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Establishing bio-mitigation systems at landfills for reducing greenhouse gas emission – State-of-the-art

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Introduction

Landfills receiving organic wastes produce biogas containing methane (CH_4). Landfills are significant sources of CH_4, which contributes to climate change. At some landfills utilization of landfill gas (LFG) is not or cannot be carried out, and the gas is either flared with risk of producing toxic combustion products or just emitted to atmosphere. As an alternative to gas utilization systems or as a follow-on technology when a gas utilization system gets non-cost-effective, bio-mitigation systems may be implemented. Bio-mitigation systems – also called biocover systems - are defined here as systems based on microbial removal processes implemented at landfills to reduce emission of methane (or other harmful substances). Experiments have documented that a very high CH_4 oxidation rate can be obtained in soils, compost and other materials, high enough to significant reduce the CH_4 emission from landfills. Landfills may be fully covered with biological active materials, so-called biocovers. Bio-mitigation systems may also imply establishment of biofilters reducing CH_4 concentration in LFG extracted from the existing gas collection system.

The objective of the paper is to describe a developed protocol for establishing biocover systems at landfills and to describe the different types of bio-mitigation systems, reviews the reported bio-mitigation system implementation described in the literature, and highlights the existing challenges for obtaining systems with high mitigation efficiencies.

Important factors for the microbial methane oxidation process

The aerobic microbial oxidation of CH_4 occurs in the biosphere wherever CH_4 and oxygen (O_2) are present at the same location. In landfill covers CH_4 and O_2 may appear at the same depth due to emission of CH_4 from the waste and diffusion of O_2 from ambient air, which provides needed conditions for the development of methanotrophic bacteria, Scheutz et al. (2009). Aerobic CH_4 oxidation proceeds according to the following overall reaction, producing a significant amount of heat:

$$CH_4 + 2\,O_2 \rightarrow CO_2 + 2\,H_2O + \text{heat} \quad \Delta G° = -780\,\text{kJ/mol}\ CH_4 \qquad (1)$$

The reaction is carried out by the so-called methanotrophic bacteria (or methanotrophs), which are unique in their ability to utilize CH_4 as a carbon and energy source, Scheutz et al.(2009). Landfill cover soils can exhibit high capacities for CH_4 oxidation. Very high rates of CH_4 oxidation in landfill cover soils (>100 µg CH_4 g^{-1} h^{-1} and >200 g CH_4 m^{-2} d^{-1} in batch and column experiments, respectively) have been reported, Scheutz et al. (2009).

The oxidation of CH_4 is controlled by several environmental factors such as soil texture, temperature, soil moisture content, CH_4 and O_2 supply, nutrients, etc. This implies that the climatic conditions are of huge importance for the actual CH_4 oxidation rate. In landfill soil covers or engineered bio-mitigation systems, temperature and soil moisture are very important parameters controlling CH_4 oxidation, Scheutz et al. (2009). Especially temperature is an important factor in temperate and arctic climate where ambient temperature can be limiting for the biological process during the winter season. However, several later studies of bio-mitigation systems using compost as bio-active material have shown significant elevated temperatures in the CH_4 oxidation layer during cold periods (Philopoulos et al.(2008), Pedersen(2010), Dever et al.(2011), Scheutz et al.(2014), Cassini et al(2015)), which affect the biocover ability to oxidize CH_4 in a positive direction. This is supported by laboratory experiments, which investigated the influence of the temperature on CH_4 oxidation and respiration in compost samples, Scheutz et al.(2011a). Compost material was collected from the bio-mitigation system at Klintholm landfill and incubated in the laboratory at ten different temperatures varying between 4 ºC and 70 ºC. The temperature optimum of the methanotrophic community in the biocover material was 45 °C, which was much higher than the temperature optimum for CH_4 oxidation in landfill cover soils (reported to be in the range of 15 to 38 °C, Scheutz et al.(2009). The results indicate that a moderately thermophilic methanotrophic community adapted to the elevated temperature conditions in the biocover had developed. The temperature optimum was comparable to maximum temperatures measured in the deeper parts of the biocover at Klintholm Landfill, Scheutz et al.(2011a).

Moisture content may also be an important environmental factor. LFG flowing through the CH_4 oxidation layer (MOL) may be heated up due to the elevated temperatures (as described above) and evaporate water contained in the MOL. Even though that the CH_4 oxidation process produces water (confer equation 1) and that the LFG often is water saturated when leaving the waste layers, a desiccation of the MOL may be observed especially in hot, dry region with little infiltration of rain.

Biocover systems – scenarios and types

There are different scenarios under which biocover systems may be implemented. It could be either a stand-alone mitigation system on a closed landfill without LFG utilization or flaring, or a system taking over when LFG utilization gets non-cost-effective or flaring technical challenging due to low CH_4 content. The different scenarios are shown in Table 1.

Table 2 defines the different bio-mitigation systems, which can be used for mitigation of CH_4 emissions from landfills. A *full surface biocover* is a landfill cover system that has been designed to optimize the environmental conditions for biotic CH_4 consumption, so that the system functions as a vast bio-filter (Figure 1). The cover typically consists of a basal 'gas distribution layer' (GDL), with high gas permeability to homogenize LFG fluxes, and an overlying 'methane oxidation layer' (MOL), designed to support the methanotrophic populations that will consume the CH_4. Since biocovers are typically spread over an entire landfill area or landfill cells, cost becomes a critical factor in material selection, and often composted waste materials, such as garden waste, food waste, straw, stabilized dewatered sewage sludge etc., are used. Another critical factor is the permeability of any interim soil cover below the biocover. If the gas permeability is too low to allow the generated LFG to flow to the biocover, hot spot CH_4 releases may occur at points or areas where less tight soil cover materials have been used (e.g. landfill slopes, etc.) or from the leachate collection system.

Table 1. Scenarios for establishment of a bio-mitigation system at landfills.

Sc.	Description
1	No gas collection system (GCS) is in place, the LFG generation is modest either due to a high landfill age or due to disposal of waste with low organic content. Installation of a GCS and a gas engine (or similar energy conversion unit) is not cost-efficient, but LFG emission is regarded as above legal limits. 1a. No leachate collection system is present nor gas vents, which could be the major LFG escaping route 1b. A leachate collection system or gas vents are present, which may be the major LFG escaping route
2	A GCS is in place. The gas engine (or similar energy conversion unit) is old with high running maintenance costs. A replacement of the energy conversion unit is considered non-cost-efficient. 2a. Significant fugitive or un-collected emissions from slopes, uncovered part, leachate collection system, etc. are foreseen 2b. No significant fugitive emissions are foreseen - may be as a result of the presence of a gas tight engineered top cover
3	A GCS and a gas flaring system are in place. The flares have difficulties to run without the use of supporting fuel, but LFG emission is regarded as above legal limits. 3a. Significant fugitive or un-collected emissions from slopes, uncovered part, leachate collection system, etc. are foreseen 3b. No significant fugitive emissions are foreseen - may be as a result of the presence of a gas tight engineered top cover

A *biowindow system* accommodates the problem of an existing low permeable soil cover by construction of areas where the cover soil is replaced by biofilters, so-called biowindows (see Figure 1). This option reduces the areas over which the LFG is escaping, leading to lower gas retention times in the filter material. A biowindow system is therefore most relevant at reduced LFG generation rates and at landfills, which are finally covered with relatively gas impermeable materials. For both the biocover and the biowindow, the gas is loaded passively to the filter.

Biofilters, like biocovers, exploit CH_4 oxidizing bacteria to mitigate low calorific landfill CH_4 emissions. Operated as self-contained fixed bed reactors with a packing material to support and sustain a methanotrophic biofilm, biofilters can accomplish high CH_4 removal rates. Unlike biocovers, biofilters require a supply of gas, which is usually provided by a gas collection or drainage system. The supply can be either passive supported by the elevated gas pressure inside the landfill as a result of the gas generation process, or active by use of gas pumps. A biofilter can be open bed (allowing oxygen diffusion from the atmosphere) or closed bed where the supply gas should contain all relevant gases (both CH_4 and O_2). The use of closed bed systems may be constrained by the total gas load. At high gas loads, the total volume of biofilter material needed for the biofilter may give rather costly solutions.

Table 2. Different types of systems for bio-mitigation of CH_4 emissions from landfills.

Type	Description
Full surface biocover	The whole landfill area is covered with a homogenous layer of bioactive coarse materials (such as a coarse soil or compost) underlain by a gas distribution layer of gravel. Gas is loaded passively to the biocover.
Biowindow system	A system incorporating the presence of an existing, low permeable soil cover. Areas of the existing cover is replaced by gas permeable, bioactive materials (such as a coarse soil or compost) underlain by a gas distribution layer of gravel. Gas is loaded passively to the biowindows.
Biofilter passive, open bed	A system consisting of a volume of bioactive materials where LFG is fed passively from below through a gas distribution layer. Open to the atmosphere so oxygen can diffuse into the bioactive material from above.
Biofilter passive, closed bed	A system consisting of a volume of bioactive materials where LFG is fed passively from below/above through a gas distribution layer. Closed to the atmosphere (for instance in a container) so oxygen is to be part of the loading gas.
Biofilter active, open bed	A system consisting of a volume of bioactive materials where LFG is actively pumped from below through a gas distribution layer. The biofilter surface is open to the atmosphere so oxygen can diffuse into the bioactive material from above.
Biofilter active, closed bed	A system consisting of a volume of bioactive materials where LFG is actively pumped from below/above through a gas distribution layer. The biofilter is inclosed (for instance in a container) so oxygen is to be part of the loading gas (maybe supplied by a second pump).
Bioactive intercepting trench	A system consisting of a deep trench surrounding the perimeter of a landfill to collect and oxidize CH_4 in LFG migrating horizontally from the landfill. The trench may be filled with gas distributing materials at the bottom and bioactive materials on top. Gas is routed passively to the trench.
Combined solutions	A system combining some of the types above, for instance a full surface biocover to reduce fugitive emissions with a biofilter treating LFG collected from a gas extraction system

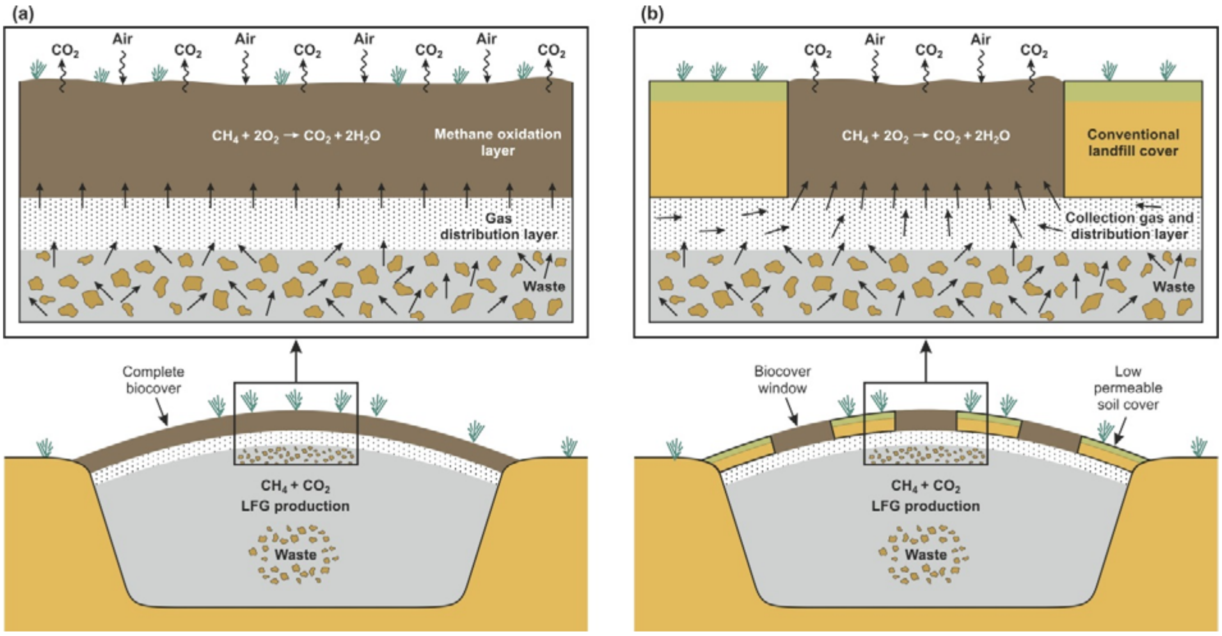

Figure 1. Illustration of the full surface biocover and the biowindows concepts to facilitate biological CH_4 oxidation, and thereby reduce greenhouse gas emissions from a landfill.

Figure 2. Description of the biocover system approach with the logical order of project activities.

Protocol for establishing a bio-mitigation systems

Through the work on establishing bio-mitigation systems at Danish landfills a protocol framework for the establishment has been developed. The framework is shown in Figure 2, which presents the different project activities. A few comments are given to each of the project steps in the following section.

Initial characterization of landfill. The objective of this task is to establish the basis for implementation of the project based on existing data (such as landfill area, total waste volume, received waste types, waste masses per year, etc.) combined with site visits and gathering of new basic data concerning the existing soil cover of the landfill. The expected gas generation from the landfill is predicted by use of a LFG generation model using the collected data on waste types, volumes and ages. This task is especially important for a Scenario 1 type project (see Table 1).

Baseline study of methane emission. The objective of this task is to obtain a measurement of the baseline emission of CH_4 from the landfill in tons per year. In order to evaluate the efficiency of an installed bio-mitigation system for CH_4 mitigation, the CH_4 emission after establishing the bio-mitigation system is to be compared with the baseline emission. The total CH_4 emission from the landfill can be determined by performance of a series of campaigns using the tracer dilution method, Scheutz et al.(2011b). The task should also evaluate the spatial distribution of fugitive emission from the landfill surface by screening surface CH_4 concentrations using a FID-detector (or similar equipment) eventually in combination with flux chamber measurements. Also the presence of point CH_4 source releases such as leachate wells, inspection wells, and gas vents should be evaluated and emissions measured (eventually using a small scale version of the tracer dilution method, Fredenslund et al.(2010). For scenario 2 and 3 types (Table 1), annual collected CH_4 by the GCS is determined and the significance of un-collected CH_4 (fugitive emitted and point source released) is evaluated.

Testing available bio-active materials. The objective of this task is to identify locally available materials for potential use in the bio-mitigation system, and test the materials and combinations of materials in the laboratory in order to determine the CH_4 oxidation capacity of available materials/combination of materials, Pedersen et al.(2011). The bio-active materials could be compost, which in many cases is produced from garden waste and sludge at the landfill. Compost is often produced in large quantities and it can be difficult to find adequate need for the compost for normal use as soil quality improvement material. The test can be done by batch incubation tests or dynamic column tests simulating the biofiltration process, Pedersen et al.(2011).

Establishing the full scale bio-mitigation system. Based on the findings from the three previous tasks the type of bio-mitigation system is chosen (see Table 1 and 2). Activities are made to reduce any fugitive emissions by improving the existing soil cover or to reduce any hot spot CH_4 releases – in case a *full surface biocover* is chosen. For cases where a GCS is in place, un-collected point sources (such as leachate wells) are connected to the GCS and a biofilter solution is chosen and dimensioned based on the measured CH_4 emission plus CH_4 collected, using the CH_4 oxidation capacity determined by the laboratory experiments (as described above) giving the needed filter volume/area.

Evaluation of methane oxidation efficiency of the bio-mitigation system. The overall objective of this task is to document the CH_4 mitigation efficiency of the establish system. After establishment of the bio-mitigation system, an initial screening of the surface CH_4 emission and the spatial variability is performed on the entire landfill surface by a FID-detector (or similar equipment). If areas where high CH_4 emissions are identified during the screening, the cover properties should be improved to avoid hot spot emissions. The total CH_4 emission from the landfill is determined again (using the method used in the baseline study) and results from the baseline study and the period after the bio-mitigation system has been established is compared and the CH_4 mitigation efficiency is determined.

Analysis of the economic viability of the biocover technology. The objective of this task is to evaluate the economic viability of the established bio-mitigation system. The annual reduction in emission of CO_2-equivalents is predicted for the following years based on the determined mitigation efficiency. The related costs is calculated including construction costs and running costs (for maintaining the bio-mitigation system), and a normalized price is determined (US$/tons CO_2-eq. mitigated).

Full scale bio-mitigation systems

During the last ten years, establishment of several bio-mitigation systems for reduction of methane emissions at landfills have been reported. The reported systems imply both full scale systems handling the CH_4 emission from a whole landfill (or landfill cell) and pilot scale systems only treating the CH_4 from a part of the landfill (or few landfill cells). In total, more than 20 projects have been reported, where eight are full-scale implementations using four different project types.

The work with the full scale implementation of bio-mitigation systems has highlighted several challenges. One is to develop a robust documentation method of the systems efficiency. In Denmark the tracer dispersion method has been used measuring the total CH_4 emission from the landfill before and after establishment of the bio-mitigation system to estimate the systems mitigation efficiency. Important technological challenges are to obtain an even distribution of the gas to the active methane-oxidizing layer and at the same time allow for excess precipitation to percolate downward through the methane-oxidizing layer for discharge as run-off from the landfill surface.

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