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Life Cycle Assessment (LCA) of landfill gas management: comparison between conventional technologies and microbial oxidation systems

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Abstract

The reduction of landfill gas emissions is a central issue of the *Directive 99/31/EC*. Biofilters and biocovers have been identified as an alternative and cost-effective technologies to mitigate impacts due to CH_4 and NMVOCs emissions. The Life Cycle Assessment demonstrates the environmental sustainability of biofiltration systems, with the aim of improving the environmental impact indicators such as Global Warming (-10.75% for Biofilter and -11.60% for Biocover) and Photochemical oxidation (-7.97% for Biofilter and -8.61%. for Biocover). This paper shows that these treatment technologies are effective for methane oxidation when the calorific value of the LFG is low, thus they maximize the amount of treated gas during the after-care phase.

Keywords: life cycle assessment, landfill gas, microbial methane oxidation, internal combustion engines, flares, biofilter, biocover

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1. Introduction

One of the main environmental challenges associated with landfills is the generation of landfill gas (LFG), produced by the anaerobic decomposition of organic waste [1]. Due to regulations, conventional landfills are being outfaced in a European context as organic waste is being treated with other technologies. Nevertheless, it is still the dominant technology worldwide in both industrialized and developing countries [2]. Therefore, the development of cost-effective strategies for landfill aftercare is in society's interest aiming at protecting human health and environment and preventing the emergency of landfills with exhausted aftercare funding [3]. LFG is mainly composed by methane (CH_4) and carbon dioxide (CO_2), and its production lasts until most of the organic material in waste is degraded, which can take several decades. Apart from CH_4 and CO_2, other gas compounds can be found in LFG such as NMVOCs, including aliphatic (alkanes, alkenes), aromatic (benzene, toluene, ethylbenzene etc.,), halogenated (dichlorodifluoromethane, vinyl chloride, etc) hydrocarbons and alcohols (ethanol, methanol, etc) [4].

The reduction of LFG emissions is a central issue of the *EU Landfill Directive (Directive 99/31/EC).* In order to reduce CH_4 emissions from the waste management sector the Directive acts through two main measures: (i) the mandatory use of LFG extraction and energy recovery systems or LFG flaring in all new disposal sites, accepting biodegradable wastes; (ii) the progressive reduction of the amount of biodegradable waste going to landfill. However, some critical issues regarding the management of LFG with low calorific value are still present. In fact, when CH_4 concentration is too low for combustion (<20%v/v) the collected gas is vented without thermal treatment, due to difficulties that can occur in sustaining combustion even within the flare [5].

This study is part of LIFE RE Mida (LIFE14 CCM/IT/000464) project which aims to encourage the development of technologies in the field of LFG management. The main goal of the project is to reduce the greenhouse effect and mitigate the impacts due to NMVOCs emissions in both managed and unmanaged landfills, with particular attention to the biofiltration systems: biocover and biofilter. The biofiltration involves biological oxidation by aerobic methanotrophic bacteria, which are established on a filter media and use CH_4 as an energy source and as a substrate for growth. Biocovers (passive biofiltration) are landfill cover system designed to optimize the growth conditions of methanotrophic microorganisms. Biofilters (active biofiltration) are fixed bed reactors containing the filter matrix.

This paper aims at comparing the performances of alternative LFG control measures by means of a site-specific life cycle assessment (LCA). LCA concepts and techniques provide an excellent framework to evaluate environmental benefits and drawbacks arising from the implementation of the assessed technologies [6].

The goal of the assessment is the comparison between different landfill gas management strategies, with reference to different time frames: the first 20 years are the *operational management phase*, in which the waste is landfilled, and the gas is collected and treated. The following 50 years are the *after-care phase* characterized by monitoring and control activities of polluting substances. The last 30 years concern the after *after-care phase,* where the monitoring and control activities of polluting substances continue. In particular, three alternative scenarios (*Scenario 1, Scenario 2, Scenario 3*) are compared with a reference scenario (*Scenario 0*).

This work presents the results of the comparison performed in order to assess the environmental sustainability of microbial methane oxidation technologies among the reference treatment technologies.

Nomenclature

ICE	internal combustion engine
LFG	landfill gas
VOC	volatile organic compounds
LCA	life cycle assessment
NMVOCs	non- methane volatile organic compounds
GW	global warming
LHV	low heating values

2. Materials and methods

LCA consists of the following phases: goal and scope definition, inventory analysis, impact assessment, and interpretation and improvement [7]. In the following paragraphs, each step is described with regard to this work.

2.1. Goal and Scope definition

The aim of this study is to compare different LFG management strategies compliant with the European and Italian legislation requirement for landfills receiving biodegradable waste, by performing a life cycle-based environmental assessment. The Functional Unit is the overall production of LFG (Nm^3) over a period of 100 years from a non-hazardous urban waste landfill, with specific reference to the real case of Podere il Pero landfill in Castiglion Fibocchi (Italy). In general, the reference system is illustrated by the scheme in Fig. 1, from which the different scenarios are derived, according to different assumptions for the treatment technologies. The system includes the landfill, the LFG generation and treatments. Concerning LFG, it is divided into *collected LFG*, that is the fraction collected and treated as required by legislation, and *LFG emission* that is the fraction directly released through the top cover.

Furthermore, uncollected gas (*LFG emission*) transits across the landfill soil cover before being released to the environment. Near the landfill surface, bacteria degrade methane and volatile hydrocarbons through a reaction with atmospheric oxygen [8]. This degradation was accounted for the four compared management scenarios here described and the assumptions are reported in Table 1.

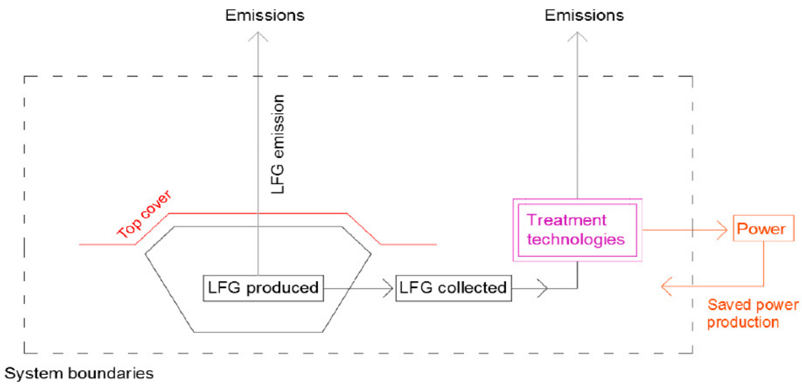

Fig. 1. System boundaries

Scenario 0 represents the reference scenario. The collected LFG is combusted with energy recovery for the first 19 years in an ICE. In the following 50 years, the LFG is burnt in flares until its Low Heating Values (LHV) is enough, and when the LHV is not enough it is released into the atmosphere through the top cover with no treatment; independently from the LHV, no treatment is applied after the 70th year.

Scenario 1: the collected LFG is combusted with energy recovery for the first 19 years in an ICE; in the following 50 years, it is burnt in flares and when the LHV is not enough, additional fuel is used until the CH_4 concentration is > 5%; no treatment is applied after the 70th year.

Scenario 2: the collected LFG is combusted with energy recovery for the first 19 years in an ICE; in the following 50 years, it is burnt in flares until its LHV is enough; when the LHV is too low to sustain the combustion, the LFG is processed by mean of an active biofiltration system (biofilter). This biofiltration system is designed with the method described in [9]. Biofiltration is kept active even after the 70th year.

Scenario 3: the collected LFG is combusted with energy recovery for the first 19 years in an ICE; in the following 50 years, it is burnt in flares until its LHV is enough; when the LHV is too low to sustain the combustion, the LFG is not collected and it is processed by mean of passive biofiltration system, i.e. biocover. The biocover is installed as final coverage system and it is designed based on a rate of methane degradation equal to 535.2 gCH_4/m^2d ([10,11]). Obviously, the biocover will continue to work even after the 70th year.

Both biofiltration systems allow the treatment of LFG with low calorific avoiding the consumption of natural gas.

Table 1. Scenarios structure.

	1-19 years	20-69 years	≥ 70 years
Scenario 0	ICE / Flare	Flare	/
Scenario 1	ICE / Flare	Flare + fuel	/
Scenario 2	ICE / Flare	Flare + Biofilter	Biofilter
Scenario 3	ICE / Flare	Flare + Biocover	Biocover

2.2. Inventory Analysis

The inventory analysis is a quantitative description [12] of all the flows of materials and energy across the system boundaries either into or out of the system itself. Inventory data for the compared treatments are collected by different methods: data supplied by the *project partners* ([13], [14]), literature data ([2],[15],[16],[17],[18],[19]) and data from monitoring activities concerning *LIFE RE Mida Project* [10], [11], [20].

Table 2. Quantitative data about LFG (100 years).

	Scenario 0	Scenario 1	Scenario 2	Scenario 3
LFG generated [Nm^3]	67721642	67721642	67721642	67721642
LFG treated [Nm^3]	44434148	45963805	46118191	46335962
LFG released (through the top cover) [Nm^3]	23287493	21757837	21603451	21385680

The production of LFG is obtained by means of the Scholl Canyon forecasting model applied to the real case of Podere il Pero Landfill (AR) [19]. The LFG composition is obtained based on literature data [18], real data provided directly by the company managing the plant [13] and data from monitoring activities concerning the LIFE RE Mida Project ([10], [11], [20]). The contents of CH_4, CO_2, O_2, VOC's, NH_3 and H_2S are variable over time with reference to 4 different phases of gas production recognized in literature as: an initial aerobic phase, an acetogenic phase, an unstable and a stable methanogenic phase [18]. Methane concentration in landfill biogas is directly dependent on the amount of disposed organic waste [21] and its trend is reported in Fig. 2.

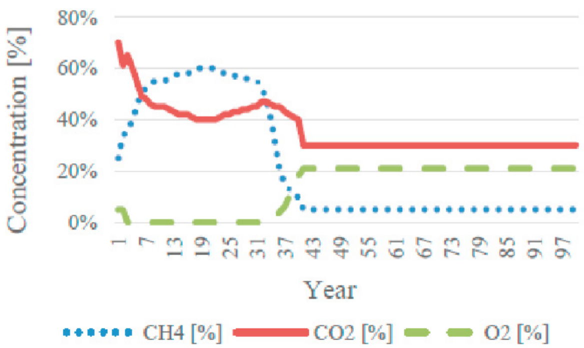

Fig. 2. Macro components composition

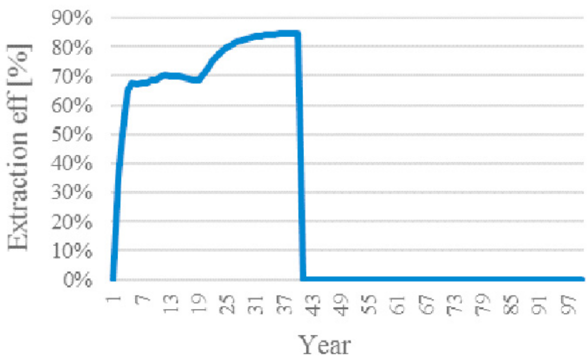

Fig. 3. Extraction efficiency

The concentration of trace gas compounds is originated from chemical and biological decomposition processes of waste within the landfill and/or from releases related to hazardous waste [17]. Their concentration is defined by means of a data reprocessing obtained from monitoring activities of LIFE RE Mida Project. Results are reported in Table 3.

Table 3. Landfill gas concentration (mg/Nm^3) and corresponding attenuation rates in top cover (%).

Substances	1-19 years	20-69 years	≥ 70 years	Period 1 (%)	Period 2 (%)	Period 3 (%)	References for rates
CH_4				35	35	80	[15]
NH_3	26.1	6.8	0	0	0	0	[17]
H_2S	606	2.93±0.73	15.88±9	20	20	40	[17]
Benzene	2.2-2.9	0.05	0.26	26	26	50	[17]
Xylenes	43.4–44.9	0.57	0.28	30	30	30	[17]
Toluene	29.4–33.4	0.42	0.34	60	60	60	[17]
Benzene, ethyl	18.1-18.27	0.145	0.124	26	26	50	[17]
Benzene, 1,2,4 - trimethyl	8.3–7.5	0.025	0.057	26	26	50	[17]
Ethene, 1,2-dichloro-	0.03–0.04	0.12	0.89	0	0	0	[17]
Vinyl chloride	0.226-0.12	1.22	1.86	74	74	90	[15]
n-butanol	0.54–1.9	0.086	0.195	20	20	40	[17]
Ethanol	0.25–2.36	0.401	0.408	20	20	40	[17]
Alpha pinene	9.8–19.22	8.4	0.7	20	20	40	[17]
Limonene	56.8-92.7	0.44	0.42	20	20	40	[17]
Pentane,3-methyl	0.94–0.97	0.2	0.5	22	22	22	[17]
n-pentane	0.03–0.03	0.42	1.45	22	22	22	[17]
Styrene	1.1–3.3	0.004	0.05	30	30	30	[17]

2.2.1. Landfill biogas utilization

The LFG collection efficiencies are based on data provided directly by the company managing *Podere il Pero* landfill (Fig. 3). For all considered scenarios, the collected LFG is assumed to be burnt first in ICE and then in flares. The emission factors of the analyzed compounds are obtained from previous literature works and reported in Table 4.

Table 4. Emission factors for landfill biogas combustion in flares and engines.

Substance	Unit	ICE	Flares	Reference
CH_4	% removal	/	99	[22]
NOx	g/Nm^3CH_4	11.6	0.631	[23]
CO	g/Nm^3CH_4	8.46	0.737	[23]
PM	g/Nm^3CH_4	0.232	0.238	[23]
Dioxins/Furans	g/Nm^3CH_4	/	$6.7x10^{-9}$	[23]
HCl	g/Nm^3CH_4	0.17	0.75	[24]
HF	g/Nm^3CH_4	0.189	0.151	[24]
VOC’s	% removal	97.15	99.23	[23]

In scenarios 2 and 3, when the calorific value of the LFG is not sufficient for its combustion, the LFG is treated with an active biofiltration system (biofilter) and a passive biofiltration system (biocover) for *Scenario 2* and *Scenario 3* respectively. Degradation efficiencies for the different compounds are obtained from monitoring activities of LIFE RE Mida Project and are reported in Table 5.

Table 5. Biofilter and biocover degradation efficiencies for different compounds.

Substance	Ox. Biof [%]	Ox. Bioc [%]	Substance	Ox. Biof [%]	Ox. Bioc [%]
CH_4	[99-100]	[60-100]	Vinyl chloride	99.8	99.9
H_2S	69.6	100	n-butanol	52.1	99.9
NH_3	0	0	3methylpentane	61.9	99.9
Acetone	93.2	99.96	α-pinene	99.6	99.9
Benzene	100	99.87	Limonene	91.6	98.3
Xylenes	55	100	Ethanol	69.1	99.7
Ethyl-benzene	0	99.7	n-pentane	100	99.9
1,2-dichloro-ethene	77.5	99.84	1,2,4-trimethyl-benzene	100	97.4
Toluene	88.7	99.75	Styrene	0	95.7

2.3. Impact Assessment

Life cycle impact assessment evaluates [12] the system mass and energy inventory input and output data in order to identify their environmental relevance and significance. This evaluation uses numerical indicators for specific subjects or categories. Indicators reflect the system environmental load and the resource depletion for each category [25]. In this study, the results of the impact assessment are presented according to the CML-IA baseline V3.02 / EU25 method, Institute of Environmental Sciences of the Leiden University (NL) [26].

3. Results

The final stage of LCA is the interpretation phase [12] where impact assessment results are summarized and discussed. Results are here presented only for Global Warming and Photochemical oxidation indicators, as reported in Fig. 4 and 5, because from the sensitivity analysis they are the most sensitive.

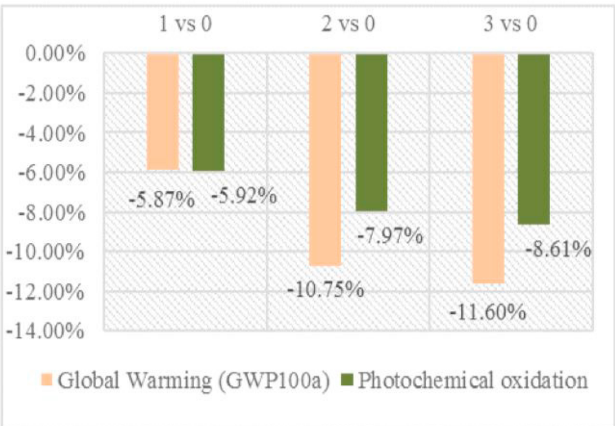

Fig. 4. Comparison between alternative scenarios and reference scenario

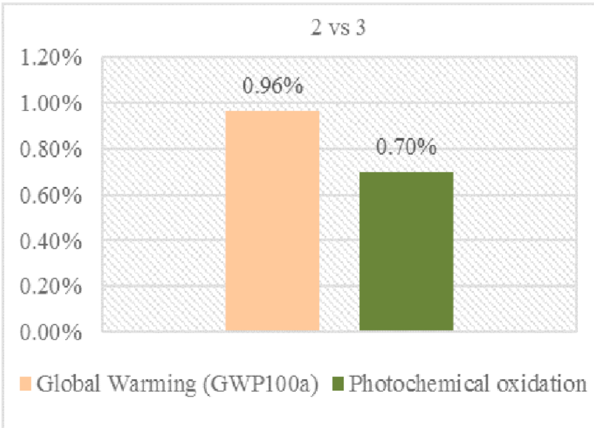

Fig. 5. Comparison between scenarios with microbial oxidation systems

Fig. 4 shows the comparison of the environmental performances of the alternative scenarios, in terms of percentage differences of the indicators calculated for scenarios 1, 2 and 3 with respect to the reference scenario (scenario 0). The negative values represent an improvement of the environmental performances. The alternative scenarios are more performing than the reference one. In particular Scenario 2 and Scenario 3, the two scenarios characterized by the use of microbial oxidation system highlight the best results. Scenario 2 shows percentage differences of -10.75% for GW and -7.97% for Photochemical oxidation; while Scenario 3 obtains percentages of -11.60% and -8.61% for GW and Photochemical oxidation respectively.

Fig. 5 focuses the attention on the comparison between Scenario 2 and 3, showing that the biocover system ensures better environmental performances, since the biofilter is not able to treat the totally produced LFG.

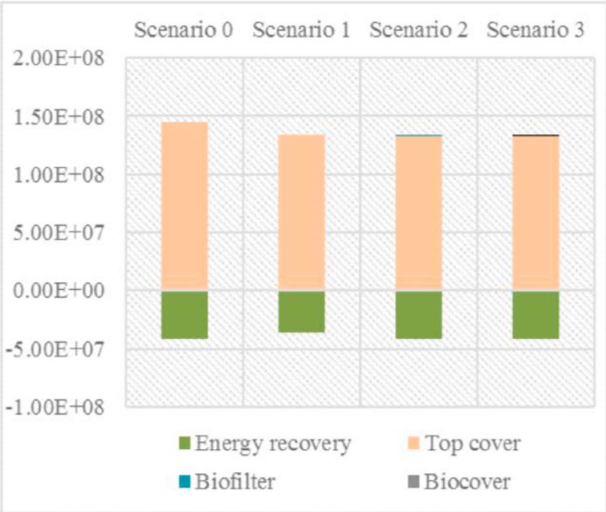

Fig. 6. Contributions to Global Warming [units: $kgCO_2$-eq]

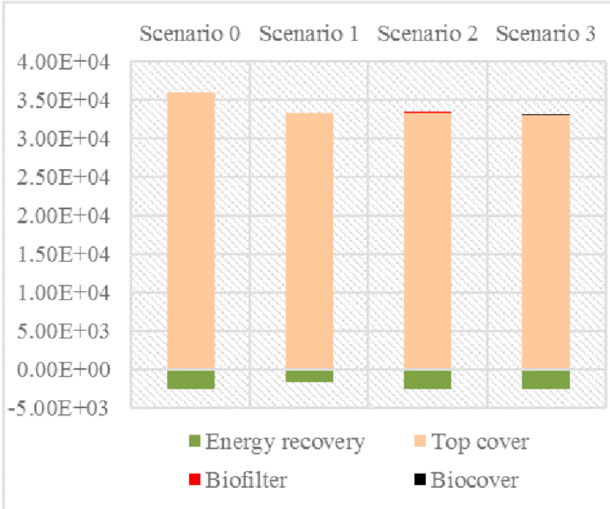

Fig. 7. Contributions to Photochemical oxidation [units: C_2H_4-eq]

Fig. 6 and 7 show the contributions of the different sub-processes – energy recovery, top cover, biofilter and biocover - to the total values of the considered indicators calculated for each scenario. The results indicate that the two sub-processes that mainly affect the indicators are energy recovery and top cover realization which play a key role in terms of savings and impacts.

4. Conclusions

This work presents the results of the comparison performed in order to assess the environmental performances of microbial methane oxidation technologies with respect to the reference treatment technologies. The results of the LCA indicate that the two sub-processes that mainly affect the indicators are energy recovery and top cover realization which play a key role in terms of savings and impacts. In general, the proposed alternative scenarios – based on microbial methane oxidation technologies (Scenario 2 and 3) - are more performing than the reference one. This result is obtained because these treatment technologies are effective for methane oxidation when the calorific value of the LFG is low, thus they maximize the amount of treated gas (i.e. CH_4 converted into CO_2) during the after-care phase and the subsequent one. In this way, the amount of LFG directly released through the top cover is reduced. Additionally, the scenarios based on microbial methane oxidation technologies allow for saving natural gas, which is otherwise used to convert CH_4 to CO_2, in conventional flaring, when the LFG low heating value is too low. In conclusions, biocovers and biofilters are effective in reducing CH_4 emission to atmosphere and result sustainable from the environmental point of view on a life cycle perspective.

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