MBT) plant and a reverse osmosis leachate treatment plant that recirculates leachate are installed since 2006. This plant provides long-term biogas monitoring that allowed to calculate, with a simplified methodology, the biogas recovery efficiency. Biogas generation modelling via the USEPA LandGEM model showed that the adoption of MBT grandly reduced the biogas production, while extraction efficiency was calculated at around 40% over the last ten years, lower than expected. Efficient separate collection leading to the reduction of both the incoming waste amount and of its biogas potential production coupled with mechanical biological treatment proved effective to reduce landfill environmental impacts. More research is needed to establish new technologies to further reduce fugitive biogas emissions from the landfill.

Keywords: biogas, extraction efficiency, greenhouse gases, landfill, Landgem model.

1. Introduction

Even in countries with modern integrated waste management systems (Calabrò et al., 2015) landfills are an essential step for the disposal of waste that cannot be further valorised. On the other hand, the biodegradation of the disposed wastes, during operation and post-closure of the landfill, generates leachate and landfill gas (LFG) (Gioannis et al., 2009; Randazzo et al., 2023). LFG, or landfill biogas, is mainly composed of CH_4, CO_2 and non-methane volatile organic compounds (NMVOCs) at low percentage (< 1% v/v) (Tassi et al., 2009). It accounts to the one-third of anthropogenic methane emissions at European level (Gioannis et al., 2009). Mechanical biological treatment (MBT) technology is widely applied in European countries to aerobically or anaerobically stabilize the organic matter still present in the residual municipal waste (Di Lonardo et al., 2015) with the aim of reducing the environmental landfill impacts (Boccarossa et al., 2021). However, the MBT output is often not completely stabilised, thus expressing residual anaerobic activity when disposed of in a landfill (Bayard et al., 2008; Carchesio et al., 2020; Tintner et al., 2012). Moreover, even though sanitary landfills are equipped with biogas collection systems, they do not allow for a total biogas extraction (Capaccioni et al., 2011) contributing to the fugitive release of greenhouse gases (GHGs) to the atmosphere.

"Il Fossetto" landfill has been active since 1988. It is owned by the municipality of Monsummano Terme (Pistoia Province, Tuscany, Italy) and its service area progressively enlarged over the years due to the increase of separate collection in the area (now about 60%) and to the lack of other available landfills. It is built in a flat area and reached over the years a total authorized volume of about 1,295,000 m^3. Initially, it was used to dispose of mixed municipal waste without any previous treatment or separate collection and then accepted also non-hazardous bottom ash and slag generated by a municipal waste incinerator. Around the year 2000, as required by National and Regional regulations, separate collection efficiency increased and included household organics. Direct landfilling of mixed municipal waste was stopped in 2003 when a mechanical and biological treatment (MBT) plant was put in operation while in 2011 also the disposal of incineration bottom ash and slag was terminated. A biogas collection and recovery system with energy production and a reverse-osmosis leachate treatment plant (with the concentrated leachate being recirculated back into the landfill body) have been installed since 2006. The biogas recovery system includes 77 extraction wells over an area of about 91,000 m^2 with one well on average covering 1,200 m^2. The biogas extracted is used for energy production and, for safety reasons, a gas flare is also present.

For more information on "Il Fossetto" landfill see available literature (Calabrò et al., 2018, 2010).

2. Materials and Methods

According to the requirements of the Control Authority (Pistoia Province), an extensive monitoring program is being regularly carried out in “Il Fossetto” landfill. A weakness is that for several parameters (e.g. leachate characteristics from each well, fugitive biogas emissions) only one measurement per year is available and therefore the uncertainty of the estimation is quite high; however this is counterbalanced by the availability of a long series of data that allow to evaluate the trends with descent reliability.

In order to calculate the average efficiency of the biogas collection system, a simple procedure has been developed and applied. First, since the collection system is active (i.e., blowers create negative pressure in the collection wells), significant amounts of air are present in the biogas (average O_2 concentration is 2.4±1.1%); therefore, the amount of biogas extracted has to be corrected. To do this, first the amount of methane extracted is calculated by multiplying the biogas extracted by the average CH_4 percentage in biogas (average of the available measurements in a given year), then, as usually done in similar calculations (Calabrò et al., 2011; Themelis and Ulloa, 2007), the biogas typical composition is set at 50% CH_4 and 50% CO_2 and therefore actual biogas extracted (indicated as LFG_{50extr}) is assumed to be equal to twice the amount of the extracted methane.

$$LFG_{50extr} = 2 \cdot (LFG_{extr} \cdot \%CH_4) \quad (1)$$

Where: LFG_{50extr} [m^3 $year^{-1}$] is the theoretical amount of biogas extracted if considered to be composed of 50% methane and 50% carbon dioxide; LFG_{extr} [m^3 $year^{-1}$] is the actual amount of biogas extracted during each year; $\%CH_4$ is the average percentage of methane in the extracted biogas.

Total biogas production, LFG_{50}, is calculated by summing the LFG_{50extr} and the fugitive emissions (measured during the annual survey) increased by 10% to account for the methane oxidation at the landfill surface (Alvarez-Cohen and McCarty, 1991; Alvarez-Cohen and Speitel, 2001; Calabrò and Lisi, 2015; Randazzo et al., 2022); (Calabrò and Lisi, 2015).

$$LFG_{50} = LFG_{50extr} + 1.1 \cdot LFG_{50fug} \quad (2)$$

Where LFG_{50fug} is the amount of landfill gas emitted by the landfill body evaluated through the experimental campaigns carried out annually.

Finally, for a selected year, the biogas collection efficiency is calculated as the ratio between LFG_{50extr} and the total estimated biogas production.

Therefore, it was possible to calculate LFG_{50extr} since 2003 and LFG_{50} total (generated) since 2008, as it was on 2008 that fugitive biogas emissions had started to be measured annually.

The well-known USEPA Landfill Gas Generation Model (LandGEM) (U.S. Environmental Protection Agency, 2005) was used to model LFG_{50} produced in the landfill. The model was calibrated by a trial-and-error method using the data of LFG_{50} calculated for the period 2008-2021. In agreement with the general approach of the model and using the overlapping principle, the two periods before (1988-2003) and after (2004-2021) the implementation of the MBT plant were evaluated separately in order to account for the different composition of landfilled waste.

In addition, since the electric energy produced from the recovered biogas is measured routinely and the GHG (CO_{2e}) emission intensity from electricity generation (kg $CO_2 \cdot kWh^{-1}$) in Italy is also available in the literature (European Environment Agency, 2022), it was possible to calculate the CO_{2e} emissions compensation due to biogas recovery for energy (Calabrò et al., 2015; Calabrò and Lisi, 2015).

3. Results and discussions

Table 1 presents actual biogas extracted, the LFG_{50} extracted, the estimated total LFG_{50} produced in the landfill and the assessed extraction efficiency. Table 2 presents the parameters of LandGEM as calibrated by trial and error while Figure 1 shows the results obtained by the model.

Table 1. Biogas extracted, LFG_{50} extracted and extraction efficiency

Year	Biogas extracted [Nm^3]	LFG_{50extr} [Nm^3]	Total LFG_{50} [Nm3]	Extraction efficiency
2003	3,059,555	2,814,791		
2004	3,326,967	3,060,810		
2005	3,031,305	2,910,053		
2006	2,592,935	2,333,642		
2007	1,768,756	1,662,631		
2008	1,408,969	1,155,355	1,799,215	64%
2009	1,310,512	891,148	2,482,402	36%
2010	741,518	563,554	3,654,082	15%
2011	821,389	755,678	4,839,590	16%
2012	853,243	716,724	3,779,658	19%
2013	1,281,781	1,286,908	4,276,258	30%
2014	1,396,315	1,424,241	2,886,723	49%
2015	1,444,641	1,415,748	2,777,052	51%
2016	1,490,925	1,252,377	2,889,621	43%
2017	1,116,045	937,478	1,903,268	49%
2018	694,881	644,850	1,739,412	37%
2019	563,326	521,640	1,579,410	33%
2020	859,428	900,681	1,691,709	53%
2021	882,261	845,206	2,151,322	39%

Table 2. Parameters of the LandGEM model

	Raw waste	MBT waste
L_0 [$Nm^3 \cdot$wet Mg^{-1}]	70	20
k [y^{-1}]	0.1	0.7*

L_0 is defined as the potential methane generation capacity
*Inventory value for wet landfills (or bioreactors)

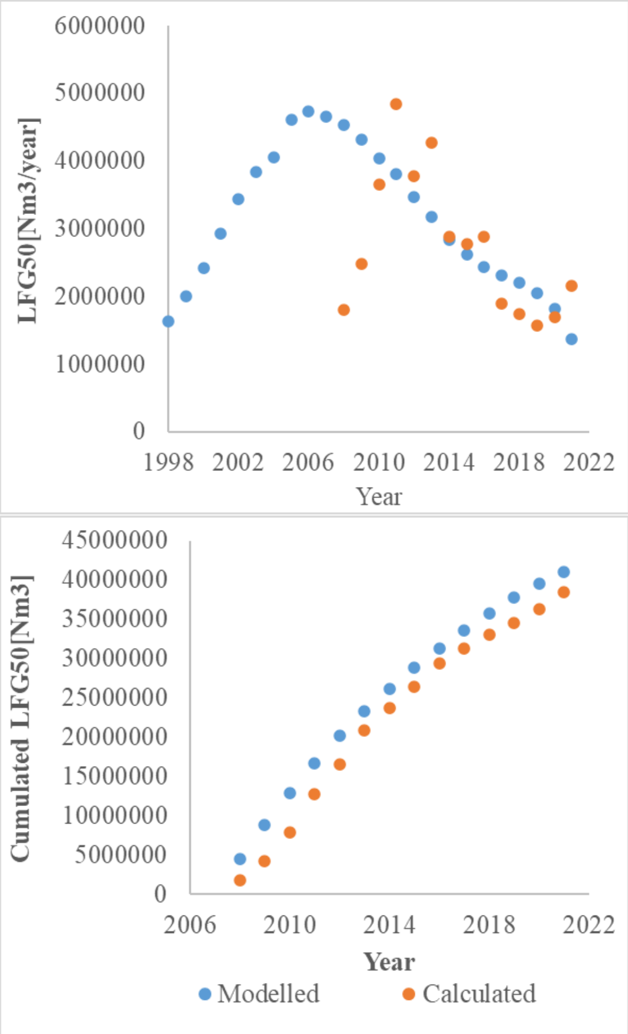

Figure 1. Comparison of calculated and modelled LFG_{50} annual generation and cumulative production

LandGEM, notwithstanding its simplicity, seems to model fairly good the calculated values of LFG_{50} produced in the landfill. Modelling clearly shows how the MBT of incoming waste (which started operation on 2003) caused a significant reduction in the value of biogas production potential respect to literature values for raw waste (even if potential biogas production does exist in pre-treated MBT waste after a long period of aerobic stabilisation (Bayard et al., 2008). Also, it is probable that the recirculation (started operation on 2006) induced a change in the production dynamics that shifted from that of a conventional landfill to a wet bioreactor like one. The aim of the use of MBT prior to landfilling is, indeed, the prevention of landfill emissions after final waste disposal (Tintner et al., 2012). The effect of MBT on the reduction of biogas production has been well documented in experimental research and full-scale studies as well. Compared to untreated waste, pre-treated MBT waste showed a landfill gas yield lower than more than 80% (up to about 90% when longer treatment period was applied) (Gioannis et al., 2009; Lornage et al., 2007) compared to untreated waste. Other than reducing biogas generation, MBT also reduces (i) the mass of waste entering the landfill (Lornage et al., 2007), (ii) the release of organic carbon and nitrogenous compounds and (iii) the long-term landfill body settlement which is a result of creep and biodegradation (Siddiqui, 2014).

The key findings reported in (Calabrò et al., 2011) and in particular the low methane yield for the MBT waste and the methane production rate for the raw waste have been confirmed. In fact, for the period 1998-2003 the calibrated value of the biogas production rate was significantly higher than the inventory value set as default in the model. This can be explained considering the annual rainfall in the area, that is around 1,100 mm/y, the fact that infiltration is facilitated due to the lack of an impermeable cover and the fact that cells L2 and L4 were periodically re-opened for filling using the volume created after waste settlement over the years.

The results obtained by the model for the very first years (2008-2010) do not fit the calculated LFG_{50} data while for the period 2011-2021 the trend is simulated fairly well. In fact, in 2021, the difference between calculated and modelled cumulative LFG_{50} is about only 6.2%.

The reason for the bad performance in the first years of calculation is probably attributed to the large variation in the assessment of the fugitive emissions during the experimental campaigns in that period. The average fugitive flux was estimated to be 122 ± 73 $Nm^3 \cdot h^{-1}$ in the years 2008 and 2009 and then sharply rose to 360 ± 57 $Nm^3 \cdot h^{-1}$ for the period 2010-2013. In the following 8 years (2014-2021), fugitive fluxes were on average 132 ± 30 $Nm^3 \cdot h^{-1}$. These high fluxes can be due to a number of reasons: i) need to optimize the measurement procedure, ii) imperfect management of the extraction system, iii) frequent operational interventions on the extraction system (wells disconnection for raising or addition of new ones). The average extraction efficiency in the period 2008-2021 is equal to 40±14% but large variations (maximum 64%, minimum 15%) are present due to the problems related to the management of the extraction system and to the uncertainty linked to the assessment of fugitive emissions.

Finally, according to the calculations carried out, the measured electricity production from biogas recovery in the period 2008-2021, would compensate only about 1% of the total emissions due to fugitive methane (in CO_{2e}).

4. Conclusions

The key message of the analysis carried out in this paper is that the reliability of the modelling of the biogas production will be increased if more data are available. In particular, more frequent measurements of the biogas composition and of the fugitive biogas emissions would be needed for the precise assessment of the landfill biogas production rates and for a better calibration of the model.

The efficient separate collection leads to the reduction of the incoming waste amount and of its biogas yield. Moreover, the mechanical biological treatment proved effective to reduce the environmental impact of the landfill. The average assessed efficiency of the biogas recovery system is quite low from the Fossetto landfill and energy recovery from biogas eventually provides a small compensation of the total GHGs emissions. Therefore, more research is needed to further reduce the fugitive biogas emissions from the landfill body.

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