Biofiltration of low levels of landfill gas: Human Health Risk Assessment of volatile and malodorous compounds emissions

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Abstract

Purpose: The aim of this study is to perform a Health Human Risk Assessment to evaluate the risk from exposure to landfill gas emissions and the impact on the environment of odour compound emissions from a post-closure landfill site in which an active biofilter was built for the biological oxidation of low-calorific value landfill gas.

Methods: The HHRA analyses three different scenarios of landfill gas management strategy and evaluates the risk from inhalation exposure to 9 Non-Methane Volatile Organic Compounds (cyclohexane, n-hexane, 2-methylpentane, 3-methylpentane, benzene, xylenes, toluene, dichlorodifluoromethane, vinyl chloride). At first, during three monitoring campaigns, a sample of the raw LFG and three air samples were collected and analysed according to US EPA, 1995 and US EPA TO-15, 1999. Then, the concentration levels and the emissive rates of the pollutants were calculated. In particular, dynamic olfactometry, according to EN 13725:2003, was applied to evaluate the odour concentration at each sampling point. Finally, CALPUFF model permits to evaluate the concentration of pollutants and odour compounds at eleven sensitive receptors.

Results: The individual risk from inhalation exposure of non-cancerogenic and cancerogenic compounds resulted for all the scenarios of many orders of magnitude under the limit value ($HI \leq 1$ e $R < 10^{-6}$). For example, the highest cumulative risk value for non-cancerogenic compounds was 1.32E-02 and for cancerogenic compound was 4.21E-11. Regarding odour compounds, the maximum peak hourly odour concentration of 5.62E-02 OU/m^3 was detected at the nearest receptor to the landfill site in an up-wind area, but it is two orders of magnitude lower than 1 OU_E/m^3.

Conclusion: The comparison of the three scenarios showed that the biofilter mitigates the risk associated to LFG emissions from the post-closure landfill site on average of 91% and 72% for non-cancerogenic and cancerogenic compounds. The odour impact resulted negligible for all the scenarios investigated and at each receptor.

Keywords

Health-human risk assessment, residual landfill gas, biofiltration, odour compound, NMVOCs

1. Introduction

Landfilling is still the dominant waste management disposal treatment in Europe and in 2016 1.018.320.000 tonnes of non-hazardous waste were landfilled [1]. Inside the body of a landfill, due to the absence of oxygen (O_2), the organic fraction of the waste is mainly turn in liquid and gaseous residues. The latter is landfill gas (LFG) and is principally composed of methane (CH_4) and carbon dioxide (CO_2) and other gases (H_2S, NH_3, O_2, H_2, non-methane volatile organic compounds – NMVOCs - and odorous compounds). The last, are generally at low concentration levels (ppb or ppm) and accounts only for the 1% in volume of the total LFG emissions [2]. At first, CH_4 is a green-house gas (GHG) with a Global Warming Potential (GWP) 28 times higher than CO_2, secondly H_2S is a malodorous compound, and third NMVOCs are mainly aliphatic, aromatic, organ-halogen, sulphur compounds that have acknowledge toxicological, cancerogenic and malodorous proprieties [3]. At last, odour compounds can have nuisance effects and are reason of complaints and concern of the population living in the surroundings of disposal site [4].

For reasons previously explained, a Human Health Risk Assessment (HHRA) can be applied to evaluate the risk from exposure to inhalation of NMVOCs both for workers and the population nearby the landfills. Furthermore, the impact on ambient air quality due to odour compound emissions can be evaluated [5-7].

The first step of the HHRA is to collect data on the pollutant emissive sources. Within the methods for the screening and the evaluation of NMVOCs emission rates, air samples can be collected using Radiello tubes [8], sorbent tubes [9], dynamic accumulation chamber [10] and canisters [11]. The second step is to identify the pollutants to assess in the HHRA. In general, benzene, toluene, ethylbenzene, xylenes (BTEX), vinyl chloride and polycyclic aromatic hydrocarbons [5,7,12,13] because of their toxicological proprieties are the NMVOCs principally studied. In fact, benzene is an acknowledge cancerogenic and mutagen compound, toluene, ethylbenzene and xylenes are flammable, toxic if inhaled and skin and eye irritable [14]. On the other hand, among

the odour compounds, sulphur compounds account for a significant part of the LFG [15]. Specifically, dimethyl sulphide dominates at the operating, inoperative and soil-covered areas of the landfill [16].

The evaluation of the odour impact in the environment surrounding a landfill site is particularly complex and lacks a regulation that identify a unique odour measurement, sampling and estimation methodology [4]. In Italy, guidelines on the characterization of gaseous emissions were developed by Regione Lombardia (D.G.R. 15 febbraio 2012 e n. IX/3018) [17]. In Europe, Germany and Austria developed an own regulation [4]. Nonetheless, dynamic olfactometry (EN 13725:2003) [18] is the most common method used nowadays to measure odour concentration. At the moment, also dispersion modelling is a diffuse methodology to evaluate both the exposure to NMVOCs and to odour compounds [19-21]. In particular, CALPUFF, a lagrangian puff-model, is one of the main used dispersion models because of its capability of modelling non-steady state situation, wind calms and complex terrain situation [22-24].

Within the LIFE RE Mida Project were identified 241 landfill sites that are in post-closure, in aftercare or at remediation stage [25]. In these site, the control measures imposed by the Landfill Directive [26] to prevent LFG emissions are inefficient, because of the low calorific value of the LFG (residual LFG). As a result, LFG is emitted without any treatment and concern about the exposure of LFG emissions among the population arises.

Many recent studies investigated the biological CH_4 oxidation, engineered in active or passive biofilters, as alternative and complementary techniques to internal combustion engines and flares for the treatment of residual LFG [26] and, among them, a part focusses on the reduction of NMVOCs and odour concentration due to the microbiological process. Accordingly, is possible to assess the mitigation on NMVOCs and odour compounds emissions and to compare different strategies for the LFG management to define the one that leads to the highest reduction of the risk from exposure to LFG emissions.

Consequently, the aim of this study is to evaluate the mitigation of the risk from exposure to NMVOCs and odour compounds emitted from an aftercare landfill site comparing three different scenarios of LFG management in which the biofiltration is a technique used to treat residual LFG. Up to now, biofilters for the treatment of exhausted air are studied mainly as a source of odour impact [24]; instead, the application of the biofiltration for the biological methane oxidation to reduce the risk from exposure to NMVOCs and odour compounds emitted from a post-closure landfill site was not investigated yet.

2. Materials and methods

2.1. Site characterization and investigated LFG management scenario

The site investigated in this study is Podere il Pero landfill, a non-hazardous waste disposal site. Since 2015 the landfill is closed and currently is in the post-closure stage. The plant is located in a rural area, is surrounded by farmlands and forests and in a radius of 3 km are located the biggest villages (Castiglion Fibocchi and Levane), and few isolated farms. The landfill covers a total area of 50.000 m^2 and reached a final disposal capacity of 674.000 m^3. At the site a leachate and a LFG collection systems are installed. The last is an active extraction system and conveys the LFG to a flare, where is burnt [26].

In recent years, because of the low quantity and quality of the LFG, the flare showed combustion problems. As a result, in the frame of LIFE RE Mida project, a biofilter for the biological oxidation of CH_4 was built. Specifically, the biofilter is complementary to the flare for the treatment of LFG with low calorific value. Clarifying, LFG is divided in two fractions: the part with high calorific value is burnt in the flare while the part with a low calorific value fed the biofilter. Briefly, the biofilter is made of two layers: the bottom layer is made of gravel and ensure the drainage in case of leachate formation, while the upper layer is made of a mixture of compost and sand, in a volume of 5:1, in which occurs the biological oxidation of CH_4 due to the development of methanotrophic bacteria. A dedicated blower conveys the LFG to the biofilter with a constant flow of 20 Nm^3/h, while an automatic analyser verifies continuously the composition in terms of CH_4 and O_2.

Focusing on the HHRA, the aim of this work is to compare the risk from exposure of LFG emissions considering three scenarios for management of LFG. In this case study, the emissions of LFG changed when started the proper functioning of the active biofilter. For this reason, three different scenarios where investigated:

- *Scenario 0* considered LFG emissions from the landfill surface before the construction of the biological CH_4 oxidizing biofilter; in other words, LFG that is collected by the active extraction system is burnt in the flare, while the uncaptured fraction is directly emitted by the landfill surface, and as conservative assumption the CH_4 oxidation process and NMVOCs abatement due to the final capping layer was not considered;
- *Scenario 1* considered LFG emissions from landfill surface when began the proper functioning of the active biofilter; equally to Scenario 0 CH_4 oxidation process and NMVOCs abatement due to the final capping layer was not considered; by contrary was assumed that abatement efficiency of NMVOCs, odour compounds and H_2S of the biofilter was 70% and 100% respectively. The assumption was made considering the lower limit indicated by Integrated Pollution Prevention and Control Directive [27] on abatement efficiencies and emission levels associated with biofiltration;

- *Scenario 2* considered emissions from the landfill surface as evaluated in Scenario 1, but in this scenario the abatement efficiency of NMVOCs, odour compounds and H_2S of the biofilter was evaluated with experimental data collected during three monitoring campaigns.

2.2. Description of the emissive sources

The main sources of LFG emissions at Podere il Pero are diffusive emissions from landfill and biofilter surface. Specifically, we treated both emissive areas as passive sources [17]. In fact, the specific LFG volumetric flow from the landfill and the biofilter surface is lower than the imposed limit of 50 $m^3/m^2/h$. The flare was not considered as emissive source because we could not sample and characterize the emissions; however, many studies include flares as point emissive sources [5,13,26].

The area emissive sources were characterized in terms of NMVOCs and odorous compounds emissions according to the methodology reported in the sections below. Furthermore, also the raw LFG conveyed at the biofilter was characterized in terms of NMVOCs, but was not analysed by dynamic olfactometry because of its toxicological proprieties. As a result, three monitoring campaigns were performed on a six-monthly base from March 2017 to March 2018.

2.2.1. NMOVCs emissions

NMVOCs emissions from the landfill were calculated from the diffusive emissions of LFG and the concentration levels find in the raw LFG. In particular, the static chamber accumulation method [30] was used to evaluate diffuse emissions and the raw LFG was sampled once for each moniotring campaign with a bag of PVF film directly from the collection tube that conveys residual LFG to the biofilter. As a conservative approach we did not consider the effects on NMVOCs abatement due to the final capping layer that instead are highlighted in other previous studies [28]. For the landfill emissions an only emissive factor was considered because the entire surface is completely covered with the final capping layer.

On the other hand, NMVOCs concentration at the biofilter surface was evaluated in accordance to US EPA TO-15, 1999 [11]. The samples were collected in accordance to US EPA, 1995 [10] using a dynamic chamber that was located on three emissive hot-spots and setting a sweep air (nitrogen) at 4.5 l/min. Globally, the samples were analysed examining 177 NMVOCs. Then, NMVOCs emission rates were calculated multiplying the NMVOCs concentration by the sweep air and dividing by the area of the flux chamber [20]. Finally, H_2S concentration in the raw LGF and at the biofilter surface was assessed according to NIOSH 6013:1994.

2.2.2. Odour compounds emissions

Concerning Scenario 0 and Scenario 1, odour emissive rate from the landfill surface were calculated considering the odour threshold concentration (OT) of five malodorous compounds (ethlymercaptan, dimethyl sulphur, ethanol, limonene and H_2S) and the specific concentration of each compound that was detected in the raw LFG. Then, was calculated an Odour Activity Value for each compound (OAV_i) [6,17,19]. Then, the Sum of each OAV_i (SOAV) gave an approximatively odour concentration of the mixture. Because of the difficulty to find reliable OT values the OAV is affected by a great imprecision [20]. In this study, as OT were used the values defined in [17] that were estimated by dynamic olfactometry.

Concerning Scenario 2, odour concentration at the biofilter surface was evaluated in accordance with EN 13725:2003 by dynamic olfactometry and the dynamic flux chamber method was applied to collect the gas samples. Then, the Specific Odour Emissive Rate (SOER) was calculated by multiplying the odour concentration (OU_E/m^3) by the sweep air (Nm^3/h) and divided by the area of the chamber (m^2) [20]. In particular, the maximum odour concentration value detected in the triplicate samples was used.

2.3. Pollutant and odours dispersion modelling

The concentration of NMVOCs and odorous compounds were estimated using the CALPUFF model [22]. The input data are mainly meteorological data, topographical data and emissive data [19]. As first step, meteorological data (wind direction and speed, ambient temperature and moisture, atmospheric pressure and rainfalls), collected by the meteorological station located at the plant, were analysed in the period 2013-2017 to find a year with a complete set of data [19]. 2015 was the most complete year: for each meteorological parameter only the 16% of the data were missing. Then, the wind field was reconstruced in a domain of 10x10 m^2 centred at the landfill, with a horizontal resolution of 200 m and a vertical resolution of 8 layers at 0-20-50-100-200-500-1000-2000-4000 m above the sea level.

As second step, the landfill was divided in 4 parts covering an area of 54153 m^2 to better model the pollutant emissions. Instead, the biofilter have an emissive area of 270 m^2. Table 1 summarizes the main characteristics of the emissive sources as implemented in the CALPUFF model. In particular, CALPUFF to consider the orography of the domain the base elevation heights of each receptor were identified as an average value between the minimum and the maximum height value of the emissive areas.

Tab. 1 Characterization of the emissive area sources

	CD1	CD2	CD3	CD4	Biofilter
Emissive area [m^2]	12360	14970	24092	2731	270
Base elevation [m a.s.l]	283	279	275	262	
Effect height [m]	0	0	0	0	2

As third step, focusing on the NMVOCs cyclohexane, n-hexane, 2-methylpentane, 3-methylpentane, benzene, xylenes, toluene, dichlorodifluoromethane, vinyl chloride, H_2S, CH_4 and odour compounds were modelled. In particular, were selected the pollutants that were always detected in the samples and that have documented toxicological and nuisance proprieties already studied in the literature [5-7,33,34]. Table 2 shows the emissive rates ($g*m^{-2}s^{-1}$) for each NMVOC. The emissive rates were calculated considering the maximum concentration value detected in the monitoring campaigns. The simulation domain was set to comprise an area of 6x6 km^2 and with a horizontal resolution of 100 m to include eleven discrete receptors in a radius of 3km from the centre of the plant and to obtain a major resolution (3600 horizontal cells).

Tab. 2 Dispersion modelling – Emissive rate for each modelled pollutant

Pollutant	Emissive Rate [g/m^2s] Landfill Surface		Emissive Rate [g/m^2s] Biofilter	
	Scenario 0	Scenario 1/2	Scenario 1	Scenario 2
Ciclohexane	5.00E-10	1.40E-10	4.75E-09	2.39E-08
n-hexane	6.50E-11	1.82E-11	6.11E-10	0.00E+00
2-metylpentane	1.42E-10	3.98E-11	1.33E-09	3.13E-09
3-metylpentane	1.28E-10	3.59E-11	1.20E-09	2.90E-09
Benzene	6.76E-11	1.90E-11	6.42E-10	0.00E+00
Xylenes*	6.94E-10	1.95E-10	6.59E-09	8.40E-09
Toluene	4.35E-10	1.22E-10	4.14E-09	0.00E+00
Dichlorodifluoromethane	6.10E-10	1.71E-10	5.74E-09	0.00E+00
Vinyl chloride	8.01E-10	1.71E-10	7.53E-09	0.00E+00
H_2S	3.28E-09	2.25E-10	0.00E+00	0.00E+00
CH_4	2.45E-04	4.50E-05	1.27E-03	2.39E-08
Odour compounds	4.44E-03	1.24E-03	1.35E-02	6.14E-02

*sum of m-xylenes, p-xylenes, o -xylenes

Concerning the receptors, where identified 9 single-detached houses or farms located in a radius of 1 km from the landfill, and two small city centre of 2164 and 5000 inhabitants respectively located in a radius of 3km from the landfill (Table 3).

Tab. 3 Discrete sensitive receptors

ID	X-UTM [m]	Y-UTM [m]	Distance [m]
R1	719850	4823429	1118
R2	720472	4823677	783
R3	720563	4822740	468
R4	721245	4822771	484
R5	721280	4822943	447
R6	721798	4823420	1010
R7	721773	4822860	926
R8	721273	4822116	1014
R9	720434	4822113	1039
R10	723327	4823152	2458
R11	719585	4820801	2592

At last, the results of the odour compounds' simulations were post-processed with the software CALPOST to obtain the average hour concentration and CALRANK to obtain the 98° percentile of the hourly average odour concentration. AA peak to mean ratio of 2.3 was considered to obtain the maximum odour concentration [17,20].

2.4. Assessment of the toxicological risk and air quality

All the pollutants assessed by this study can be modelled as gases and for this reason the only exposure pathway that was considered in the HHRA was inhalation. Three different scenarios were analysed to compare the risk related to LFG emissions before and after the installation of the active biofilter at the eleven sensitive receptors.

The risk associated to the non-cancerogenic and cancerogenic compounds was evaluated relating the exposure data and the toxicological proprieties of each pollutant compound [35]. Concerning the only one cancerogenic compound (benzene) assessed by this study, the cancer risk (R) was estimated as follows:

$$R = E \cdot SF$$

Where SF is the Slope Factor or cancer slope factor that estimate the probability of an individual to contract cancer during its lifetime by the exposure to cancerogenic compounds, E is the daily Exposure dose that is estimated combining the Concentration of the pollutant in air (C_{air}) and the Effective daily Exposure (EE) that is the amount of air inhaled per day per unit of body weight. In this study is evaluated an EE adjust (EE_{adj}) considering both the inhalation exposure to children (EE_{ch}) and adults (EE_{ad}) an average lifetime (AT_c) of 70 years, a Exposure Duration for adults (ED_{ad}) of 24 years and for children (ED_{ch}) 6 years, as follows:

$$EE_{adj} = EE_{ch} + EE_{ad} = \frac{B_{OBch} \cdot EF_{go} \cdot ED_{ch} \cdot \mathrm{EF}}{BW_{ch} \cdot AT_C} + \frac{B_{OAd} \cdot EF_{go} \cdot ED_{ad} \cdot \mathrm{EF}}{BW_{ad} \cdot AT_C}$$

Instead, concerning non-cancerogenic compounds EE is estimated as follows:

$$EE = \frac{CR \cdot EF \cdot ED}{BW \cdot AT}$$

Where CR is the amount of air inhaled per unit of time (m^3/d), EF is exposure frequency (day/year), ED is the exposure duration (years), BW is the body weight (kg) and AT is the average exposure time (days). CR can be estimated by multiplying the inhalation rate outdoor and the hour that a receptor daily spends outside. Finally, the risk, expressed as a Hazard Index (HI), was calculated combining EE and the Reference Dose (RfD). In this case study, we refer to Reference Concentration Dose (RfC) despite of RfD because inhalation was the only exposure pathway considered. Individual exposure doses and the health risk were calculated for children receptors (Table 4). In fact, because of their low body weight and the more time they spend outdoor than an adult the risk will be generally higher than adults [5]. Lastly, cumulative Hazard Index (HQ_T) was calculated by adding the individual hazard index for each pollutant in the pathway of concern.

Tab. 4 Toxicological proprieties of the pollutant for the human-health risk assessment

Pollutant	Ciclohexane	n-hexane	2-methylpentane	3-mehylpentane	Xylenes
CAS Number	110-82-7	110-54-3	107-83-5	94-14-0	1330-20-7
RfD – SF Inal. [mg/kg/day]	5.00E+00***	4.00E-02****	5.14E+00*	5.14E+00*	2.86E-02**
Pollutant	Toluene	Dichloro-difluoromethane	Vinyl Chloride	H_2S	Benzene
CAS Number	108-88-3	75-71-8	75-01-4	7783-06-4	71-43-2
RfD – SF Inal. [mg/kg/day]	1.43E+00**	2.00E-01**	3.00E-03**	2.00E-03**	1.43E+00**

*[36]; ** [37], ***[38] **** [39]

The risk is considered acceptable if HI≤1 in case of non-cancerogenic compounds and if $R \leq 10^{-6}$ in case of cancerogenic compounds [35].

Finally, concerning the odour impact assessment were considered three odour threshold values of 1, 3 e 5 OU_E/m^3 accounting respectively for the 50%, 85% and 90-95% of the population that detects the odour [17].

3. Results and discussion

3.1. LFG characterization

Concerning the raw LFG, the concentration levels of NMVOCs confirmed that the LFG had a low calorific value as reported in previous studied [31,41-43]. In fact, in the samples were detected dichlorodifluoromethane and vinyl chloride as organ-halogenated compounds at a maximum concentration of 930 and 1220 µg/m³ respectively, aromatic compounds (benzene, xylenes, ethylbenzene and toluene) had appreciable concentration levels with a maximum value of 104, 1068, 278 and 670 µg/m³ respectively, but the most abundant were aliphatic compounds (cyclohexane, 770 µg/m³; n-hexane, 99 µg/m³; 2-methylpentane, 216 µg/m³; 3-methylpentane, 195 µg/m³) Concerning malodorous components H_2S had a maximum concentration value of 5040 µg/m³ and was always detected in the samples. Ethlymercaptan, dimethyl sulphur, ethanol and limonene were detected with a maximum concentration of 40, 27, 401, 3170 µg/m³ respectively.

3.2. Results of the dispersion modelling

The wind speed and wind direction data were analysed in terms of frequency and, the wind-rose of the site was developed thanks to WRPLOT Figure 1. East-northeast resulted the dominant wind direction with a frequency of 11.3%, while the secondary wind direction resulted East with a frequency of 10.5%. The maximum wind speed

recorded by the station was included in 8-11 m/s. Considering the overall period, highest frequency (46.4%) of the wind speed was in the class 0.5-2.1 m/s, the average wind speed was 1.27 m/s and wind calm hours were of 30.3%.

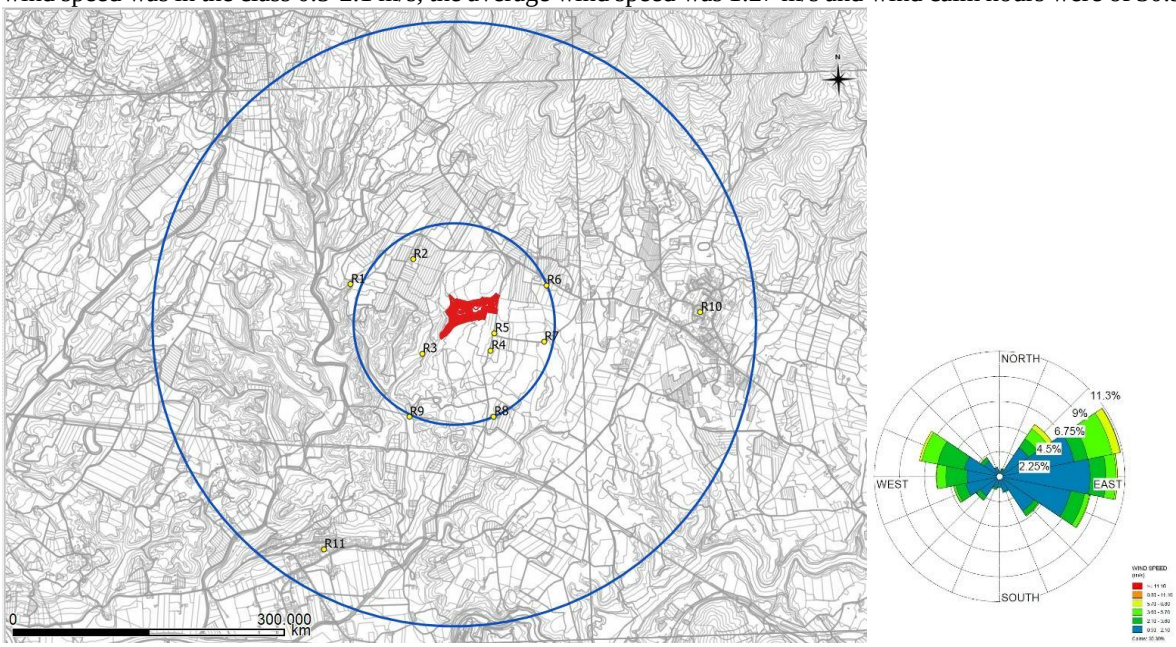

Fig. 1 Dispersion modelling: receptors identification (qGIS software) and wind-rose of the site

With reference to the three scenarios (Scenario 0, Scenario 1 and Scenario 2) in Table 5 are reported the hourly maximum and average Concentrations on annual base in air (C_{air}) of the NMVOCs implemented in the dispersion modelling. Focusing on the results, above all, the highest value of C_{air} was obtained for Scenario 0, while Scenario 1 and 2 showed similar values both for the average and the maximum concentration values; however, Scenario 2 had lower C_{air} in respect to the other scenarios. As second, in all scenarios and among the other pollutants, H_2S resulted those with the maximum value of C_{air}. As third, benzene concentration resulted for the overall period and at each receptor ten times less than the limit value (5µg/m^3) indicated in the European Directive on ambient air quality and cleaner air [43]. Finally, among the receptors, R5 resulted those where were estimated the highest C_{air} for each NMVOCs and for all the scenarios considered. In fact, R5 is both the nearest receptor to the landfill site, as reported in Table 3, and is located in the wind-rose sector in which there are the dominant wind (north-east and south-east). Clarifying, emerges that the abatement of NMVOCs due to the biofiltration process and that was evaluated with the experimental data is higher than the 70% defined in Scenario 1.

Tab. 5 Average and maximum annual concentration of the NMVOCs modelled in the scenarios

	Scenario 0		Scenario 1		Scenario 2	
C_{air} [mg/m^3]	Max	Average	Max	Average	Max	Average
Cyclohexane	3.18E-06	9.39E-07	9.43E-07	2.96E-07	1.16E-06	4.32E-07
n-hexane	4.13E-07	1.22E-07	1.22E-07	3.84E-08	1.16E-07	3.42E-08
2-metylpentane	9.02E-07	2.67E-07	2.68E-07	8.40E-08	2.88E-07	9.67E-08
3-metylpentane	8.13E-07	2.40E-07	2.42E-07	7.58E-08	2.61E-07	8.78E-08
Benzene	7.96E-09	2.97E-09	2.53E-09	1.00E-09	2.24E-09	8.35E-10
Xylenes*	4.41E-06	1.30E-06	1.31E-06	4.12E-07	1.33E-06	4.25E-07
Toluene	2.76E-06	8.17E-07	8.21E-07	2.58E-07	7.75E-07	2.29E-07
Dichlorodifluoromethane	3.88E-06	1.15E-06	1.15E-06	3.61E-07	1.09E-06	3.21E-07
Vinyl chloride	5.09E-06	1.50E-06	1.17E-06	3.74E-07	1.09E-06	3.21E-07
H_2S	2.08E-05	6.16E-06	1.43E-06	4.23E-07	1.43E-06	4.23E-07

The HHRA was evaluated exclusively for inhalation exposure both to non-cancerogenic (NC) and cancerogenic (C) compounds at each receptor. Specifically, the only C compound considered in the study is benzene.

As first step, we estimated EM only for children. The complete results of EM evaluation are not reported in this paper. In general, concerning NC was obtained the highest EM of 2.24E-05 and 5.47E-06 for Scenario 0 and for H_2S and vinyl chloride respectively; equally, concerning C compound was obtained the highest EM of 1.54E-09 for Scenario 0.

As second step, the individual risk for inhalation exposure at each receptor and for each NC and C compound was evaluated. Then, the cumulative risk for all the compounds and all exposure pathways was calculated. In Table

6 the HQ_T at each receptor is reported. Firstly, we observed that HQ_T and R are always many orders of magnitude lower than the maximum acceptable value ($HI \leq 1$ e $R < 10^{-6}$) [35]. In general, Scenario 0 resulted as the worst-case scenario with the highest value of 1.32E-02 for HQ_T and 4.21E-11 for R; instead, HQ_T and R resulted almost one order of magnitude lower for Scenario 1 and 2 than for Scenario 0, but Scenario 2 resulted to be the best-case scenario by comparison with Scenario 1. Concerning Scenario 1, HQ_T varied between 1.25E-03 at R5 and 5.13E-05 at R11, while the cancer risk varied between 1.34E-11 at receptor R5 and 8.59E-13 at receptor R11.

Tab. 6 Human Health Risk Assessment for non-cancerogenic and cancerogenic compounds

	Scenario 0		Scenario 1		Scenario 2	
Receptor	HQ_T [-]	R benzene [-]	HQ_T [-]	R benzene [-]	HQ_T [-]	R benzene [-]
R1	2.33E-03	1.75E-11	2.23E-04	5.73E-12	2.15E-04	4.91E-12
R2	3.20E-03	1.57E-11	3.09E-04	4.90E-12	2.95E-04	4.42E-12
R3	5.57E-03	2.43E-11	6.10E-04	9.84E-12	5.22E-04	6.82E-12
R4	8.33E-03	2.21E-11	7.93E-04	7.70E-12	7.68E-04	6.23E-12
R5	1.32E-02	4.21E-11	1.25E-03	1.34E-11	1.22E-03	1.18E-11
R6	2.16E-03	1.59E-11	2.03E-04	4.93E-12	1.99E-04	4.48E-12
R7	3.26E-03	1.65E-11	3.08E-04	5.36E-12	3.00E-04	4.64E-12
R8	1.89E-03	5.09E-12	1.85E-04	1.82E-12	1.74E-04	1.43E-12
R9	1.57E-03	5.91E-12	1.56E-04	2.12E-12	1.45E-04	1.66E-12
R10	9.27E-04	5.07E-12	8.81E-05	1.65E-12	8.54E-05	1.42E-12
R11	5.06E-04	2.44E-12	5.13E-05	8.59E-13	4.69E-05	6.87E-13

Concerning Scenario 2, HQ_T varied between 1.22E-03 at R5 and 4.69E-05 at R11, while the cancer risk varied between 1.18E-11 at receptor R5 and 6.87E-13 at receptor R11. At last, the maximum HQ_T e R are found at R5 confirming that this receptor is most sensitive because of its distance from the source and the exposure to the dominant wind. By contrast R11 is the less sensitive because the most far from the site and outside the dominant wind sector. Concluding, the risk for the population to incur in diseases or develop cancer due to exposure to non-cancerogenic and cancerogenic compounds emitted by the landfill site is far lower that the acceptable value that are imposed by the current legislation; furthermore, Scenario 2, in which residual LFG is treated in the biofilter, resulted the best-case scenario.

Then, the percentage change HQ_T and R were calculated for Scenario 1 vs 0, Scenario 2 vs 0 e Scenario 2 vs1 to compare the results achieved considering different LFG management strategies; results are reported in Table 7. Focusing on the results, the reduction of cumulative risk and cancer-risk resulted maximum for Scenario 1 and Scenario 2 in respect to Scenario 0 both for NC and C compounds. Concerning NC compounds, the percentage decrease varied between a minimum of 89.1% at R3 in Scenario 1vs 0 to a maximum of 90.8% for Scenario 2 vs 1; on the other hand, for benzene (the only cancerogenic compound assessed by this study), the percentage decrease varied between a minimum of 59.5% at R3 for Scenario 1 vs 0 to a maximum of 71.9% for Scenario 2 vs 0 at all the receptors. Again, emerged that Scenario 1 and 2 are comparable: the percentage decrease is quite low at all receptors, but we still observed that Scenario 2 is better than Scenario 1 and the highest percentage decrease of 14.4% and of 30.7% respectively for NC compounds and for benzene occurred at R3.

Tab. 7 Comparison of the LFG management strategies – Percentage change of the risk exposure

	Scenario 1vs 0		Scenario 2 vs 0		Scenario 2 vs 1	
Receptor	NC	C	NC	C	NC	C
R1	-90.4%	-67.2%	-90.8%	-71.9%	-3.8%	-14.4%
R2	-90.3%	-68.8%	-90.8%	-71.9%	-4.4%	-9.8%
R3	-89.1%	-59.5%	-90.6%	-71.9%	-14.4%	-30.7%
R4	-90.5%	-65.2%	-90.8%	-71.9%	-3.1%	-19.1%
R5	-90.6%	-68.2%	-90.8%	-71.9%	-2.4%	-11.6%
R6	-90.6%	-69.1%	-90.8%	-71.9%	-2.3%	-9.1%
R7	-90.6%	-67.5%	-90.8%	-71.9%	-2.5%	-13.4%
R8	-90.2%	-64.2%	-90.8%	-71.9%	-5.8%	-21.6%
R9	-90.0%	-64.2%	-90.7%	-71.9%	-6.9%	-21.5%
R10	-90.5%	-67.5%	-90.8%	-71.9%	-3.1%	-13.5%
R11	-89.8%	-64.8%	-90.7%	-71.9%	-8.5%	-20.1%

Concluding, the HHRA, that was performed to evaluate the risk from exposure to LFG emissions from old landfill sites and the contribution to NMVOCs and malodorous compounds emissions mitigation using a biofilter to manage LFG with low calorific value, showed that the application of the methane oxidation (Scenario 2)

mitigate the risk associated to LFG emissions from old landfill site on average of 91% and 72% for NC and C compounds respectively. Furthermore, Scenario 1in which was assumed an abatement efficiency of 70% for NMVOCs and a complete abatement of H_2S at the biofilter resulted to be more conservative in respect to Scenario 2 in which experimental data were used to calculate the efficiency of the reduction of NMVOCs and H_2S at the biofilter.

3.3. Odour impact

Table 8 reports the maximum odour concentration or peak hourly odour concentration, that was estimated at the eleven sensitive receptors using the CALPUFF dispersion model and applying a peak to mean ratio of 2.3 [17]. At first, emerged that the odour concentration levels are up to three orders lower than the limit value of 1 OU_E/m^3 at any receptors [17]. Furthermore, the highest peak hourly odour concentration was estimated for Scenario 0. Secondly, Scenario 1 and Scenario 2 showed that the peak hourly odour concentration is at least one order less than Scenario 0. Concerning these scenarios, the highest value of 1.57E-02 and 1.69E-02 were detected at R5 for Scenario 1 and Scenario 2 respectively. By comparison, Scenario 1 emerges to be the best case.

Tab. 8 Peak hourly odour concentration evaluated using CALPUFF model at each receptor

Receptors	Odour concentration [OU_E/m^3]		
	Scenario 0	Scenario 1	Scenario 2
R1	1.02E-02	2.84E-03	3.28E-03
R2	1.49E-02	4.28E-03	4.92E-03
R3	2.56E-02	7.43E-03	1.10E-02
R4	3.76E-02	1.05E-02	1.19E-02
R5	5.62E-02	1.57E-02	1.69E-02
R6	9.88E-03	2.76E-03	3.04E-03
R7	1.35E-02	3.99E-03	4.42E-03
R8	7.33E-03	2.13E-03	2.63E-03
R9	6.50E-03	1.94E-03	2.42E-03
R10	3.19E-03	9.47E-04	1.13E-03
R11	2.17E-03	6.32E-04	8.20E-04

To compare odour impact of each scenario, the percentage change was estimated, and the results are reported in Table 9. Scenario 1 resulted the best case-scenario. By comparison, the odour impact is reduced on average by 71.2% and 65.5% for Scenario 1 and Scenario 2 respectively, than Scenario 0. Finally, the odour impact in Scenario 2 resulted higher than Scenario 1 on average by 19.2%. Clarifying, emerges that the odour impact for Scenario 2, in which the SOER were evaluated using the dispersion modelling and the experimental data collected in the field it is higher than Scenario 1 in which the SOER derived from the assumption of average odour reduction efficiency due to the biofilter of 70%. As such, the assumption of this reduction efficiency it is too high and should be revised in light of the results obtained.

Tab. 9 Comparison of the LFG management strategies – Percentage change of the odour impact

Receptors	Scenario 1 vs 0	Scenario 2 vs 0	Scenario 2 vs 1
R1	-72.05%	-67.71%	15.51%
R2	-71.22%	-66.94%	14.86%
R3	-71.01%	-57.10%	47.99%
R4	-72.05%	-68.46%	12.86%
R5	-72.06%	-70.00%	7.38%
R6	-72.05%	-69.25%	10.03%
R7	-70.49%	-67.33%	10.71%
R8	-70.99%	-64.04%	23.96%
R9	-70.15%	-62.76%	24.77%
R10	-70.33%	-64.71%	18.94%
R11	-70.82%	-62.17%	29.64%

At last, Figure 2 reports the maps of the isopleth of 0.05 OU_E/m^3 of the peak hourly odour concentration at 98° percentile of Scenario 0. The peak hourly odour concentration is under 1 OU_E/m^3 at any receptors. Only R4 and R5 reported a peak hourly concentration between 0.05 and 0.1 OU_E /m^3. Consequently, the odour impact is negligible at all receptors.

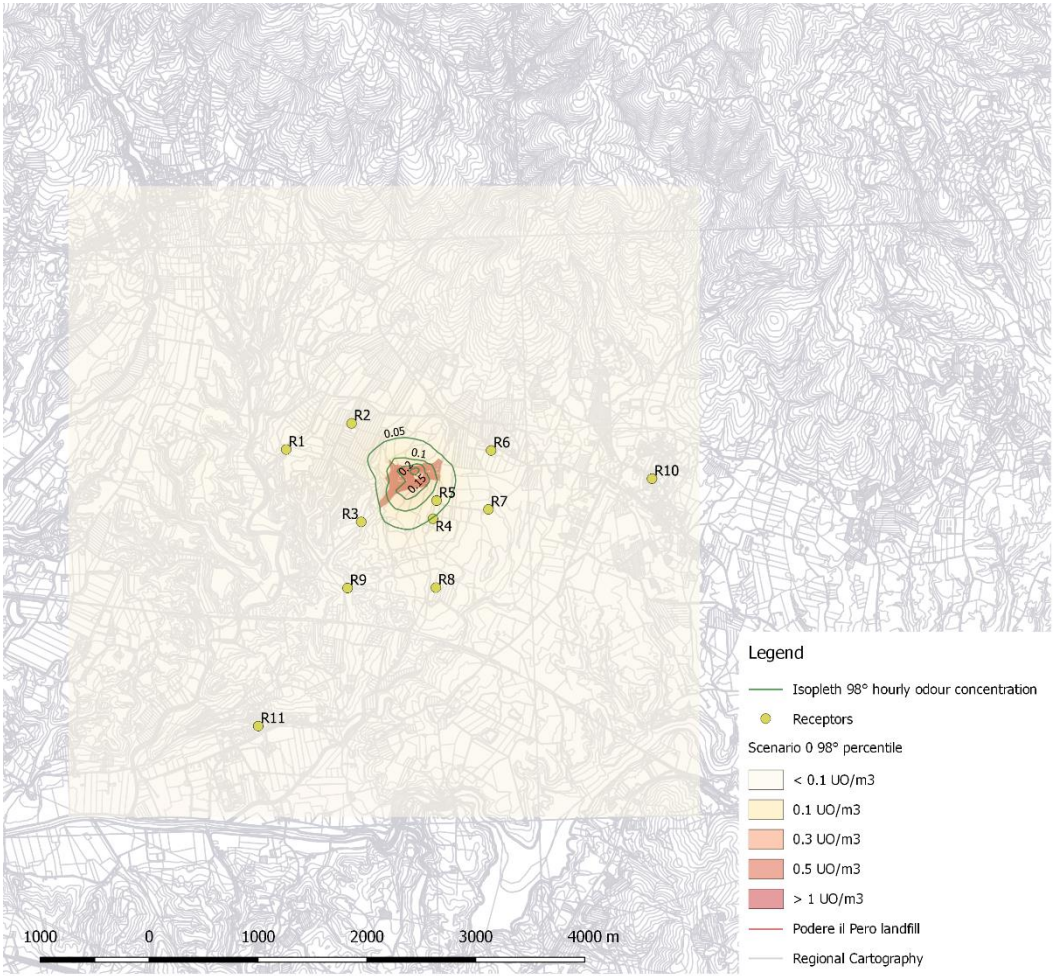

Fig. 2 Isopleth of peak hourly odour concentration at 98° percentile – Scenario 0

4. Conclusion

A human health risk assessment and an odour impact evaluation was performed concerning landfill gas emissions from a post-closure landfill. Three scenarios in which the biofiltration of residual landfill gas was considered as integrative and complementary technology to the flare were compared. Concerning, the human health risk assessment, combining the results of the dispersion modelling and the reference dose concentration emerged that the risk associated to inhalation exposure both for cancerogenic and non-cancerogenic compounds is many orders of magnitude under the limit value at any sensitive receptors. Furthermore, by comparison to Scenario 0 and Scenario 1, emerged that the risk is reduced on average of 91% and 72% for NC and C compounds respectively at each receptor for Scenario 2, in which the abatement efficiency of non-methane volatile organic compounds is evaluated using experimental data. Finally, emerged that the risk was maximum at the receptor nearest the plant and located in the sector of the dominant wind.

Focusing on the odour impact assessment, the results of the dynamic olfactometry showed that emissions from the biofilter were always under 300 OU_E/m^3, while H_2S was the malodorous compound that most contribute to the odour activity value of the raw landfill gas. Moreover, from the dispersion modelling emerged that odour impact was negligible at each receptor resulting two orders of magnitude lower than 1 OU_E/m^3. By contrast to the risk assessment, Scenario 1 emerged to be the best case scenario and as a result the initial assumption of 70% of odour abatement due to the biofilter need to be reviewed.

In conclusion, many data and information are needed to conduct a human health risk assessment and evaluate the impact of odour compounds emissions on the environment surrounding a landfill. In particular, concerning this study, the preliminary conservative assumptions should be revised. For example, the abatement on non-methane volatile organic compounds and odour compounds due to the final capping layer could be considered, an evaluation on the seasonal variability of landfill gas composition should be performed and at last, air sampling campaigns on the landfill surface could be performed to directly assess odour concentration by dynamic olfactometry.

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