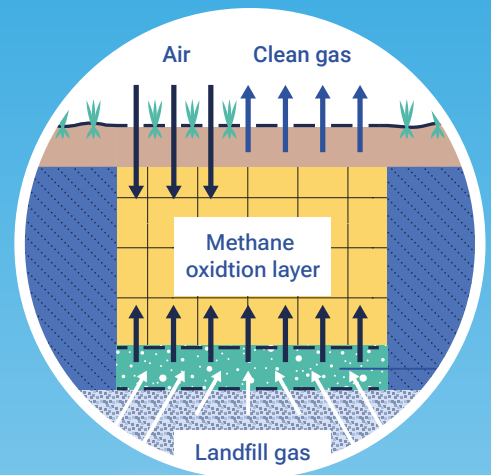


Reducing Methane Emissions from Landfills

The potential of biocover systems



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Executive Summary

Methane is a powerful greenhouse gas, its high global warming potential and shorter lifetime in the atmosphere make methane action a critical piece in combatting climate change and turning down the heat in the near-term. The Global Methane Pledge (GMP) has increased attention to the need to rapidly reduce methane emissions.

Landfills are responsible for approximately 11% of anthropogenic methane emissions and consequently a significant source of anthropogenic methane. This contribution to greenhouse gases (GHG) is rising, mainly due to increasing amounts of waste that accumulate on managed and unmanaged sites in large parts of the world, which emit methane decades after disposal. However, this trend can be reversed. Measures to reduce landfill methane emissions include landfill gas capture and treatment and biocovers. They come with additional health and air quality benefits. Well-designed methane oxidation covers not only reduce methane emissions but can also reduce odour and the emission of Volatile Organic Compounds (VOCs) and other toxic substances.

This Climate and Clean Air Coalition (CCAC) Technology and Economic Assessment Panel report (TEAP) provides general guidance for decision makers, policymakers in national and local governments, entrepreneurs, investors, and project managers. The report addresses the emerging technology of one bio-mitigation system which is of increasing interest for policymakers, researchers and investors in dealing with landfill-based emissions. It addresses:

- How suitability of biocovers in different contexts can be assessed
- What complementary actions need to be taken, including from policymakers
- What the methane reduction impact could be
- What the costs are and how biocovers can be effectively designed, financed, constructed and maintained.

This document intends to demonstrate options for mitigation actions that can be done in most country contexts, and how to maximize impact with limited means.

The report draws on a broad base of scientific literature on biocovers, an example of a Microbial Methane Oxidation System (MMOS), also known as bio-mitigation systems. It draws on the work of the International Waste Working Group's (IWWG) task group CLEAR (Consortium for Landfill Emission Abatement Research). CLEAR is a network of researchers and industry practitioners focused on advancing understanding and sharing experience related to methane oxidation systems.

Microbial methane oxidation can occur in covers, windows and filters. This document focuses on covers. For the sake of brevity, this document uses biocover for a microbial methane oxidation cover. Biocovers have a limited average oxidation rate. That makes them suited for landfills with typically low methane generation rates, or for shallow dumpsites where it may not be feasible to install viable gas collection systems. Many developing countries have shallow, poorly managed and unmanaged dumpsites¹ therefore biocovers are particularly suited for such contexts where gas recovery systems are difficult to implement, thereby offering a practical and effective solution for methane abatement. **The potential methane abatement using biocovers is significant**, at nearly 50% for an unmanaged landfill, but design, maintenance and monitoring (which are addressed in this report) is critical for maximum mitigation benefit. Biocovers can also be used for landfill closure and remediation, allowing for future uses of often valuable urban land.

¹ This report uses landfill to indicate a controlled facility which has been engineered and is managed, in contrast to unmanaged landfills or dumpsites which lack planning, investment and control and include mixed unregulated waste. The latter are often also sites of open burning, lack leachate control and are sources of odours and air pollutants (UNEP, 2024).

Methane generation modelling remains the standard approach for estimating landfill methane emissions. It is relatively simple, low-cost, and could be adopted by all landfill operators as a baseline planning tool. Modelling provides valuable forecasts of methane generation, recovery, and oxidation, helping operators understand expected emissions and assess the potential effectiveness of mitigation measures, such as biocovers. The decision to build a biocover should be a stepwise process which this report guides through, including costs, assessing the suitability and the potential impact of a biocover on a landfill, in a specific climate, and with materials that are locally available and affordable.

Careful design and dimensioning of the system are of utmost importance – to ensure proper functioning and cost-effectiveness. A biocover consists of 2 to 5 different layers that must be planned and configured to each other, to the local climatic conditions and to the methane load of the landfill. Given that the properties and thickness of layers are interdependent, they may need to be revised during the design process. Detailed guidance on design is available and clarifies how much methane can be oxidised.

Construction of a biocover follows the principles of civil engineering construction with special care for avoiding over compaction of materials. The construction costs for a methane oxidation cover can vary from US\$ 50,000 to US\$ 250,000 per hectare. Purchase of suitable material can be as high as two-thirds of the costs. Obtaining materials for free or with minimal transportation costs, makes a significant difference in both affordability and practicality.

For continued positive mitigation performance of the biocover, inspection and maintenance are essential. Inspection is necessary to identify settlement, cracks and erosion of the topsoil. Maintenance includes mowing of the vegetation and repair of settlement, cracks and erosion, and repair requires the same precautionary measures to prevent compaction as during construction. Related guidance is provided in section 7.

The choice of monitoring methods depends on technical concerns, available capacity, the target of the measure and possibly regulatory requirements. Monitoring methods can range from simple visual inspection to complex emission measurements. Accurate and reliable performance assessment requires that monitoring campaigns are carried out frequently. As this entails ongoing costs,

funding of monitoring should be carefully considered. Annual maintenance and monitoring costs can vary between US\$ 3,000 and US\$ 24,000 per hectare per year. This report addresses how such costs can be offset, or finance sourced.

The overall cost effectiveness of biocovers typically ranges from US\$ 5 to US\$ 15 per tonne carbon dioxide equivalent. Carbon markets and climate finance can potentially generate income for a biocover project, but several challenges remain. Voluntary markets (US\$ 0.5 per tonne carbon dioxide equivalent in 2025) can currently not offer prices that make a biocover project attractive. A project can only benefit substantially if the project would have access to a compliance market (US\$ 10 to 70 per tonne carbon dioxide equivalent in 2025). Construction and monitoring requirements for methane oxidation make the costs per tonne of carbon dioxide equivalent for the Clean Development Mechanism (CDM) methodology relatively high. In combination with a cap on the eligible amount of carbon credits per project per year, this might explain why the methodology has not yet been applied. Methane oxidation layers, (at least partially) constructed of compost, might be eligible for funding through a methodology for composting of organic waste. The need for a greater range of financing options to support landfill covers, and capping in closure, is addressed in the final sections of the report. Notably, in addition to cleaner air and healthier environments, several countries have demonstrated that capped and closed landfills can become valuable land assets for urban development and investment.

A lack of knowledge, sharing of technology and experience, and investment hampers wider application of biocovers. However, there is increasing interest, in both the global north and south. In recent years Europe, Canada and the United States of America have developed research and guidelines, which this report draws from. In addition, countries as diverse as South Africa, Australia and Tunisia have invested in biocovers. **This report serves as an additional step in raising awareness for the benefits of application of biocovers, including their mitigation and air quality potential, providing guidance on their design and benefits for better landfill management and waste management systems.** Promotion of the applicability and use of biocovers can additionally be supported by the organisation of training courses, which could share information, capital and support technology transfer from countries involved in developing biocover projects.

01 Introduction



Photo: Esteban Dupinet/Adobe Stock

1.1 The potential of biocovers for landfill methane abatement

There is increasing pressure to act on dumpsites and uncontrolled landfills, which for many countries remain the principal end point for municipal solid waste (MSW), and a key source of methane emissions and other pollutants. Management of solid waste has long posed challenges for municipalities. Concerns over revenue and cost recovery, collection rates and managing growing volumes of increasingly complex waste are typical challenges, now added to by national and global concerns regarding landfills and waste systems as significant and growing contributors to climate change, environmental degradation and poor air quality.

Both landfills and uncontrolled dumpsites are increasingly recognised as sources of dangerous emissions and gases, such as methane and volatile organic compounds (VOCs). Landfill sites generally also generate hydrochlorofluorocarbons (HCFCs) and chlorofluorocarbons



Photo: Kay Gebauer/Adobe Stock

(CFCs) (Scheepers & van Zanten, 1994; Environment Agency, 2004). Biodegradation of organic waste can typically take 2-3 decades, with methane emissions continuing for up to 100 years at landfill sites (Huber-Humer et.al, 2009). Community concern over odours, and the impact of uncontrolled landfill fires feeding off methane from unmanaged dumping of organic waste, have increased pressure for investment in separation and diversion of organic materials into circular economies, but also changed practices at landfills themselves.

Typically, implementation of landfill gas capture and extraction is offered as the principal solution to methane emissions at landfill sites, and in some circumstances such investments are affordable and can provide a safe release of methane, as well as a potential source of energy (Huber-Humer, 2009). In some instances, over 90% recovery has been achieved in landfills with efficient gas recovery systems (Bogner et.al., 2007; Berger & Lehner, 2022), though a default level of 50% is more typical. The IPCC has noted though, that to achieve lifetime efficiencies, gas recovery systems need to be in place early in a landfill's use. Otherwise, lifetime recovery may be as low as 20% (Bogner et.al., 2007). For countries with uncontrolled and ageing landfills, including those with declining organic loads, such investments may be logistically and financially impractical. In addition, efficient gas recovery requires infrastructure that is well maintained over decades (Bogner et.al., 2007).

An alternative, and often complementary approach to landfill gas recovery over time, is the development of biocovers. Biocovers offer a cost-effective solution for lower income countries and municipalities pursuing and investing in diversion of organic waste from landfills, and a rapid reduction in emissions. For many countries, including developed countries where experience is greatest, biocover establishment can also offer a solution in reducing methane emissions over the long term, as they can oxidise methane throughout the entire landfill lifecycle, including through landfill closure and decommissioning. In landfills with low and declining methane gas loads, biocovers may be the more appropriate cost-effective mitigation approach.

In this document, the term biocover refers to a landfill cover, or large parts thereof, that is designed to provide optimized conditions for the process of microbial oxidation of landfill methane, while also warranting the other functions of a landfill cover. Alternative configurations for the same purpose include biofilters and biowindows. All three are technically referred to as microbial methane oxidation systems (MMOS) (Gebert et al., 2022).

1.2 What is landfill gas?

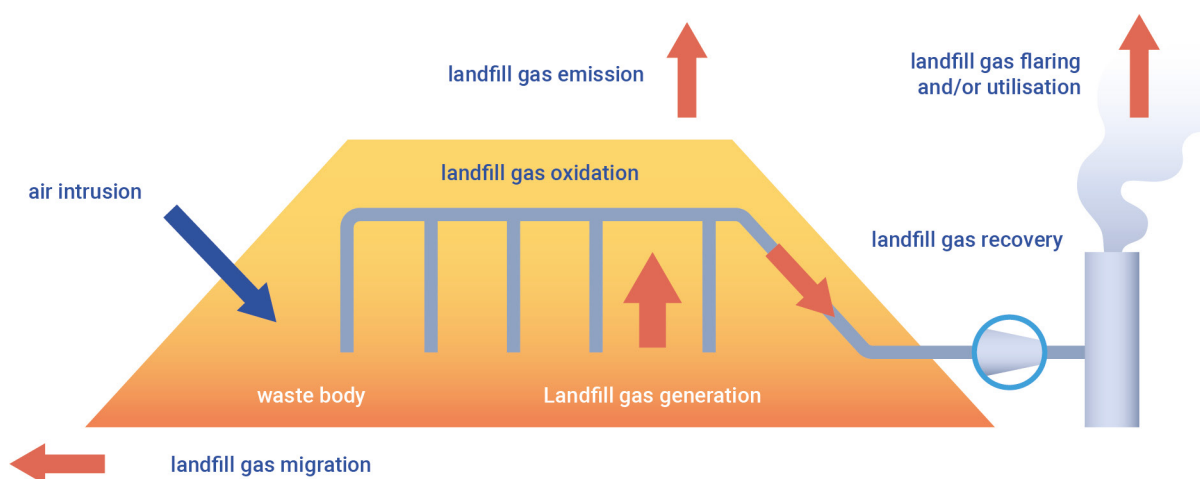
Landfill gas is the product of decomposition by microbes of degradable organic carbon in waste in the absence of oxygen (anaerobic conditions). Landfill gas consists mainly of methane and carbon dioxide. Methane is a highly potent greenhouse gas having between 28 (over 100 years) or 84 (over 20 years) times greater global warming potential than carbon dioxide (Wedderburn-Bisshop et.al., 2015). Waste is responsible for approximately 20% of total global anthropogenic methane emissions (UNEP/CCAC, 2022). Landfills, at 11%, make up the largest part and represent the fastest growing source (UNEP/CCAC, 2022). Methane is relatively quickly degraded in the atmosphere. Within 12 years half of the methane emitted in any given year has already been degraded, whereas natural removal of carbon dioxide from the atmosphere takes over a century.

Methane emission reduction can therefore help to limit global warming quickly. Landfill gas is produced from organic material, and carbon dioxide in landfill gas is generated by the biodegradation of organic matter that itself was biosynthesized from atmospheric carbon dioxide prior to waste deposition. This short-term carbon dioxide cycling is therefore considered climate-neutral and hence not included in the greenhouse gas accounting of emissions (IPCC 2006a). The conversion of landfill methane to carbon dioxide results in a large GHG emission reduction.

Bacteria decompose degradable organic carbon in landfilled waste in different stages. Solid organic matter is first degraded to dissolved compounds, then to fatty acids and alcohols, then to acetic acid, hydrogen and carbon dioxide and finally to methane and carbon dioxide (Scheepers & van Zanten, 1994). Bacteria thrive in a moisture film around waste particles. Moisture in the waste is a requirement for gas generation, and since carbon dioxide is more soluble in water than methane, higher levels of moisture in the landfill may enhance the dissolution of carbon dioxide and consequently increase the measured methane content in recovered landfill gas (Scharff & Gronert, 2015).

Generation of methane occurs in the absence of oxygen, i.e. under anaerobic conditions (IPCC, 2006b). On unmanaged landfills, waste is not covered immediately. On shallow landfills, the surface that is exposed to oxygen is large compared to the volume of waste. On unmanaged landfills fires frequently occur, resulting in significant black carbon emissions. This results in loss of organic matter, that can no longer contribute to methane generation. Development of disposal sites away from open dumping is a necessity to prevent unacceptable health and environmental impacts (Rushbrook and Pugh, 1999). It should however be noted that the current situation is that most unmanaged landfills generate less methane per tonne of waste than well-managed deep sanitary landfills, though they are responsible for a broader range of health and air quality dangers.

Figure 1.2: Gas generation, recovery, oxidation, migration and emission schematic



It is not only food waste that results in landfill gas/ methane generation - commercial waste and residues from construction and demolition waste recycling can, for instance, contain large amounts of relatively dry paper and cardboard. Paper and cardboard are biodegradable

under landfill conditions. Such wastes can contain more kilogram of biodegradable carbon per tonne of waste than food waste, which has a high moisture content (Scheepers & van Zanten, 1994).

1.3 Landfill gas components

Landfill gas composition varies per landfill and may change over the life of a landfill. The factors that affect the composition of landfill gas at any point in time are typically (Scharff & Gronert, 2015):

- waste composition (the amount of readily degradable organic material)
- age of disposed waste (or the amount of methane that was generated in the past and has emitted)
- density of the disposed waste (higher density means more carbon per cubic meter landfill)
- moisture content and moisture distribution through the waste mass (dry pockets do not degrade)
- acidity / alkalinity (pH) (neutral conditions (pH 5 to 8) is required for methane generation)
- nutrient availability (to feed the microbes)
- temperature (20 to 55°C)
- presence of toxic agents and chemical inhibitors

Degradable organic carbon primarily consists of carbohydrates. Degradation of carbohydrates results in approximately equal amounts of methane and carbon dioxide. Degradation of fat and protein results in more methane than carbon dioxide production. On average the fat and protein content of landfilled waste is low. The Intergovernmental Panel on Climate Change (IPCC) recommends assuming 50% methane and 50% carbon dioxide for landfill gas generation. Landfill gas can also contain trace components, such as organic acids and esters, hydrogen sulphide, mercaptanes and solvents (e.g. benzene) or degradation products of solvents (e.g. vinylchloride) (Environment Agency, 2004) (see Tables 1.3.a and b). The toxic nature of some of these substances requires management of landfill gas in order to control exposure.

Table 1.3.a: Main components in landfill gas (Environment Agency, 2004)

	Typical value %v/v	Observed maximum %v/v
Methane	63,8	88,0
Carbon dioxide	33,6	89,3
Oxygen	0,2	20,9 #
Nitrogen	2,4	87,0 #
Hydrogen	0,1	21,1
Water vapour (typical % w/w, 25°C)	1,8	4,0

Derived entirely from the atmosphere

1.3.1 Methane

Methane is an odourless, flammable gas at normal atmospheric temperatures and pressures. It is explosive at concentrations of between 4.4% and 16.5% (by volume) in air with a minimum of 14.3% oxygen at 20°C and 1 bar atmospheric pressure. These limits are known as the lower explosive limit (LEL) and upper explosive limit (UEL) of methane (Environment Agency, 2004).

However, these concentrations are only a guideline as the presence of other components in landfill gas alters the explosive range. Because of this, the flammability limits of landfill gas will vary and should be addressed with safety margins.

1.3.2 Carbon dioxide

Carbon dioxide is an odourless, non-flammable gas normally present in the atmosphere at a concentration of 0.04% by volume. It is also a normal product of human metabolism (for example) and acts upon vital functions

in several ways. In higher concentrations it increases breathing and heart rates and changes body acidity levels. At very high levels, it displaces oxygen in the body and makes breathing ineffective.

Table 1.3.b: Trace components in landfill gas (Environment Agency, 2004)

Name	Median concentration mg.m ⁻³	Average concentration mg.m ⁻³
1,1-Dichloroethane	13,3	476,2
Chlorobenzene	11,9	246,6
1,1,1-Trichloroethane	12,9	189,8
Chlorodifluoromethane	11,6	167,4
Hydrogen sulphide	2,8	134,2
Tetrachloroethene	16,6	112,7
Toluene	12,0	86,2
Chloroethane	5,2	77,9
n-butane	13,6	67,4
Chloroethene	5,6	64,7
Carbon monoxide	5,8	63,0
Ethylbenzene	6,5	37,8
1,2-Dichlorotetrafluoroethane	3,2	34,0
α-pinene	9,3	33,2
cis-1,2-Dichloroethene	7,7	33,1
Xylene	4,7	23,9
Dichlorofluoromethane	3,5	20,1
n-hexane	5,0	19,9
Dichloromethane	1,2	19,1
n-nonane	8,1	19,0
Butan-2-ol	5,4	18,7
1,2-Dichloroethane	1,6	16,5
3-Methyl-2-butanone	2,0	13,6

1.3.3 Trace components

Landfill gas will also contain many trace components, the nature of which is defined by the waste itself.

These trace components can cause odour and may be toxic. They also are of importance when considering landfill gas utilisation. Concentrations of trace components vary significantly. They depend on waste composition and generally are significantly reduced when the waste ages.

The minor constituents of landfill gas will vary according to the makeup of the waste, its age, and the level of degradation. They usually constitute no more than 0.5%

of the total gas volume. However, the minor constituents are responsible for the distinctive smell of landfill gas and for its corrosive nature (Environment Agency, 2004). These characteristics can change as more organic waste is diverted from landfill. For example, this can lead to increased levels of hydrogen sulphide and thus making odour control even more important. Due to binding of sulphuric compounds to iron compounds in soils, biocovers can mitigate odour emissions. **In laboratory studies (e.g. Scheutz et. al., 2009b) it has been demonstrated that biocovers can also mitigate some fluorinated and chlorinated compounds.**

1.4 Challenges associated with landfill gas composition and emissions

Without landfill gas control most of the generated landfill gas will emit uncontrolled from the landfill. This release of landfill gas can cause several problems:

- On a global scale, emissions of methane contribute to global warming. This an important driver for measures against methane emission. Landfills are responsible for approximately 11% of anthropogenic methane emissions. This number is rising, mainly due to increasing amounts of waste that is landfilled in large parts of the world (UNEP 2024).
- On a local scale landfill gas can cause odour nuisance that can contribute to unhealthy labour conditions on the site and might cause problems with people living on or around landfill sites (Environment Agency, 2004).
- Landfill gas may contain toxic substances that, when inhaled continuously or regularly, may cause health problems (Environment Agency, 2004).
- In specific situations, landfill gas can migrate and accumulate in less ventilated enclosures, and methane and carbon dioxide heap up. Mixtures of methane and air might cause fires or even cause explosions; higher concentrations of carbon dioxide may cause suffocation. There are numerous examples or serious accidents on or next to landfills due to landfill gas.

- Landfill gas generation entails the transformation of solid materials to gaseous compounds that escape. This creates cavities in the landfill body. Normally that results in gradual settlement of the landfill. However, when not properly constructed, and e.g. when situated on a slope of a hill, or when unmanaged a landfill might become instable. Incidents such as a landfill gas explosion, fires, and landslides from increased moisture content of waste can sometimes with catastrophic consequences for people present on the landfill or living at the lower end of the landfill.

TAKEAWAYS:

- Methane is a powerful greenhouse gas.
- Methane and trace gases are released by landfills in significant amounts.
- Uncontrolled releases of methane may result in explosions and open fires which can last for months, generating significant air pollution.
- Releasing non-methane toxins and pollutants may cause environmental and health problems.
- Landfill gas capture and treatment and biocovers offer effective management solutions which can be seen as complementary.

02 Landfill Gas Control

2.1 Landfill gas control strategies

- **Organic waste diversion from landfills.** Degradable organic waste that is not landfilled can no longer generate landfill gas. Depending on the effectiveness of the landfill diversion strategy, landfills in a state, region or municipality emit less methane than before over the longer term. Nevertheless, they might still benefit from the application of biocovers, and one or more of the following strategies.
- **Pretreatment of organic waste prior to landfilling.** Degradable organic waste can be pretreated with the aim to lower the amount of degradable organic matter before landfilling the residue. Pretreatment consists of a controlled organic carbon degradation process (e.g. composting and anaerobic digestion). Landfill methane generation and emissions are lower than without pretreatment of organic waste. Depending on type and correct operation of the treatment, more or less of the available organic matter is degraded. It should be observed that methane is not emitted during pretreatment. The nature and the amount of the residues that are landfilled could still benefit from application of active or passive gas control.
- **Active gas control.** Active gas control entails installing gas wells in the landfill body and extracting and treating the gas from these wells by means of a technical installation. Depending on the design and the correct operation of the active gas control system and additional measures such as e.g. a surface sealing gas recovery rate between 20% and 100% of the generated gas can be achieved. Landfills with a low gas recovery rate could consider to either take technical measures to improve the gas recovery rate or to realise passive gas control in addition to the active gas control.
- **Passive gas control.** As a result of landfill gas generation, gas pressure in the waste body increases. Due to the pressure gradient, landfill gas is forced to move up to the atmosphere or horizontally out of the waste body into permeable soil layers. Passive landfill gas recovery makes use of the pressure build-up to force the gas into gas wells or structures with a higher air-filled porosity than the waste itself. This can guide the gas to a passive treatment system.

Though complementary actions in reducing emissions from landfills, organic waste diversion and pretreatment of organic waste are not discussed in detail here. The focus of this report is biocover methane oxidation, at landfill. Methane oxidation can play a role in both active and passive gas control. It should be mentioned that it is considered best practice to operate landfills on a cell-by-cell basis and keep the tipping face as small as possible. This reduces nuisance (odour, wind-blown litter, etc.) and it provides better options for gas control. If each cell is operated for 1 to 4 years, it can be covered relatively quickly. If that cover is a methane oxidation cover, gas control kicks in early and increases overall methane emission reduction from the landfill.

2.2 Active gas control

In landfills with high gas generation (active sites with especially high volumes of untreated organic waste), active recovery of the gas can be necessary to prevent a build-up of landfill gas pressure. High gas pressure in the site could result in flow of landfill gas out of the landfilled waste into the sub-surface environment. In active gas recovery a blower is used to create a negative pressure on

landfill gas wells. It extracts the gas from the surrounding waste into the well and subsequently transports the gas through the collection pipes to a landfill gas utilisation unit, a flare or a methane oxidation system (Environment Agency, 2004). If biocovers are used in such contexts (e.g. the closing of cells), active gas control systems are important.

2.3 Passive gas control

Passive recovery can be considered in various situations:

- **Low gas generation landfills:** Landfills with a low gas generation rate run less risks of dangerous build-up of gas pressure. Under these conditions, passive gas control may suffice to prevent problems related to landfill gas. There can be various reasons for a low gas generation rate. It can be a small shallow landfill or dumpsite. It could be that persistent and re-occurring landfill fires have reduced the available amount of organic carbon. It could be a landfill for predominantly inorganic waste. Or it could be that upstream actions, such as organic waste diversion or organic waste pretreatment have reduced the available amount of organic carbon.
- **Limited infrastructure or capacity:** In situations where power supply is unreliable, investment in technical installation is difficult to obtain or expertise to operate and maintain the technical installation is difficult to sustain. In such cases, passive gas control (even when suboptimal) is an alternative. Passive gas recovery in combination with microbial methane oxidation does not require energy consuming and maintenance intensive electrical and mechanical equipment.
- **Supplement to active recovery:** Passive recovery in the top layer of the landfill may also be used to complement the gas recovery performance of the active gas recovery system.
- **Post-closure application:** After closure, when landfill gas generation has declined, and active gas control can no longer be sustained, passive gas control can provide ongoing environmental protection.

Passive gas control does not imply that additional measures are not necessary. Gas drainage layers and piping may be necessary to make the gas flow to passive flares or microbial methane oxidation measures. Some form of lining of the landfill base and sides may be required to create a barrier to sub-surface gas flow. A semi-permeable or impermeable cover may be necessary to force gas to the gas treatment system and reduce emission to the atmosphere (Scharff & Gronert, 2015). Passive recovery systems should always be equipped with some form of gas treatment. When passive wells are connected to a vent, the landfill gas is released to the atmosphere. This practice does not reduce odour and greenhouse gas emissions and should be discouraged.

TAKEAWAYS:

- Active gas control is most suited for large and high landfills and landfills (managed or unmanaged) with high gas generation rates.
- Passive gas control is most suited for shallow landfills, dumpsites and landfills with low gas generation.
- Passive gas recovery combined with well-designed microbial methane oxidation using non-degradable materials (see Chapter 3) offers a low-maintenance solution that does not rely on energy-intensive electrical or mechanical equipment.

03

Microbial Methane Oxidation

3.1 How does it work?

Microbial methane oxidation in covers is carried out by a group of bacteria called methanotrophs. Depending on conditions, such as temperature and moisture, these bacteria are more, or less active. Some understanding of the processes and some monitoring for signals of failure are necessary. Other than that, many microbial methane oxidation systems are particularly suited for passive gas control. Methane and oxygen are consumed and converted to carbon dioxide and water. Two molecules of oxygen are required to oxidise one molecule of methane.

This highlights the importance of oxygen supply for the complete oxidation of methane fluxes. Methanotrophic bacteria are everywhere and particularly abundant where methane meets atmospheric oxygen, e. g. in marsh soils, but even more so in landfill covers. Methane fluxes on landfills exceed those measured in natural soils by several orders of magnitude. The resulting abundant populations of methane oxidising bacteria achieve methane oxidation rates that are among the highest reported.

3.2 Types of Microbial Methane Oxidation Systems

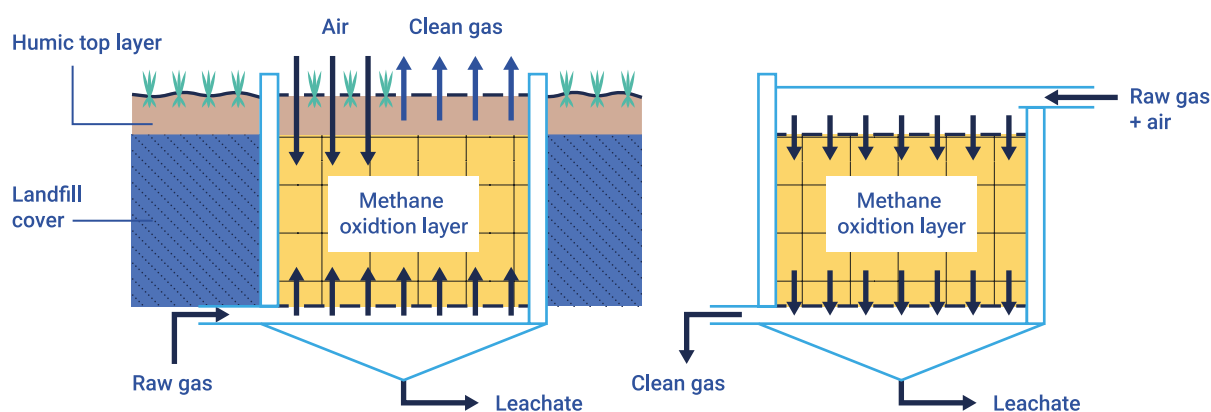
Depending on the status of the cover (an interim or final cover) and the technical infrastructure (lining, gas extraction system) different systems for microbial methane oxidation are distinguished. In principle, there are three approaches:

- **Methane Oxidation Filters (Biofilters):** These are self-contained fixed-bed reactors built into, on top, or outside the landfill cover.

Figure 3.2.a:

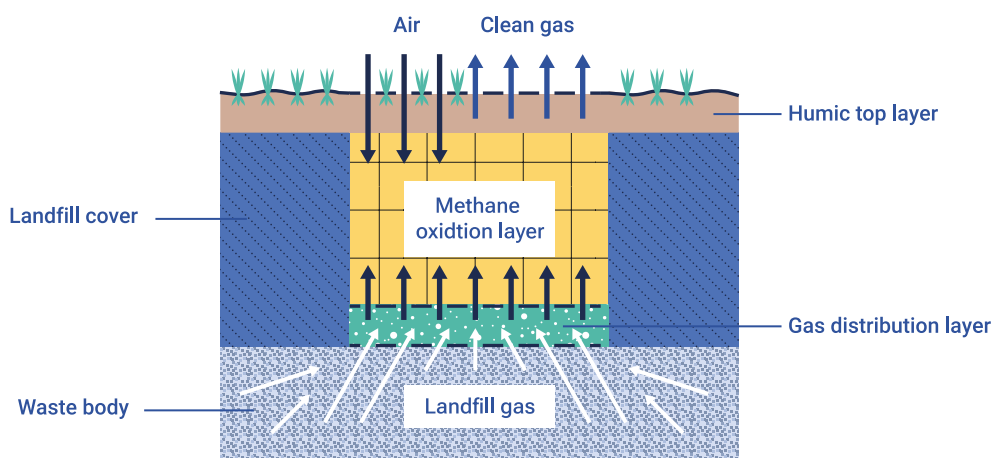
Left: open methane oxidation filter integrated into the landfill cover, in 'upflow' mode.

Right: closed methane oxidation filter in 'down-flow' mode. Adapted from Huber-Humer et.al., 2008 (not to scale).



- **Methane Oxidation Windows (Biowindows):** Biowindows are open compartments integrated into the landfill cover that can have, but do not require, connection to a gas recovery system. Biowindows are also suited to remediate emission hot-spots.

Figure 3.2.b: Methane oxidation window. Adapted from Huber-Humer et.al., 2008 (not to scale).

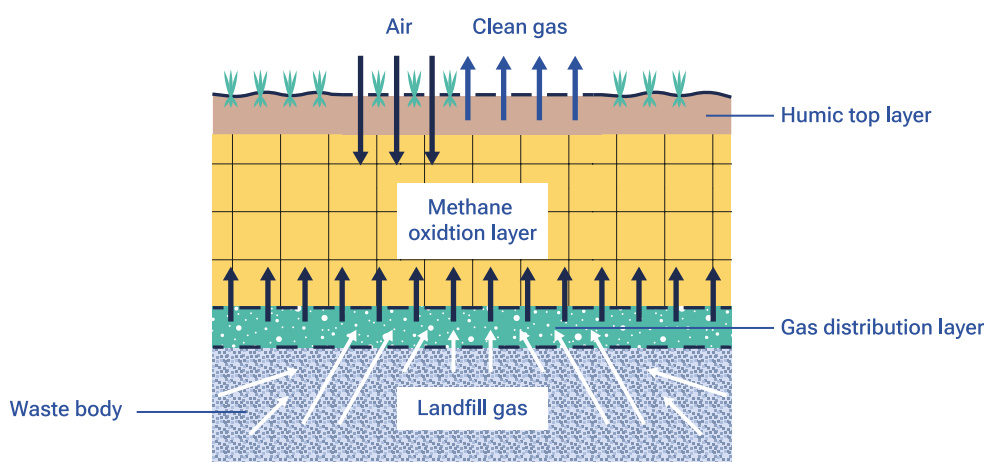


Windows and filters require that the gas is transported to those structures and does not emit from the remaining landfill surface. This may involve low permeability caps and/or gas collection pipes (active or passive recovery). This is considered conventional landfill technology (see

e.g. Scheutz and Kjeldsen, 2011) and not elaborated in this report. Windows and filters save costs on the MMOS but increase costs of other infrastructure. For that reason, this report focuses on methane oxidation covers.

- **Methane Oxidation Covers (also referred to as Biocovers):** Biocover systems use large parts of or the entire cover as active methane oxidation layer.

Figure 3.2.c: Methane oxidation cover. Adapted from Huber-Humer et.al., 2008 (not to scale).



More information is available in Huber-Humer et al. (2008) and Scheutz et al. (2009a).

3.3 Requirements and effectiveness

Methane oxidising bacteria require methane, coming from the landfill, and oxygen, from the atmosphere. They also need moisture. In a very dry methane oxidising layer bacterial activity is low. Materials with a small grain size retain more moisture. These materials are however prone to blocking of pores due to excess water. To provide sufficient oxygen to the bacteria and enable transport of methane, part of the pores in the methane oxidising layer should still be filled with air (air-filled porosity) while the material is moist. This condition can be provided by many types of materials, but it narrows down the range of particle sizes for the methane oxidation layer and introduces the need to avoid compaction (see section 5).

The bacteria thrive under warm conditions. Below 5°C and above 50°C bacterial activity is very low. In very cold climates or conditions, for example, using compost-based materials is an advantage, as more insulation results (Environment Agency, 2017). The applicability of microbial methane oxidation systems in very arid, very cold and very humid climates is discussed in Appendix 1. Conversion rates vary greatly with environmental conditions and properties of the methane oxidising layer. The choice of a

material with adequate physical and chemical properties as well as the design and dimensioning of methane oxidation systems in adaptation to the expected methane fluxes and the climatic conditions are very important to achieve high methane oxidation efficiencies.

Research into methane oxidation systems has driven investment and development and made methane oxidation systems more effective and affordable. In active landfill cells, methane is typically produced at rates between 200 and 300 g CH₄ per m² per day. In laboratory-scale studies under controlled conditions, methane oxidation rates have reached several hundred grams of CH₄ per m² per day (Scheutz et al., 2009a) (see Chapter 4). However, real-world data shows that actual oxidation rates are lower (see Appendix 1). Full-scale systems, including biocovers and biowindows (e.g., Geck et al., 2016b; Scheutz et al., 2014; Almeida et al., 2024), typically achieve oxidation rates from 20 to 80 g CH₄ per m² per day. For typical, non-optimized landfill covers in temperate climates, Gebert et al. (2011a&b) suggest a conservative annual average of 17 g CH₄ per m² per day.

3.4 Applicability

Biocovers, and microbial methane oxidation systems generally, are particularly effective at landfill sites with relatively low methane generation rates. These conditions are often found in:

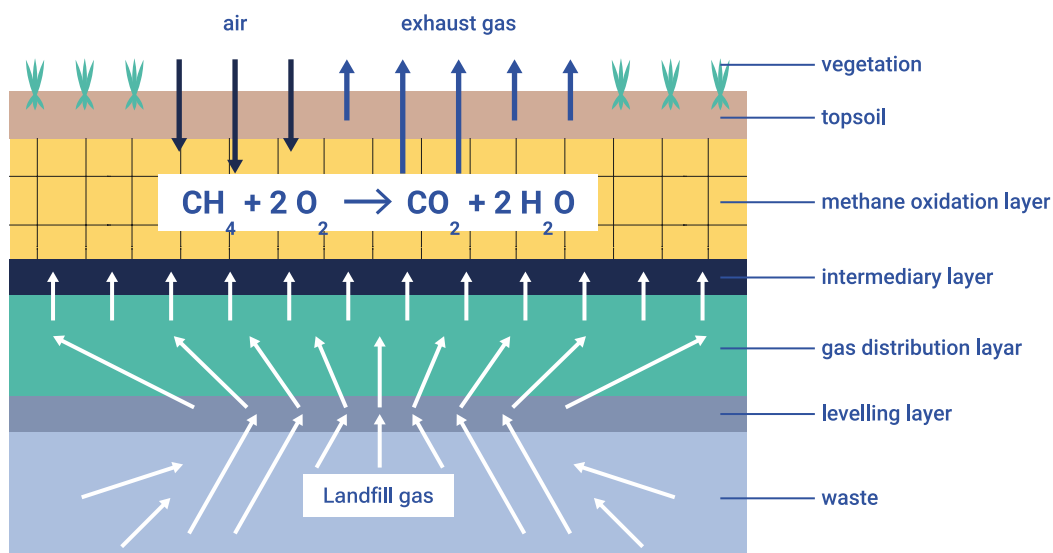
- Landfills containing waste with low gas generation potential, such as contaminated soils or dredged materials.
- Sites storing pre-treated wastes (e.g., stabilized organic waste with reduced biodegradability).
- Landfills in the early operational phase before peak gas production has been reached.
- Closed or legacy landfills and dumpsites that were poorly managed, shallow, and primarily aerobic in nature, resulting in low methane emission rates (typically below 15 to 20 g CH₄ per m² per day).

Methane oxidation systems can also be valuable in situations where waste exhibits low porosity, which limits the effectiveness of gas wells due to a reduced radius of influence or where active recovery is performing inefficiently for other reasons. In such cases, microbial methane oxidation can serve as a complementary emission control strategy. Additionally, these systems are well-suited for treating residual methane emissions following the cessation of active gas recovery, or on older landfill sites where no gas collection infrastructure exists. **Biocovers can be particularly effective and attractive as investment in the process of landfill closure, and remediation, to ensure emissions over several decades after closure are reduced as much as possible.**

3.5 Layers in methane oxidation systems

The set-up and principle of the different layers within a methane oxidation system and the operational conditions for each option are briefly described in this section.

Figure 3.5: Layers in a methane oxidation system. Adapted from Huber-Humer et.al., 2008 (not to scale).



More information on the layers in a methane oxidation system and requirements on physical properties and chemical properties of materials are presented in Appendix 2. From bottom to top systems, microbial methane oxidation consists of the following layers:

- The levelling layer or remaining temporary cover evens out any unevenness in the terrain. It should be sufficiently permeable to not impede gas transport. At the same time, it should allow for sufficient carrying capacity and (slope) stability for the construction of the other layers of the methane oxidation system.
- The gas distribution layer facilitates horizontal distribution of the gas prior to its entry into the methane oxidation layer. To equalise the spatial methane load, gas needs to easily travel horizontally. Indicatively, the permeability coefficient of the gas distribution layer should be two to three orders of magnitude greater than that of the methane oxidation layer. If the permeability coefficients would be similar, the gas would travel to the atmosphere vertically instead of horizontally. That is the shortest and easiest route through material with a similar resistance. If this is considered insufficiently there is a huge risk that a serious percentage of the construction of the methane oxidation layer is wasted money, simply because the gas does not reach it. The exact dimensioning depends on the expected gas load, the pressure loss and the area to which this load should be distributed. The aim of the design should be to equalise the pressure loss over the available area. Although suboptimal, microbial methane oxidation systems consisting of only a gas distribution layer and a methane oxidation layer have been built and demonstrated to perform.
- The intermediary layer can be applied where a sudden change of permeability between a gas drainage layer and a methane oxidation layer may result in undesired effects. If the difference in particle size between the two layers is big, the smaller particles of the top layer might be flushed into the bottom layer and block gas transport. Downward water transport may also be impeded. Pending water hinders gas transport. An intermediary layer can solve these problems.

- The methane oxidation layer subsoil enables microbial oxidation of methane to carbon dioxide, more particularly in the area where landfill gas mixes with atmospheric air. In methane oxidation systems that are optimised with respect to gas diffusivity, atmospheric air can penetrate effectively into the soil. Under these conditions the deeper layers in the subsoil can also contribute to methane oxidation. This is desired since a larger thickness of the methane oxidation layer increases the effectiveness of methane oxidation. When the soil properties enable oxygen transport deeper into the soil, the oxidation process is better protected against unfavourable conditions that can occur closer to the surface, such as summer heat, winter frost, superficial drying, rainfall causing superficial water saturation etc.
- The methane oxidation layer topsoil and vegetation consist of a humic topsoil that improves water availability for the vegetation and bacteria. It provides nutrients for vegetation and bacteria. Humic topsoil furthermore provides a good environment for soil organisms. Healthy vegetation in turn protects the soil against erosion and allows for optical integration of the methane oxidation system into the vegetated recultivation layer of the landfill.

3.6 Limitations and risks

- The methane load to the biocover is the main limitation for the application of a biocover. Although higher loads are theoretically possible, full-scale projects demonstrate that an average annual oxidation rate of 80 g CH₄ per m² per day is rarely exceeded. Chapter 4 will show that in the first 15 years of operation of a managed landfill cell the methane generation can be 2 to 5 times higher. Biocovers cannot mitigate that methane generation as a single technology approach. This requires active gas recovery and attention to reducing organic material at landfill. In such cases the risk of a biocover without active recovery is low cost-effectiveness of the biocover and high methane emissions.
- Biocovers typically are only constructed after reaching final height in a landfill cell. This implies that biocovers cannot mitigate the high methane generation rates during and immediately after disposal. This also requires active gas recovery. Any attempt to install a biocover as temporary or intermediate cover has the risk of very low cost-effectiveness due to the short period in which the biocover will be active before it is covered with the next layers of waste.
- Biocovers should be constructed of bio-active course and porous materials (e.g. soil, compost, clay pellets) to ensure that sufficient oxygen can enter the methane oxidation layer. The risk of limited porosity in biocover materials is a lower oxidation rate and hence higher methane emissions than necessary.
- Biocovers should be constructed of biologically stable materials in order to prevent that oxygen is consumed to oxidise the biocover material and hence cannot oxidise methane. The risk of biologically instable material is a competition over oxygen and therefore lower methane oxidation and higher methane emissions. Partly stabilised organic materials in a methane oxidation layer can even generate methane and result in higher methane emissions than those that originate from the landfill.

- Biocovers can only perform adequately when they are homogeneously 'loaded' with methane. This implies that biocovers always require a properly dimensioned gas distribution layer. Landfills have heterogeneous emission patterns. Landfill gas is mainly transported through preferential pathways. If these preferential pathways enter the methane oxidation layer without proper re-distribution, locally the methane load to the biocover will exceed the oxidation capacity. The risk of an insufficient gas distribution layer is that the bulk of the landfill methane emission follows pathways that lead to the atmosphere with hardly any methane being oxidised.
- The key requirements for a biocover can be adapted for each specific situation by a proper design. The key requirements that can be influenced are air-filled porosity, water drainage capacity, suitable physical and chemical characteristics. If the design criteria are not met in the realisation of the project (e.g. by choosing cheaper, but less suitable materials), the risk is that the actual oxidation rate will be lower than the expected oxidation rate and the methane emission will be higher.
- Especially for biocovers constructed with organic materials, it is important that inspection, maintenance and repair is executed as planned. If this does not happen the risk is that increasingly larger parts of the biocovers become ineffective. The overall oxidation rate will be lower, and the methane emission through such gaps will be higher than anticipated.

TAKEAWAYS:

- Because many shallow, poorly managed, and unmanaged landfills in developing countries emit less methane than achievable oxidation rates, microbial methane oxidation systems are highly suited and potentially transformative for these regions.
- As more countries seek alternatives to landfills, and look to close and cap existing sites, biocovers can help offset emissions which will continue for many years beyond closure.
- To obtain the highest conversion rate, the choice of materials for the methane oxidation layer and the design and dimensioning of the system are of utmost importance.
- A microbial methane oxidation system consists of 2 to 5 different layers that must be carefully designed and configured to each other, to the local climate conditions and to the methane load of the landfill. The bacteria require methane, oxygen, moisture and an appropriate temperature range
- The main risks are that the design and maintenance requirements are not met. If that happens, the oxidation rate is lower and the methane emission higher than expected.

04 Decision Making For Effective Biocovers

4.1 Determining the methane load

The first step in the decision-making process for implementing a methane-oxidizing biocover is to determine the methane load reaching the cover from the landfill. The load of methane to the biocover is very hard to measure accurately. When no appropriate cover is installed, in conformity with IPCC (2006b) recommendations, methane oxidation should be considered absent. If in addition there is no gas recovery, the load to the cover equals the amount of methane generated. That can be estimated by means of methane generation modelling.

A number of models exist to help calculate methane emissions from landfills, with the IPCC widely recognized as the leading authority. Many landfill gas (LFG) generation models are based on the same principles as the IPCC's

First Order Decay (FOD) model (Scharff & Jacobs, 2006). The feedstock for the bacteria generating methane is biodegradable organic carbon in the waste. In the first 4 to 12 months after disposal the bacteria population still must grow (IPCC, 2006b). **Methane generation peaks approximately a year after disposal of the degradable organic carbon.** Then the feedstock slowly depletes, and the methane generated from the amount disposed in that year declines. **If the landfill continues operation, every year more waste is disposed. The degradation of that waste follows the same methane generation pattern.** As a result, the overall methane generation typically continues to grow until the landfill is closed. Because no new feedstock is added from that moment on the methane generation steadily declines, but emissions will continue for several more years if no action is taken.

4.2 Required data for modelling

To model methane generation, it is necessary to either have or estimate data on annually disposed amounts of waste and their composition (IPCC, 2006b). Different types of waste contain different percentages of biodegradable carbon and different types of biodegradable carbon, for example food waste will degrade easier than straw or wood. If weighbridge data are available for each type of waste collecting the annual amounts of waste for each waste type is easy. Composition can be determined by means of sampling, sorting tests and analysis of

samples. If such data are not available, annual amounts and composition of waste can be estimated based on known waste generation and disposal information and waste composition data of similar communities. Such an estimate might be checked against a volume measurement of the landfill. The estimate is more difficult to make if it is known that the landfill has regularly caught fire or if waste has been washed away in an uncontrolled environment.

4.3 Principles of modelling methane generation

Because of the depletion of feedstock, methane generation is assumed to follow first order decay (IPCC, 2006b). First order decay is characterised by a half-life. The half-life applied is different for different types of degradable carbon. IPCC distinguishes three categories of degradability (IPCC, 2019). The three categories have different decay rates for different climatic conditions. In addition, it is assumed that under landfill conditions the three categories do not decay completely and to a different extent.

Furthermore, the type of landfill management can cause that a part of the carbon is burnt or degraded aerobically and consequently does not generate methane. IPCC (IPCC, 2019) has proposed correction factors for different types of landfill management (Table 4.3).

Table 4.3: Methane correction factor (MCF) default values for various types of landfills according to IPCC

Type of landfill	MCF
Managed – anaerobic	1.0
Managed well – semi-aerobic	0.5
Managed poorly – semi-aerobic	0.7
Managed well – active-aeration	0.4
Managed poorly – active-aeration	0.7
Unmanaged – deep (more than 5 m waste) and /or high water-table	0.8
Unmanaged – shallow (less than 5 m waste)	0.4
Uncategorised SWDS	0.6

In the framework of methane generation modelling IPCC (2006b) has defined ‘managed landfills’ as those landfills that have controlled placement of waste. This entails waste directed to specific deposition areas, a degree of control over informal waste picking and a degree of control of fires. In addition, managed landfills have applied mechanical compacting, levelling of the waste and/or a cover material. A degree of control of fires on managed sites implies that IPCC considers unmanaged sites to not have control of fires.

All these aspects need to be considered when estimating methane generation of a landfill. Modelling landfill gas generation is low cost and simple, if the landfill operator has the required expertise. The result does provide the landfill operator with an understanding of the landfill’s methane emission. When there is a large discrepancy between modelled result and other indicators on the landfill (low or high recovery, lots of vegetation damage, large odour emission, etc), operators can try to understand causes and identify solutions to further reduce emissions or correct the input parameters for the model. More details on methane generation and emission modelling can be found in the IPCC guidance documents (IPCC, 2006a; IPCC, 2006b; IPCC, 2019).

4.4 Typical development of landfill gas generation over time.

Operation time of landfills is typically more than 20 years. The time in between closure and final cover varies per landfill and depends on site specific conditions. Very often gas collection systems are only installed when the landfill is capped. At that moment, typically more than half of the methane, that the sum of the waste deposited can generate in 100 years, has already emitted. It should be noted that this also applies when the cap is a biocover.

To illustrate the differences in methane generation rates under varying conditions, six modelling scenarios were developed. These scenarios consider both temperate and tropical climates, and compare three types of landfill management: managed, unmanaged-deep, and unmanaged-shallow. In each case, it is assumed that the landfill receives 150,000 tonnes of municipal solid waste (MSW) per year over a five-year operational period, with waste deposited into a single cell. The managed landfill is assumed to reach an average height of 25 meters, the

unmanaged-deep landfill an average of 15 meters, and the unmanaged-shallow landfill an average of 5 meters. These differences in fill height reflect typical operational practices and physical constraints associated with each landfill type.

Methane generation was modelled in accordance with IPCC 2019 guidelines, applying the recommended parameters for wet temperate and wet tropical climates, and incorporating the appropriate methane correction factors (MCFs) for each landfill type (IPCC, 2019). The results, presented in Figures 4.4b and 4.4c, illustrate the expected methane generation profiles for each scenario, highlighting the influence of climate, landfill depth, and management practices on methane production potential. The results are compared with the potential methane oxidation rate of 80 g CH₄ per m² per day (green line in Figures 4.4.b and 4.4.c) of a well-designed microbial methane oxidation system (paragraph 3.2).

Figure 4.4.a: Typical development of landfill gas generation over time.

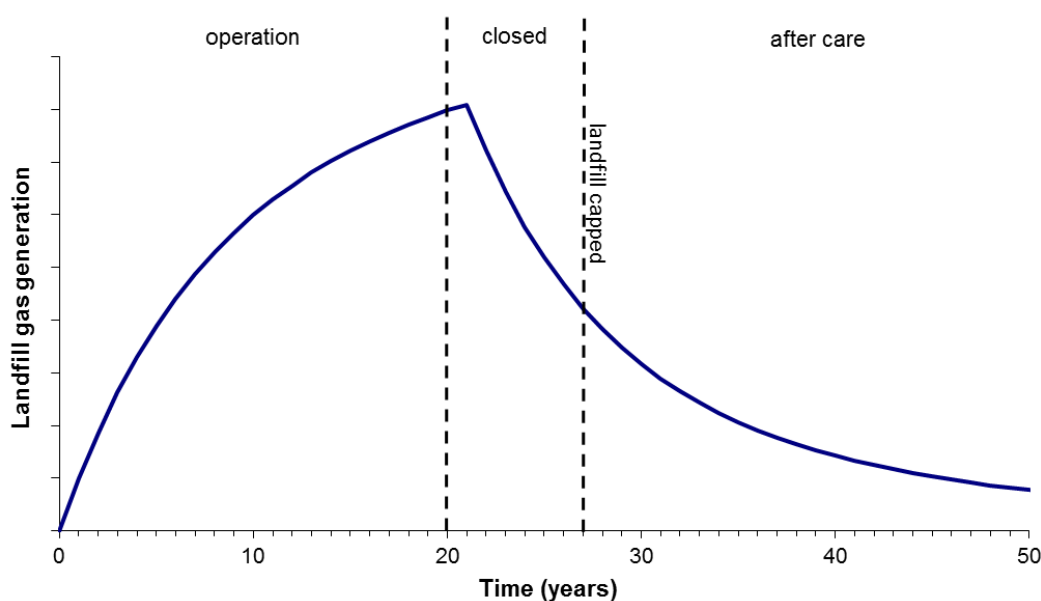


Figure 4.4.b: Example methane generation in a dry temperate climate.

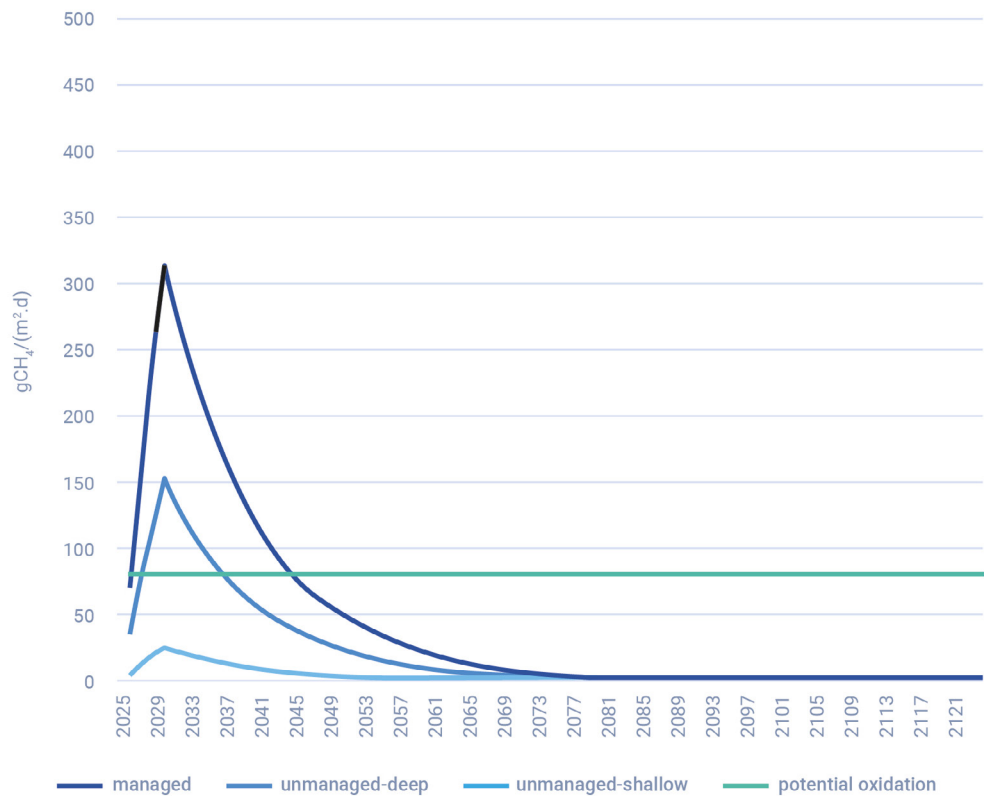
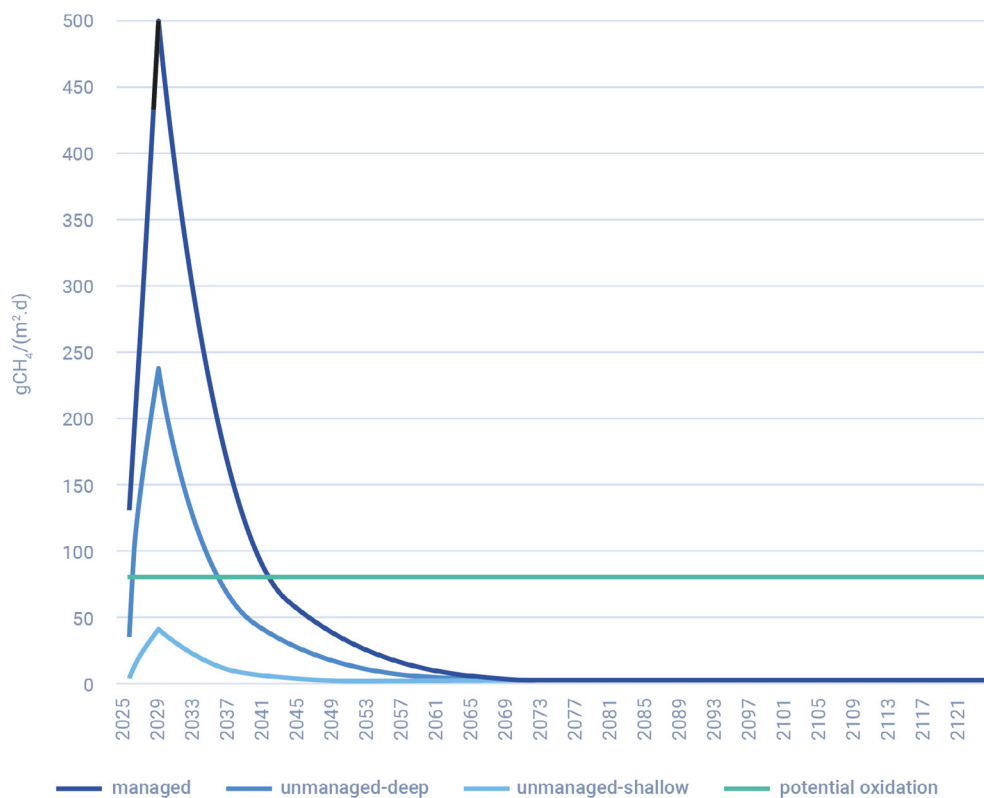


Figure 4.4.c: Example methane generation in a wet tropical climate.



The black and blue lines in Figures 4.4.b and 4.4.c represent modelled methane generation rates over time. In a managed landfill with an average height of 25 meters, located in a dry temperate climate, methane generation can reach approximately **300 g CH₄ per m² per day** about five years after the start of waste disposal. In comparison, methane generation proceeds more rapidly in a wet tropical climate, where it can peak at around **500 g CH₄ per m² per day**. However, in tropical climates, methane production also declines more quickly after waste disposal ends, as evident in Figure 4.4.c. These figures underscore that a significant portion of methane is generated and emitted during the first few years following waste disposal, regardless of climate or landfill type. This finding reinforces the importance of implementing methane control measures, such as biocovers or active gas recovery systems, early in the landfill lifecycle. Notably, even at engineered sanitary landfills, gas recovery infrastructure is often not installed during the first years of operation, allowing substantial methane emissions to occur during this critical period.

In contrast, methane generation on unmanaged landfills is significantly lower, not only due to the absence of compaction and cover, but also because of the substantially lower average fill height. In the modelled scenarios, unmanaged-deep and unmanaged-shallow landfills reach heights of 15 meters and 5 meters, respectively. As a result, the total methane generated

is distributed over a larger surface area, reducing the emission rate per square meter. This demonstrates that landfill height is a key parameter influencing methane generation intensity. Moreover, the IPCC guidelines assume that a portion of degradable organic carbon (DOC) in unmanaged landfills does not contribute to methane production, due to aerobic degradation, burning, or long-term stabilization. Specifically, it is assumed that 20% of DOC is lost in unmanaged-deep landfills, and 60% in unmanaged-shallow landfills, further reducing the methane generation potential in these cases. As shown in Figures 4.4.b and 4.4.c, under the same assumptions for waste tonnage and composition, the peak methane generation rate in unmanaged scenarios ranges from approximately **25 to 40 g CH₄ per m² per day**, substantially lower than in managed systems, highlighting applicability of biocover as fugitive methane emission abatement systems in these scenarios.

It should also be noted that dry climate scenarios are not presented in the current figures. However, methane generation in a dry tropical climate tends to follow a similar pattern to that of a wet temperate climate, albeit at slightly reduced levels. In contrast, methane generation in dry temperate climates is significantly lower than in wet temperate conditions, reflecting the critical role of moisture availability in driving microbial methane production in landfills.

4.5 Potential methane abatement of biocovers

As explained in paragraph 3.2 a well-designed methane oxidation cover under **optimal conditions** can **oxidise fluxes of up to 80 g CH₄ per m² per day (green line in Figures 4.4.b and 4.4.c)**. Allowing for suboptimal conditions and compromises in the choice of materials a biocover is **likely to reduce 20 and 40 g CH₄ per m² per day**. In a temperate climate methane oxidation comes almost to a complete standstill in the winter months. Therefore, it is assumed that a realistic annual average methane oxidation rate is 20 g CH₄ per m² per day. In the example of the wet tropical climate, it is assumed that an annual average methane oxidation rate of g CH₄ per m² per day can be realised.

The higher oxidation rate is however almost entirely compensated by the faster methane generation, or in other words more methane has already emitted before the cover can be installed and become effective. This implies that in both the wet temperate and wet tropical climate the maximum methane abatement potential on the managed landfill example is most likely in the order of 15% of the methane generation over 100 years from the start of disposal. **Higher landfill lifetime abatement percentages can only be achieved by combining biocover methane oxidation with organic waste diversion from landfills and/or early gas recovery** (Bogner et. al, 2007; Scharff et al, 2023; Finlay & Scharff, 2024).

In developing countries, landfills are often not managed. On the unmanaged landfill site examples, the methane generation rate and consequently the load to the methane oxidation cover is a lot lower. Methane oxidation cover can be more effective on unmanaged landfills, as the lower methane loading remains well within the oxidation capacity of a properly designed system. In the examples

of Figures 4.4.b and 4.4.c a methane abatement potential of 50% of the methane generation over 100 years from the start of disposal respectively in the wet temperate and the wet tropical climates could be achieved by means of biocovers.

These examples represent two extremes in methane abatement potential on landfills with different types of management. It is impossible to determine a reliable distribution of management types for all landfills in the world.

However, a conservative estimate of global abatement potential of biocovers across unmanaged and managed landfills would be 20% of the methane generated and a more optimistic estimate would be 40% of the methane generated.

The World Bank (Kaza et.al., 2018) estimated that 1.6 billion tonnes of carbon dioxide equivalent greenhouse gas emissions were generated from solid waste management in 2016. This is almost entirely from landfill methane emissions and about 5 percent of global emissions. Without improvements in the sector, the World Bank anticipated solid waste related emissions to increase to 2.6 billion tonnes of carbon dioxide equivalent by 2050. Methane emission is not the same as methane generation. Assuming that worldwide 20% of the methane generated is somehow not emitted, then worldwide methane generation could be in the order of 3.2 billion tonnes of carbon dioxide equivalent by 2050. **Full application of biocovers might provide a reduction of 0.6 to 1.2 billion tonnes of carbon dioxide equivalent on a worldwide basis by 2050.**

4.6 Limitations of modelling

Because of the financial implications of accurate measurement, methane generation models have to date not been validated to scientific standards. Modelling is still the common method to estimate methane generation and emission. Monitoring protocols in various countries (e.g. European Commission, 2006) require that methane generation and emission are determined by means of modelling. A model is always a simplified description of reality. It can never include all factors that play a

role. Therefore, there are uncertainties in the result of a modelling exercise. On individual landfills the modelled result can deviate from reality by 50%. The largest uncertainty is however not in the model itself, but in the landfill operator's records of amounts and degradable organic carbon content of the disposed waste (IPCC, 2006b). Data on waste type and volume is essential to ensure the right systems are established.

4.7 Methods to measure methane emission

Because modelling has its limitations, it would be better to measure methane emissions at source. Unfortunately, due to the huge temporal and spatial range of landfill methane emissions, most measurement methods have uncertainties in the same order of magnitude as modelling. Nevertheless, measurement of landfill methane emissions is often required by regulators or in carbon trading to determine the baseline emission before the mitigation measure and in regular intervals after realisation of the mitigation measure in order to verify and certify the carbon credits. Walk-over surveys, flux-box measurements and tracer plume measurements are the most widely applied measurements techniques for determination of landfill methane emissions.

Walk-over surveys (or surface screens) and flux-box measurements are sometimes required by competent authorities to verify landfill methane emissions. Walk-over surveys are methane concentration measurements carried out just above the landfill surface on multiple locations on the landfill. It should be noted that the results provide an indication where methane emissions on the landfill might occur. If that location can be related to a malfunction in the gas control system, it might be fixed. Walk-over surveys cannot quantify the level or rate of emission. An emission is a concentration times a flux. The flux and consequently the emission cannot be measured with a walk-over survey.

Flux-box measurements can measure both the concentration and the flux. They are also carried out on multiple locations on a landfill. It takes about 10 to 20 minutes to carry out one flux-box measurement and relocate to the next spot. The size of a flux-box usually varies from 0.3 to 1.0 m². It requires a large number of flux-box placements to obtain a reliable indication of the methane emission of the entire landfill. The method is therefore very time consuming. Flux box measurements are useful for process studies on small surfaces to understand driving environmental parameters (e.g. Geck et al., 2016a,b).

Tracer plume measurements are capable to estimate the methane emission of entire landfills (e.g. Hensen & Scharff, 2001; Scheutz et al., 2011). They require flat terrain, a road downwind of the landfill and specific wind conditions. The measurement takes place several hundred meters away from the landfill. The results are compared to the measurements results of the known amount of



Photo: Alpha/Adobe Stock

tracer that is released simultaneously. Dilution causes that the methane concentration in the plume is often just above the background concentration of methane in the atmosphere. The measurement device is mounted in a van or car that drives through the plume. That means that the measurement device must be very sensitive and must measure very fast. It is a complicated and expensive measurement that requires highly educated staff to operate. Therefore, it is expensive.

Repeated use of measurement techniques has provided the insight that landfill methane emissions varies greatly both from location to location (spatial variation) on the landfill, and over time (temporal variation). Landfill covers always contain so-called preferential pathways (animal holes, pockets of coarse material, etc.). Preferential pathways are small structures that are easy to miss with walk-over survey or a flux-box placement, but they often cause the bulk of the methane emission. A high-pressure front may cause gas being 'pressed back' into the waste body. A low-pressure front may cause additional methane release. Rain may cause blockage of gas-filled pores and hold back the methane in the waste body. Warm weather in the summer enhances methane oxidation in the cover. Cold weather in the winter slows it down. A tracer plume measurement can overcome the problems of spatial variation. It gives an accurate estimate of the methane emission of the landfill on the day of measurement. It would however require many measurement campaigns per year to obtain a reliable estimate for the average annual methane emission. Beyond methane emissions, monitoring leaks can also be important for air quality and odour control.

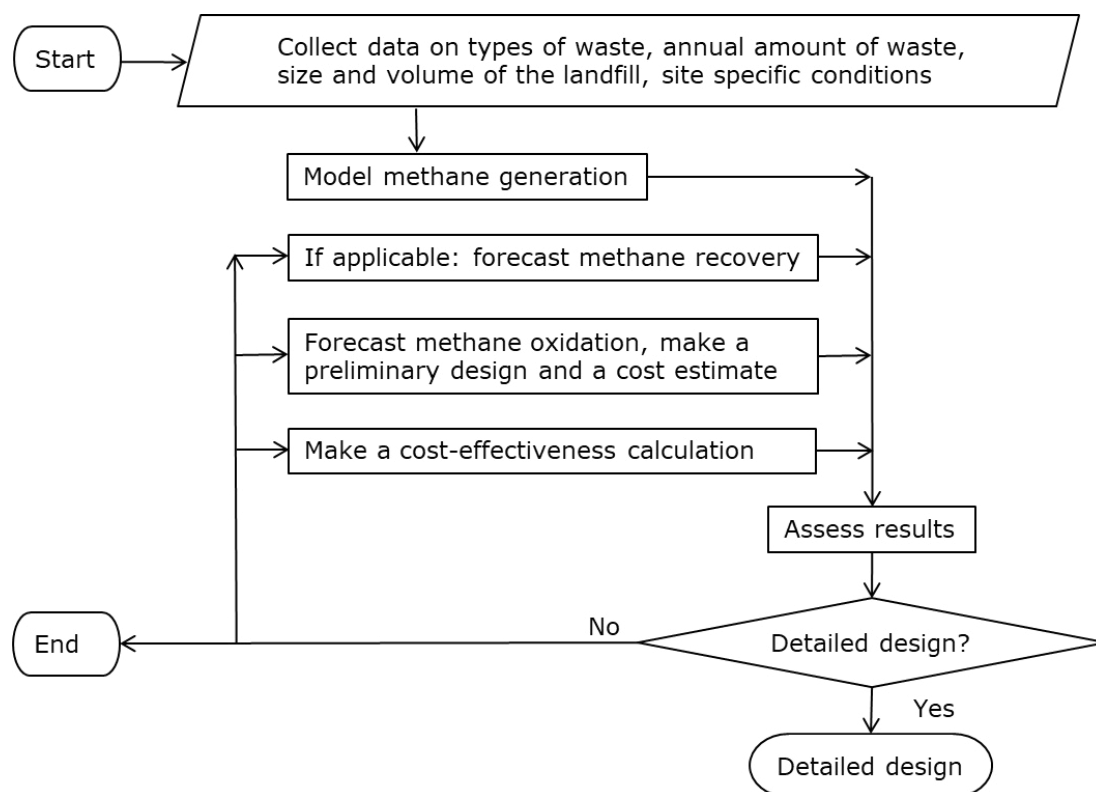
4.8 Choice of system and preliminary design

After the methane generation forecast has been made, a forecast of landfill gas recovery (if applicable) and a forecast of the methane oxidation efficiency of a suitable system for a particular landfill can be decided upon. The methane generation minus the methane recovery minus the methane oxidation provides an estimate of the remaining emission. In this stage only a methane oxidation system choice and a preliminary design is made. The choice of system depends on the methane load and on the abatement target. It should be noted that the methane load is never distributed evenly. This can be considered in the design of the gas distribution layer.

The targets for implementing a methane oxidation system can be many-fold. The level of emission reduction to be achieved should be subject to consideration by the relevant stakeholders. A high level of reduction in general requires a low methane load of the system. If the actual methane load is low enough, the gas can be treated on a smaller surface than the entire landfill cell. In that case a window or a filter might be the system of choice.

All open methane oxidation systems consist of 2 to 5 layers as presented in paragraph 5.2. Based on climate considerations and assumptions on available materials, an oxidation rate between 10 and 80 g CH₄ per m² per day can be selected (Gebert et al, 2011a&b). The cost of the methane oxidation system is estimated based on the choice of layers and assumptions for available materials. If desired, the cost-effectiveness and its development over a period of 10 to 20 years can also be estimated. A comparison with available financial means serves as a basis for a decision. In this stage it is only decided to invest further efforts into a more detailed design and cost-estimate that will serve as the basis for a decision to start the tendering process. A decision-making flow scheme is provided in Figure 4.5.

Figure 4.5: Decision-making flow chart for suitability assessment.



TAKEAWAYS:

- Methane generation modelling remains the standard approach for estimating landfill methane emissions. It is relatively simple, low-cost, and should be adopted by all landfill operators as a baseline planning tool.
- Despite inherent uncertainties, modelling provides valuable forecasts of methane generation, recovery, and oxidation, helping operators understand expected emissions and assess the potential technical effectiveness and cost-effectiveness of mitigation measures like biocovers.
- Biocovers can offer a practical and effective solution for methane abatement, particularly in developing countries, where landfills and dumpsites are often poorly managed and lack gas recovery systems.
- On an unmanaged landfill a methane abatement potential of 50% to 70% is conceivable.
- Based on forecasts in combination with a preliminary design and a preliminary cost estimate, a decision can be made to draw up a more detailed design and cost-estimate that in turn can serve as the basis for a decision to start the tendering process.

05

Design And Costs

5.1 Recovery test or demonstration project

A methane generation estimate is more uncertain as there is less information on (remaining) waste amounts and the degradable organic carbon content of the waste. Also, it is not possible to include all the specific circumstances for every individual landfill in the calculation of the estimates.

To improve confidence in design decisions, site-specific data can be collected through small-scale landfill gas pump tests and biocover test pads. A pump test provides a direct estimate of the landfill's methane generation rate and can typically be completed within a few months,

including preparation and analysis. In parallel, a methane oxidation pilot (e.g. biocover test pad) allows for field validation of the biocover design, material performance, and oxidation potential under local conditions. However, this approach requires a longer timeframe (typically 2 to 3 years including preparation, construction, growth of the microbes and monitoring) to generate meaningful results. Together, these small-scale tests offer a practical, phased approach to inform full-scale methane mitigation strategies tailored to the specific characteristics of the landfill.

5.2 General setup of a design

The first step in a detailed design is to verify or amend the system choice and preliminary design. The system choice may need to be reconsidered based on better information on the methane load to the cover. The preliminary design and the number of layers may need to be reconsidered based on more detailed information of available materials or the difference in cost between different materials. It should also be noted that in some countries application of biocovers, and consequently their design, may be limited by other regulatory requirements for final cover design. This may apply for example to layer thickness or the use of low permeability or geosynthetic materials. In the latter case biowindows or biofilters may be considered.

Official guidance documents on the design of microbial methane oxidation systems are available in Australia (Swarbrick et. al., 2010), Austria (in German) (ÖVA, 2008), Basque Country (in Spanish) (Scharff & Gronert, 2015 and Germany (in German) (LAGA, 2020). The taskgroup CLEAR has recently issued a more fundamental guidance document (Gebert et.al., 2022). Based on field observations on the depth of the methanotrophic horizon and in conclusion to sections 2 to 4 this document proposes the following setup for any open methane

oxidation filter, a methane oxidation window or a methane oxidation cover from bottom to top:

- > 5 cm levelling layer (if necessary).
- 20 to 50 cm gas distribution layer.
- 0 to 20 cm intermediary layer.
- 40 to 60 cm methane oxidation layer.
- 20 cm humic topsoil supporting vegetation.

This adds up to a total thickness of 80 to 150 cm. A total thickness of 80 cm (ÖVA, 2008) or even 100 cm (LAGA, 2020) should be considered as a minimum requirement. Thicker layers are possible and even recommendable when permit requirements for other reasons specify e.g. that the total thickness of the soil cover should be 100 cm or more. A major part of methane oxidation is assumed to occur in the top 40 cm of the methane oxidation layer (Gebert et.al., 2011).

The 'oxidation horizon' can fluctuate throughout the year due to changes in atmospheric pressure and in temperature changing microbial activity. In a dry season, it is necessary to ensure sufficient water storage capacity in the topsoil. Therefore, redundancy in the thickness is recommended (Gebert et.al., 2022). The topsoil should be

of a texture like that of the methane oxidation layer. The setup of encased methane oxidation filters with an aerated gas mixture at the inlet and not supporting vegetation can deviate. The spatial dimensions are to be chosen according to the expected load and the assumed methane oxidation rate.

Very detailed guidance on how to design a methane oxidation system can be found in Gebert J., Huber-Humer M. and Cabral A.R. (2022) Design of Microbial Methane Oxidation Systems for Landfills (Front. Environ. Sci. 10:907562; doi: 10.3389/fenvs.2022.907562). Appendix 2 explains what is recommended by Gebert et.al. (2022). Some essential steps are presented below. A decision-making flow chart for detailed design and cost estimate is presented in Figure 5.1.

5.3 Selection of materials

Various materials have been used in methane oxidation windows and covers. For gas distribution layers materials such as gravel, crushed stone, crushed concrete and wood chips have been used. For the methane oxidation layer materials such as sand, soil, compost, digestate and sewage sludge or mixtures have been used. The largest quantities of material are required for the gas distribution

and methane oxidation layers as these are usually the thickest layers. They represent the highest costs should they need to be transported over larger distances. The design process starts with identifying local materials that might be suited for the gas distribution and methane oxidation layers. Samples can be analysed in a laboratory.

5.4 Requirements on materials

The most important aspect for a gas distribution layer is that it has a much higher porosity than the methane oxidation layer. If not, then gas will not be homogeneously distributed horizontally over the entire window or cover. Local 'hot spots' will occur. In these hot spots the oxidation efficiency is limited because the maximum load of the cover or window is exceeded. At the same time other areas receive insufficient methane and perform less than they could.

The most important aspect for a methane oxidation layer is that it enables oxygen transport from the atmosphere into the methane oxidation layer. This can be guaranteed at a certain air capacity of the material. Air capacity is the air-filled porosity of a material at field capacity, i.e. with the maximum amount of moisture the material can contain. It can be determined in a laboratory or derived from tables. Air capacity depends on particle size distribution and bulk density (Gebert et.al, 2022). The latter is strongly influenced by compaction due to the use of heavy machinery. This suggests that consideration should be given to requirements on compaction and restrictions on machinery applied.

Organic materials do degrade, and gas permeability deteriorates over time. The methane oxidation layer and especially the topsoil does benefit from some organic carbon in the form of natural humic substances. They enhance nutrient availability, a favourable soil structure as well as water retention (Gebert et.al., 2022). These factors are relevant both to the activity of the microbial community and to sustain a vegetation cover. To save costs and efforts enough samples should be taken to also determine the chemical parameters. The parameters that need to be assessed are presented in Appendix 2.

The selection of materials is a compromise between costs and suitability of the material. The selection of materials for the gas distribution and methane oxidation layers determines whether an intermediary layer is necessary. If that turns out to be the case, the main requirement is particle size that is in between that of the selected materials for the gas distribution and methane oxidation layers. This prevents the finer particles of the methane oxidation layer from washing out into the gas distribution layer.

5.5 Determination of surface and thickness

In the preliminary design based on the methane generation forecast it was already determined whether the methane oxidation system could be a filter or a window or whether the entire surface of the landfill should be covered. The methane load per square metre determines this choice. The choice is preferably confirmed with a recovery test or demonstration project. A thin layer reduces costs and has a higher gas conductivity. The drawback is that with a relatively high load (or a passing low-pressure front) the oxidation might move upwards. Oxidation might have to

occur in a zone with unfavourable conditions (temperature, moisture). Another drawback of a thin methane oxidation layer is that the gas permeability of the gas distribution layer must be even higher. This can only be compensated by selecting a more porous gas distribution layer or by increasing the thickness of the gas distribution layer. Both will result in higher costs. **The material selection and the dimensioning of the thickness of the layers are therefore interdependent.**

5.6 Estimate of the effectiveness of the design

The effectiveness of a specific design of a methane oxidation system can be estimated by applying the guidance provided in Gebert et al. (2022). Alternatively, one can resort, for example, to the German guidance document on the construction of methane oxidation layers (LAGA, 2020) or to the Methane Oxidation Tool (Gebert et.al, 2011). The Methane Oxidation Tool has chosen a standard (conservative) methane oxidation capacity for

a methane oxidation layer with a specific porosity under specific temperature and moisture conditions. For the three main aspects, porosity, temperature and moisture, the Methane Oxidation Tool provides correction factors for other porosities, temperature and moisture conditions and thereby enables a site and material specific approximation of methane oxidation capacity.

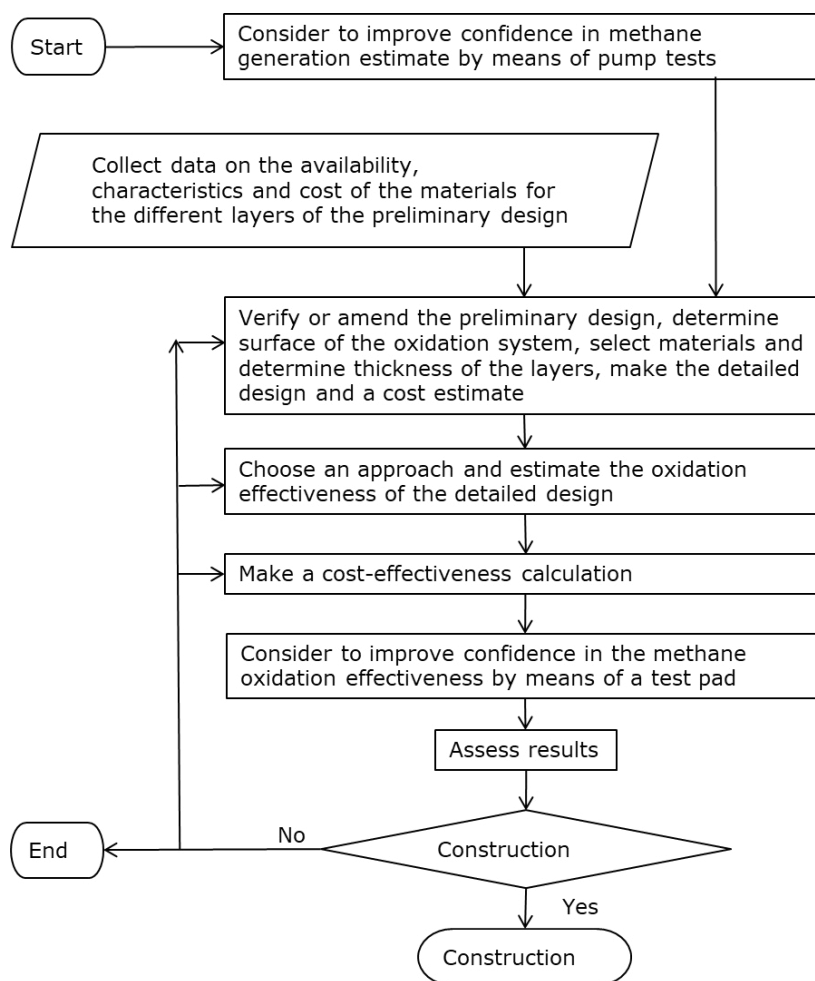
5.7 Detailed design and cost estimate

The detailed design entails several aspects:

- The methane load per square meter.
- The selected approach (filter, window, cover).
- The selected layers in the system.
- The selected materials, their characteristics and local access.
- The estimated effectiveness of the design.
- A cost estimate of the design
- The detailed design clarifies how much methane can be oxidised and consequently how much methane still is emitted. The cost estimate enables a decision to proceed to tendering and construction.

To obtain more certainty on the oxidation effectiveness of the design, a methane oxidation pilot project could be considered. A surface area of approximately 500 m² can be considered representative for full-scale application (LAGA, 2020). However, it should be noted that this may delay the project by 2 to 3 years and so should be considered against the costs of business-as-usual.

Figure 5.1: Decision-making flow chart for detailed design and cost estimate.



TAKEAWAYS:

- To obtain more certainty on the methane load it is recommended to carry out a gas recovery test.
- Material selection requires sampling and analysis for at least porosity, stability and chemical properties of several locally or regionally available materials and will be a compromise between costs and suitability of the material.
- The properties and thickness of layers are interdependent and may need to be revised during the design process.
- A detailed design clarifies how much methane can be oxidised. The cost estimate enables a decision to proceed to tendering and construction.
- To obtain greater certainty on oxidation effectiveness, it is recommended to carry out a methane oxidation pilot project.

06

Construction, Inspection, Maintenance And Repair

6.1 Construction

The construction of a methane oxidation system can follow the principles of civil engineering construction. The different materials used for the methane oxidation system are typically prone to compaction. Where in civil engineering compaction is often desired, for methane

oxidation systems compaction should be minimised. Compaction deteriorates specific qualities of the materials and reduces their functionality. Recommendations on avoiding compaction are presented in Appendix 3.

6.2 Inspection

Operation of a methane oxidation cover is relatively straightforward – the work being done by methane oxidising bacteria. Operational activities mainly concern periodic inspection. Inspection serves to check whether the conditions for favourable methane oxidation still exist. Serious settlement, cracks, erosion of the cover, occurrence of methane emission hotspots (indicated by vegetation damage or violet discoloration of soil) are examples of problematic conditions that should be identified by inspection. If affordable and technically possible, surface methane concentrations can be measured to identify emission hotspots. These conditions can either cause a reduction of the gas permeability or lead to preferential pathways. Both situations result in a reduction of the oxidation efficiency and should be solved.

With respect to methane oxidation windows and filters it should be noted that they sometimes include piping, valves and control boxes. Before operation starts it must be checked whether safe conditions for start-up exist. This mainly concerns explosive gas mixtures in confined spaces where ignition sources could be present. In some cases, operation will entail adjustment of control valves, condensate management, inspection and maintenance. As the focus of this document is on methane oxidation covers, operation and management of windows and filters will not be addressed here.

6.3 Maintenance

Maintenance of the topsoil entails periodic mowing of the vegetation. Mowing serves several purposes. It assures that the vegetation remains homogeneous. Species that are susceptible to mowing will disappear. This often includes species that develop deep roots. Deep roots may damage, or block underlying layers or cause preferential pathways. A relatively short vegetation makes the cover easily accessible for inspection and monitoring. Mowing is

preferably carried out with tracked and/or light machines (see Appendix 3).

Maintenance of layers below the topsoil of the methane oxidation system mainly relates to settlement and subsequent decrease in gas permeability as well as to clogging effects at layer interfaces. Settlement can easily be monitored by means of a ruler and settlement beacons

with a plate installed at the bottom of the methane oxidation layer (and the gas distribution layer if that is also constructed with organic materials) and the known length of pipe just peeking out of the topsoil. If requirements on chemical and physical properties are observed, maintenance of adequately dimensioned systems based on mineral materials is not required.

If industrially produced materials such as porous clay are employed, maintenance may involve adjustment of favourable pH values and nutrient status. Systems based on organic materials such as compost are prone to clogging and settlement. Maintenance works include loosening and possible replacement of the filter, window or cover material.

6.4 Repair

The impact of settlement and erosion reduces the effectiveness of the methane oxidation system. Repair is necessary and consists of replacing part of the system to restore the original conditions. A methane emission hotspot is often associated with damage in the methane oxidation layer or the gas distribution layer and requires repair. The remediation would be digging the material out and reconstructing the layers of the biocover. The same conditions with respect to avoiding compaction apply as during construction (see Appendix 3). For repair it is inevitable that machines run over the methane oxidation system. The use of pressure reducing plates or boards is recommended. Any compaction and vegetation damage occurring despite all precautionary measures needs to be addressed.

TAKEAWAYS:

- Construction of a methane oxidation system follows the principles of civil engineering construction with special care for avoiding compaction of materials.
- Operation of a methane oxidation cover is relatively simple: it is mostly limited to inspection.
- Inspection is necessary to identify vegetation damage, settlement, cracks and erosion of the topsoil.
- Maintenance is largely limited to mowing of the vegetation.
- Repair of settlement, cracks and erosion requires the same precautionary measures to prevent compaction as during construction.

7.1 Monitoring methods

Several methods can be used to monitor methane oxidation system performance (Gebert et.al., 2022). The choice of methods and equipment depends on technical concerns, as well as on requirements by the regulator, considering the target of the gas treatment and the intended after use of the landfill. Methods to consider are:

- Visual inspection and photo documentation. This is intended to identify disturbances in the soil structure such as cracks induced by settlement, shear or shrinkage processes or animal burrows as well as to disruptions in the vegetation. Preferential pathways for gas migration are frequently observed in association with the mentioned structures and phenomena. All these phenomena should be documented with photos.
- Settlement. Self-weight consolidation is frequent when soils are installed at low densities. Settlement results in the reduction of the soil's porosity. It is recommended that the extent of settlement between the base and the top of the methane oxidation layer is monitored with settlement beacons.
- Soil gas composition. Data on the composition of the soil gas phase using gas probes allows for:
 1. The assessment of the extent of aeration using the concentration of nitrogen,
 2. The localization of the depth of the methane oxidation horizon,
 3. The evaluation of spatial variability of gas flow through the system,
 4. The quantification of methane oxidation efficiency from the shift in the ratio of methane and carbon dioxide at the point of interest relative to the ratio at the base of the methane oxidation layer or the landfill gas (carbon balance method, see above, surface CH₄ concentrations).

Siting the gas probes should be representative for the area under investigation. Gas probes must be installed in several depths, including the gas distribution layer.

- Surface methane concentrations and patterns. Measurements should include active search for emissive spots. If the surface screening also includes the measurement of carbon dioxide, the methane oxidation efficiency can be assessed from the ratio of methane to carbon dioxide in the emitted gas.
- Methane emissions. In closed biofilters the quantitative assessment of the methane oxidation performance can be achieved by measuring concentration and flowrate of the base load and the emitted gas. For open biofilters, biowindows or point measurements on biocovers, methane emissions can be determined using wind tunnels, static, or dynamic chambers. For whole site emissions, methods integrating over larger spatial areas or even the entire site must be used, such as open-path methods or tracer techniques.

Further details on monitoring methods can be found in: Gebert, J., Huber-Humer, M. (eds) 2025: CLEAR Best Available Technology documents for Design, Operation and Monitoring of microbial methane oxidation systems to reduce landfill greenhouse gas emissions. Module 4: Monitoring of system performance.

7.2 Assessment of system performance

With the help of monitoring data, the performance of the methane oxidation system can be assessed. Based on the monitoring methods applied this can either be a qualitative or a quantitative assessment.

7.2.1 Qualitative assessment

If the surface screening shows no or negligible surface methane concentrations, a high efficiency of the system can be assumed. It should be verified that landfill gas enters the system and is not bypassing it. Analysis of the gas composition at the base of the methane oxidation layer using gas probes and comparison to the composition of the landfill gas can give an indication. Presence of cracks and vegetation damage indicates preferential pathways of gas emission. The inverse conclusion is not possible. It is important to note that an intact vegetation cover does not exclude significant emissions.

7.2.2 Absolute quantitative assessment

An absolute methane oxidation rate is evaluated by balancing the incoming and the outgoing methane flux. In case of a limited surface, it is possible to quantify methane emissions using static or dynamic chambers or a wind tunnel. In case of a large surface different approaches must be followed (see Appendix 4).

7.2.3 Relative quantitative assessment (efficiency)

A relative performance (the share of the methane load that is oxidised) can be determined using the carbon balance method (see Appendix 4). For this evaluation, soil gas composition as well as emission data (if both methane and carbon dioxide emissions are available) can be used. The oxidation efficiency is given as a percentage or fraction of the methane load.

7.3 Monitoring strategy and frequency

It is strongly recommended to include a baseline study in any monitoring strategy. This consists of several monitoring campaigns before construction of the methane oxidation system. Otherwise, a reliable assessment of the impact of the methane oxidation system is difficult. The monitoring strategy should consider the high temporal, seasonal, as well as the spatial variability of gas fluxes, driven by the impact of atmospheric pressure, wind, soil temperature, and moisture. Measurements should therefore be carried out in all seasons and conditions of atmospheric pressure. This points at a minimum of 4 monitoring campaigns per year and possibly more.

It should be noted that many of the monitoring methods described above require highly trained personnel and highly technical equipment. As Chapter 9 and Appendix 4 indicate, monitoring costs can become very high. It should be considered to which extent monitoring can maintain or improve the methane emission reduction impact of the methane oxidation system. In some situations, it might be more cost-effective to relinquish monitoring and use the financial means to construct larger surfaces of methane oxidation layer.

TAKEAWAYS:

- The choice of monitoring methods depends on technical concerns, available capacity, the target of the measure and possibly regulatory requirements.
- Monitoring methods can range from simple visual inspection to complex emission measurements.
- The nature of the obtained data determines whether only qualitative or also quantitative performance assessments can be made.
- The high variability of methane loads in passive systems requires that monitoring campaigns are carried out at least 4 times per year, possibly more often.
- The cost-effectiveness of monitoring should be carefully considered.

8.1 Construction costs

Construction costs very much depend on local conditions. There is limited literature on construction costs of biocovers. US-EPA (2011) estimates the construction costs for a biocover at US\$ 170,000 per hectare (corrected for inflation between 2011 and 2025). In the framework of this report a targeted global survey was carried out. The responses include one biocover example, 4 biowindows and 4 biofilters. The construction costs of the biocover and biowindows varied greatly, indicating that local costs (labour, access to cover materials and equipment etc) as well as regulatory requirements impact significantly (Appendix 4). Generally, the construction costs of the biofilters were a lot higher. It should be noted that some of these projects are the first of their kind. Competent authorities demanded a lot of safeguards. **This report**

estimates that the construction costs of a microbial methane oxidation cover with a surface of 5 to 20 hectares can be between US\$ 100,000 and US\$ 250,000 per hectare. Roughly two-thirds of the costs can consist of the purchase of suitable, local materials the cost of which may be offset by choosing effective lower-cost options. Other costs include operation, repair and maintenance, though with high local variability. A construction cost estimate must always be based on a project specific approach. In terms of mitigation to cost benefit though, overall, biocovers can be seen as a local solution with potentially high mitigation potential. They offer a pathway to older landfill emission control and closure, and the remediation of valuable urban land.

8.2 Operational costs

Operational activities mainly concern periodic inspection, monitoring performance and mowing of the vegetation. Not only the costs of periodic inspection should be budgeted, but also the potential cost of the repair of cracks or settlement. Methane oxidation covers that have been constructed with predominantly inorganic material on a landfill that was already sufficiently stable now of construction will have hardly any repair or maintenance costs. Covers with a lot of organic material are prone to degradation and will require periodic replacement.

Repair and replacement costs, if necessary, are the most important operational cost aspect. The cost of monitoring very much depends on the targets set for the methane oxidation system and the assessment that those targets involve. Some monitoring methods are very labour intensive. If there are no regulatory requirements on performance or emission monitoring

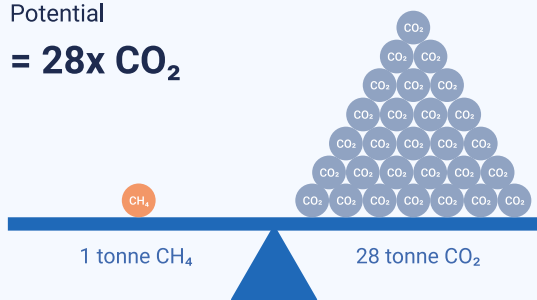
and the methane oxidation project is on a voluntary basis, it could be considered to do no performance monitoring at all. The frequency of mowing depends on the fertility of the topsoil, the climatic conditions and how high the vegetation is allowed to grow. The faster the vegetation grows, the higher the mowing costs. In general, two to four mowing campaigns per year are applied on landfills. In the survey (Appendix 4) two biowindows and four biofilters reported operational costs. One biowindow reported US\$ 39,000 per year. The biofilters reported between US\$ 70,000 to US\$ 700,000 per year, given that they are more complicated constructions than biocovers. This report estimates that the annual operational costs can vary as much as between US\$ 3,000 and US\$ 24,000 per hectare per year, depending on climatic conditions, labour costs and repairs needed.

8.3 Cost effectiveness

Cost effectiveness for the purpose of this document is defined as the total cost of the emission reduction divided by the total emission reduction over a period of 10 years expressed in US\$ per tonne carbon dioxide equivalent.

Methane's Global Warming Potential

= 28x CO₂



The UNFCCC in 2023 established the global warming potential for methane at **28 of CO₂eq**. In other words, **one tonne methane reduced is 28 tonnes carbon dioxide equivalent**.

To determine the potential emission reduction, first the methane generation of the landfill must be determined (see IPCC, 2006b; IPCC, 2019).

For this example, it was assumed that a landfill disposes 150,000 tonnes of municipal solid waste (0.19 kg DOC per kg wet waste) per year for 30 years. The waste is disposed in 6 cells of 3 hectares each, that are filled consecutively.

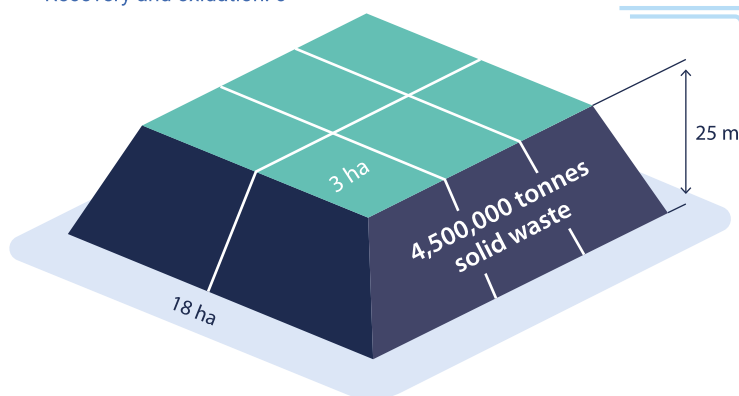
Duration: **30** years

Methane Correction Factor: 1.0

Recovery and oxidation: 0

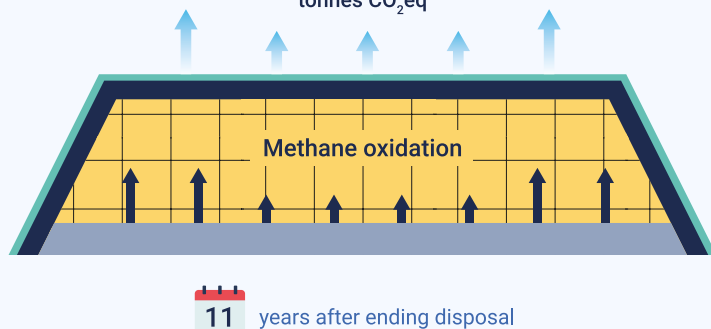
 wet temperate climate
reaction rate: 0.09 y⁻¹

The landfill reaches an average waste height of 25 m and covers a surface of 18 hectares. The landfill is situated in a wet temperate climate with a reaction rate constant of 0.09 y⁻¹. A Methane Correction Factor of 1.0 is assumed. Recovery and oxidation are assumed to be zero.



After ending waste acceptance on the landfill, each cell is in a different stage of methane generation and must be assessed separately for potential methane generation.

Emission reduction:
40,000 - 109,000
tonnes CO₂eq



It is assumed that a methane oxidation cover with a maximum oxidation capacity of 34 g CH₄ per m² an hour, or 90% of the actual methane load up to 34 g CH₄ per m² an hour, is constructed.

It can be calculated that **from 1 to 11 years after ending disposal, cells 1 to 6 reduce emissions between 40,000 and 109,000 tonnes carbon dioxide equivalent**.



The total emission reduction of the **methane oxidation system** can be estimated to be

400,000 to 550,000 tonnes
carbon dioxide equivalent.

While the survey in Appendix 4 does not include a comprehensive cost assessment in enough conditions, with some assumptions, **it can be estimated that biocovers cost between USD40 to USD45 to mitigate one tonne carbon dioxide equivalent.** Costs can vary greatly. There are several reasons for these relatively high costs. As mentioned earlier the costs are determined by the expense of regulations, which tend to be more stringent in developed country contexts. More research should be undertaken on adoption of necessary safeguards with less cost for a developing country context. Not all policy contexts or conditions are the same, and greater research on technology transfer and adoption is needed on biocovers (for example, less use of expensive equipment and more labour intensive/job creation strategies could be adopted). In addition, the countries in question have regulations requiring active gas control. MMOS are only accepted at a late stage when active recovery is technically no longer feasible. This implies that the amount of methane to be mitigated is very low. Most respondents report very low oxidation rates between 5 and 13 g CH₄ per m². The total costs must be 'carried' by a limited mitigation impact.

Without considering interest or net present value and depreciation of the construction costs in ten years, this report estimates that total costs of a methane oxidation cover on an 18-hectare landfill can typically range from US\$ 2.5 million to US\$ 7.8 million. At 522,000 tonnes carbon dioxide equivalent total emission reduction, the cost effectiveness ranges from US\$ 6 to US\$ 15 per tonne carbon dioxide equivalent (see Appendix 4).

TAKEAWAYS:

- The construction costs for a methane oxidation cover can vary from US\$ 100,000 to US\$ 250,000 per hectare.
- Around two-thirds of investment consists of suitable cover materials, which may be offset by choosing effective local and lower-cost options
- Annual maintenance and monitoring costs can vary between US\$ 3,000 and US\$ 24,000 per hectare per year.
- The repair and replacement costs (most likely for organic covers) are the most important maintenance cost aspect.
- Cost effectiveness typically ranges from US\$ 6 to US\$ 15 per tonne carbon dioxide equivalent.
- More research is needed on costs and appropriate regulatory frameworks in a greater number of countries, as data remains limited.

9.1 Revenue capture

Moving from uncontrolled dumpsites to controlled landfills provides opportunity for revenue capture, which can offset the cost of biocover establishment, maintenance and other operational costs (OPEX). Several countries have also demonstrated increased revenue capture from using biocovers in landfill closure and remediation, through improved environments, resulting in increased land prices and public amenity. For example, in Seoul, closing and capping of one of the largest landfills in Asia (Nanjido) allowed the development of a series of public ecological parks and resulted in significant

local economic development (Yoo et al., 2014). Other examples include use for solar farms, or, in the case of the former Suva landfill², closed in 2005, rehabilitation including bio-capping to mitigate methane emissions. This was complementary to the creation of a coastal park and improved amenity for the city. In contexts where older landfills and dumpsites are located in major urban areas, considerable revenue capture through improved environments and public amenity benefits can result, alongside mitigation and improved air quality.

9.2 Carbon markets

Financial support for methane oxidation projects can under specific conditions be obtained from carbon markets. Carbon markets are trading systems in which carbon credits are sold and bought. Companies or individuals can use carbon markets to compensate for their greenhouse gas emissions by purchasing carbon credits from entities that remove or reduce greenhouse gas emissions. One tradable carbon credit equals one tonne of carbon dioxide, or the equivalent amount of a different greenhouse gas reduced, sequestered or avoided. When a credit is used to reduce, sequester, or avoid emissions, it becomes an offset and is no longer tradable.

There are broadly two types of carbon markets: compliance markets and voluntary markets. Compliance markets are created because of national, regional and/or international policy or regulatory requirements. Voluntary carbon markets – national and international – refer to the issuance, buying and selling of carbon credits, on a voluntary basis. The current supply of voluntary carbon

credits comes mostly from private entities that develop carbon projects, or governments that develop programs certified by carbon standards that generate emission reductions and/or removals. Demand comes from private individuals that want to compensate for their carbon footprints, corporations with corporate sustainability targets, and other actors aiming to trade credits at a higher price to make a profit. Examples of a compliance market are emissions trading system (ETS) such as the European Union's ETS. They operate on a "cap-and-trade" principle. Regulated businesses – or countries, are issued emission/pollution permits, or allowances by governments. These add up to a total maximum, or capped, amount. Polluters that exceed their permitted emissions must buy permits from others with permits available for sale (i.e., trade). Alternatively, they may choose to step in and further reduce their emission. Ghana has also recently engaged in the international carbon market scheme under the Paris Agreement to raise finance for GHG mitigation projects including landfill management, composting and biogas.

² <https://www.hydea.it/en/projects/securing-lami-landfill-in-suva-fiji/>

9.3 Clean Development Mechanism (CDM)

Another example of a carbon market is the Clean Development Mechanism (CDM) adopted under the Kyoto Protocol in 1997 and administered by the UNFCCC. Given the expiration of the Kyoto Protocol, no new projects are being created under CDM. The CDM Executive Board is still active, and a transition is ongoing to the Paris Agreement Crediting Mechanism (PACM) (UNFCCC, 2025a). In order to realise transfer of credits according to Article 6 of the Paris Agreement, key rules have been established, but PACM methodologies still need to be drafted and decided. Detailed quantification methodologies are not yet available. UNFCCC (2025a) expects that from 2026 the number of projects using PACM methodologies will grow. This implies that currently the actual options for financing are limited. As it can be anticipated that many aspects of the CDM methodologies will find their way into PACM methodologies, some relevant CDM methodologies are discussed below.

The CDM allows a country with an emission-reduction or emission-limitation commitment under the Kyoto Protocol to implement emission-reduction projects in developing countries (UNFCCC, 2025b). Such projects can earn saleable certified emission reduction (CER) credits, each

equivalent to one tonne of CO₂, which can be counted towards meeting Kyoto targets. A CDM project must provide emission reductions that are additional to what would otherwise have occurred. When projects are already required by law, they should happen. Such a project would not comply with the 'additionality' requirement. The projects must qualify through a registration and issuance process. Approval is given by the Designated National Authorities.

Any proposed CDM project must use an approved methodology for baseline establishment and monitoring with the goal to validate, approve and register the CER credits. UNFCCC has developed more than 200 methodologies on how to assure that CER credits are real and how to quantify and verify CER credits. Baseline methodology sets standards on how to determine the baseline within certain applicability conditions. Monitoring methodology sets standards on how to determine monitoring parameters, quality assurance, equipment to be used, to obtain data to calculate the emission reductions. The verification and validation of the emission reduction credits is usually carried out by independent verification/validation bodies.

9.4 CDM methodologies for waste management

CDM has various methodologies that are applicable to landfill of waste and to organic waste diversion or organic waste pretreatment. Each of these methodologies might provide financial support for a project on composting of organic waste with the intention to produce biocover material. Eligibility must be determined on a case-by-case basis. In Figure 9.4 this paragraph only lists

potential methodologies for consideration that can be derived from the CDM methodology booklet (UNFCCC, 2022). Methodology AMS-III.F. concerns landfill methane emission avoidance through aerobic treatment by composting and proper soil application of the compost. Installing a cover soil on a landfill consisting of a soil and compost mixture is considered a proper soil application.

Figure 9.4.1: CDM methodologies for waste management and wastewater (UNFCCC, 2022).

Alternative treatment – composting	ACM0022	AMS-III.F.	AMS-III.AF.	
Alternative treatment – other technologies	ACM0022	AM0112	AMS-III.E.	AMS-III.L.
	AMS-III.R.	AMS-III.Y.	AMS-III.BJ.	
Alternative treatment – aerobic	AM0083	AM0093	AMS-III.AX.	
Landfill gas	ACM0001	AMS-III.G.		
Lagoons and biodigester – biogas	ACM0014	AMS-III.H.	AMS-III.AO.	
Manure and comparable animal waste	AM0073	ACM0010	AMS-III.D.	
Aerobic wastewater treatment	AM0080	AMS-III.I.		
Biogenic methane	AM0053	AM0069	AM0075	AMS-III.O.

9.5 CDM methodology for methane oxidation layers

CDM methodology AMS-III.AX. is applicable to project activities involving the construction of a methane oxidation layer on top of a municipal solid waste disposal site with low residual surface methane emission (less than 4 litres methane per m² and hour or 70 g CH₄ per m² per day) (UNFCCC, 2011). The purpose is to mitigate the release of methane through biological oxidation in the

methane oxidation layer. A project is only eligible for cells where disposal has stopped and where installation of a gas collecting system is impractical. Projects are capped at 60,000 tonnes carbon dioxide equivalent annually. That constitutes a relatively small number of credits and may be partly responsible for the lack of application of AMS-III.AX.

9.6 Barriers to address

CDM Methodology AMS-III.AX. has not been widely applied. The UNFCCC project search interface (UNFCCC, 2025c) out of 7,832 projects shows 223 landfill gas recovery projects and 0 microbial methane oxidation projects. This clearly indicates that a more effective methodology is required to promote carbon market financing of microbial methane oxidation projects.

The methane oxidation layer consists of methane oxidising material which in Methodology III.AX. is defined as biologically and mechanically processed biomass known as ‘refined stabilized biomass’. This implies that the much more stable soil-based methane oxidation layers are excluded. There are several criteria that the methane oxidising material must comply with (Respiration Activity over 7 days ≤ 8 mgO₂/g dry matter; > 4%ds Total

Organic Carbon, total thickness 1.2-2.5 m; <350 ppm(ds) NH_4 ; no NO_2 ; air-filled porosity at field capacity >15%; no compaction during construction). Compliance must be tested per 500 tonne methane oxidising material. Thickness as constructed must be verified. A gas distribution layer with a thickness of 0.3-0.5 m must be installed below the methane oxidising material. The material for the gas distribution layer should be stable, coarse (16-32mm), lime free material. Compliance must be tested per 500 m^2 .

The condition of less than 4 litres methane per m^2 and hour (or less than 70 g CH_4 per m^2 per day) can typically be met by shallow, poorly managed or unmanaged landfills in developing countries. The thickness and quality requirements of the CDM methodology imply that the methane oxidation system is more like the optimised methane oxidation system than like the simple methane oxidation system described in Appendix 5. The CDM project emissions monitoring requires monthly gas temperature and gas concentration measurements in gas probes at several depths in the methane oxidising material and in the gas drainage layer. Quarterly methane and carbon dioxide flux chamber emission measurements are required. The CDM monitoring requirements can make up 30% to 70% of the annual costs.

Even when it is assumed that per 10 hectares organic methane oxidising material only 0.1 hectare (1%) per year needs to be repaired, it can be estimated that the cost of 1 tonne carbon dioxide equivalent in a CDM methane oxidation project is approximately US\$ 12 (see Appendix 4). This makes it approximately US\$7 per tonne carbon dioxide equivalent more expensive than a simple methane oxidation project. The 2024 carbon prices range from around US\$ 10 to US\$ 70 per tonne carbon dioxide equivalent for the compliance markets and are around US\$ 0.5 per tonne carbon dioxide equivalent for voluntary markets (<https://carbonpricingdashboard.worldbank.org/>; <https://carboncredits.com/carbon-prices-today/>). This implies that only access to specific compliance markets would justify the extra costs for a CDM project.

TAKEAWAYS:

- Use of biocovers in landfill control and closure can also increase land value and the potential for alternative land use for municipal governments
- Various carbon markets can potentially generate income for a methane oxidation project.
- Due to the expiration of CDM and the transition to PACM, there currently are limited options for carbon market financing.
- Methane oxidation layers (partially) constructed of compost might be eligible for funding through composting of organic waste, though care must be taken that composting does not result in methane emissions.
- Due to construction and monitoring requirements, the CDM methodology for methane oxidation layers makes the cost per tonne of carbon dioxide equivalent relatively high.
- These extra costs can only be compensated if the project would have access to a compliance market.

10 Recommendations

Methane is a powerful greenhouse gas and the release of landfill gas is a key driver of climate change globally, and health problems locally. Measures must be taken to reduce landfill gas emissions. These measures include landfill gas capture and treatment and biocovers, offering important management strategies/solutions. Well-designed methane oxidation covers not only reduce methane emissions, but they can also reduce odour and the emission of Volatile Organic Compounds (VOCs) and toxic substances.

It is clear that a lack of knowledge and experience hampers wider application of methane oxidation covers. This includes country-level studies. **This report serves as a first step in raising awareness for the benefits of application of biocovers and makes the case for further financing of this technology.** At first glance, applying a biocover may seem simple. Proper design of a methane oxidation cover requires detailed investigations and careful consideration of the influence of the properties of the different layers on the other layers. Unfortunately, this is not widely recognised. Promotion of the realisation of biocovers can be supported by the organisation of training courses that address these aspects. In addition, it could be considered important to organise an ongoing expert group function, facilitated by organisations such as the CCAC that could address knowledge and capacity gaps from persons or organisations involved in developing microbial methane oxidation projects. This could include opportunities to link with funding sources.

There are limitations in acquiring theoretically available funding for methane oxidation covers. Article 6 of the Paris Agreement provides the possibility of transboundary financing of greenhouse gas emission reduction projects. Using that possibility requires a detailed instrument with boundary conditions and verification procedures. Limited application seems to imply that the current instruments, such as CDM methodologies, are insufficiently effective to promote the application of methane oxidation covers. It is recommended to design a more simple and more effective methodology. This could facilitate more investment and hence wider application.

In parallel, it would be prudent to explore other funding sources outside the UNFCCC framework. These may include climate finance mechanisms such as the Green Climate Fund (GCF), the Global Environment Facility (GEF), multilateral development banks (e.g. the World Bank or the African Development Bank), or bilateral climate and development aid programs, in addition to public finance for low-cost options. In some contexts, carbon markets or results-based financing mechanisms at national or regional levels may also offer opportunities. Private sector involvement could be encouraged through voluntary carbon market mechanisms or corporate responsibility programs. Diversifying the funding approach could help overcome current barriers and support broader deployment of methane mitigation technologies. Additionally, use of biocovers in closing landfills and in remediation of valuable urban land has created enormous opportunities for public spaces, local economic development, needed infrastructure and urban resilience. The potential for land value capture should not be underestimated.

The implementation of biocovers should be prioritized at legacy, low-emission, and unmanaged landfill sites, particularly in developing countries. One of the clear benefits of biocover systems is that they often do not require a gas capture system to be in place. As many landfills often lack gas recovery infrastructure and have methane generation rates that fall within the oxidation capacity of well-designed biocovers in such contexts, biocovers offer a cost-effective and practical solution, with the potential to mitigate up to 50% of methane emissions.

Cost-effectiveness can be maximized by using locally available materials and designing simplified biocover systems. Sourcing soil, compost, or other suitable materials from nearby locations significantly reduces transportation and procurement expenses, which often comprise the majority of construction costs. When properly matched to material properties and local conditions, these streamlined designs can achieve methane abatement at a cost as low as US\$ 5 to US\$ 15 per tonne of CO₂ equivalent. This makes biocovers a potentially valuable 'localised' and tailored solution for mitigation and waste management.

A phased, evidence-based approach should be adopted before proceeding with full-scale biocover deployment. This includes conducting methane generation modelling, small-scale recovery tests, and pilot demonstrations to assess technical feasibility and optimize system design. Such a stepwise process reduces financial risk and ensures that the final biocover is appropriately tailored to the site's climate, waste characteristics, and material availability.



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APPENDIX 1: Reported oxidation rates and applicability of methane oxidation

The CLEAR Group (<https://iwwg.eu/iwwg-task-group-on-landfill-gas-emission-and-mitigation>) in 2014 produced an overview of documented experience with large pilots or full-scale methane oxidation systems. This overview including the literature references is presented below.

Column A	B	C	D	E	F	G	H	I	J	K
Landfill Area (ha)/Waste mass (ktons)	Country	Scale ^a FS/PS	System type ^b	Typical gas composition ^c (%CH ₄ /%O ₂)	Active material ^d Type/A(m ²)/D(cm)	Gas Distr. layer ^e , D(cm)	Total efficiency evaluated? ^f GL(g CH ₄ /m ² d ⁻¹)/ME(%)	Measurement methods used ^g	Efficiency Approach ^h	Ref.
1 Aikkala (3.9/200a)	SF	FS	Cover	31-72/1-5	C/39,000/50	50	32-216/25-46%	FC, PGP	TMMB	[1]
2 Fakse (12/660)	DK	FS	Windows	40-65/0	C/5000/100	15	150/28%	WLEM, MMS, FC, PGP, SCIC	TEBA, CMB	[2]
3 Klintholm (4/480)	DK	FS	Passive filter	69/0	C/4800/80	30	50/80%	WLEM, MSS, FC, PGP	TEBA	[3]
4 Frankham (n.r./n.r.)	GB	FS	Aerated filter	20-40/n.r.	C and CP/600/130	30	530/55-99%	MSS, FC, PGP, MF	TMMB, PBE	[4]
5 Leduc and District regional	CAN	PS	Windows	n.r./n.r.	C/10 or 20/150	80	40-50/20-90%	FC, PGP	CMB	[5]
6 Outer Loop	USA	PS	Cover/ windows	n.r.	C and S/n.r./100	0/15	n.d./21-55%	FC, SCIC	LMMB	[6]
7 Kelso (n.r./3000)	AUS	PS	Passive filter	45-55/0.5	C/4x9/120	50	8-27/20-70%	FC, PGP, MF	CMB	[7], [11]
8 Leon County (n.r./n.r.)	USA	PS	Windows	54-68/n.r.	C/2x580/30 or 60	15	300-700//20-60%	FC, SCIC	other	[8]
9 Podere Casa Rota	I	PS	Windows	20-40/<1	C/4x25/70	10	n.d./64-84%	FC, PGP	CMB, PBE	[9]
10 Horsley Park	AUS	PS	Trench	49/1.9	C/15/100	250	n.d./>35%	FC, PGP	CMB	[10]
11 St-Nicéphore	CAN	PS	Passive filter	n.r./n.r.	C/23/80	30	175/73-99%	FC, PGP	TMMB	[12]
12 Landfill y	CAN	PS	Passive filter	n.r./n.r.	C/100/90	30	n.r./n.r.	FC?	?	[13]
13 Francop	DE	PS	Passive filter	n.r./n.r.	CP/17/80	20	125-600/>97%	FC, MF	TMMB	[14]
14 AV Miljø (40/2000/ 1b)	DK	PS	Aerated filter	7/12	C/500/85	40	12/97%	MSS, FC, PGP, MF		[15], [16]
15 Wieringermeer (19/1600)	NL	PS	Cover	34-48/0-1	S/510/110	20	43/30-96%	FC(large), PGP, MF	TMMB, PBE, CMB	[17]

Column A	B	C	D	E	F	G	H	I	J	K
16 2 French landfills	F	PS	Aerated filter	2-2.5/18-20	C/17m3/n.r	(30)	620/15-17%, max 60%	MF, FC		[18]
17 Tulln (1.9/280)	AT	FS	Cover	n.r./n.r.	C/18,500/120-150	50	42-96%	FC		[19]
18 St. Valentin (1.5/180)	AT	FS	Cover	n.r./n.r.	C/15,000/120-150	50	87-98%	FC		[19]
19 Ameis (2.4/200)	AT	FS	Cover	n.r./n.r.	C/24,400/120-150	50	96-100%	FC		[19]
20 Amstetten (2.4/130)	AT	FS	Windows	n.r./n.r.	O/1,400/?	?	?			[19]
21 Pausendorf (1.0/70)	AT	FS	Windows	n.r./n.r.	O/1,020/?	?	?			[19]
22 Oberaich (1,2/100)	AT	FS	Windows	~55/n.r.	O/180/80-120	20-30	?			[19]
23 Blankenbach (?/330)	AT	FS	Cover	n.r./n.r.	O/?/80-120	20-30	?			[19]
24 Ridge (?/?)	GB	FS	Aerated filter	20-40/n.r.	C and CP/600/130	30	?			[20]
25 Sherbrooke (4/?)	CAN	FS	Cover	n.r./n.r.	?		?			[21]
26 Crayenstein (7/800)	NL	FS	Windows	45/1	S/2,400/80	?	Est.70%	none		[22]
27 Hanson Landfill	AU	?	?	?	?	20	?	?		[23]
28 Deponie K	DE	FS	Windows	43/20	S/50/35-80	?	8-286/33-100%	FC, PGP	LMMB	[24]
29 Taylors Rd Landfill Lyndhurst, Melbourne	AU	PS	Cover	?	?	20	?	FC, PGP		[25]
30 Southern Waste Depot, McLaren Vale, Adelaide	AU	PS	Cover	?	?	?	?	FC, PGP		[25]
31 Stuart Landfill, Townsville	AU	PS	Cover	?	?	?	?	FC, PGP		[25]
32 Lismore Waste Facility, Lismore	AU	PS	Cover	?	?	?	?	FC, PGP		[25]
33 Henderson Waste Recovery Park, Henderson, Perth	AU	PS	Cover	?	?	?	?	FC, PGP		[25]

a: FS: Full Scale, PS: Pilot scale

b: See [29] Table 2 for explanation

c: Composition of CH₄ and O₂ in LFG

d: Active Material:

Type: S (soil), C (compost), CP (expanded clay pellets), O (other)

A: area in m²

D: Layer thickness (cm)

e: D: Thickness of Gas Distribution Layer (cm)

f: GL: Reported average gas load to biocover system

ME: Reported methane removal efficiency

g: Methods supporting performance evaluation:

WLEM: Whole landfill emission measurement using tracer dilution approach or other method

FC: Flux chamber measurements

PGP: Pore gas profiles

MSS: methane surface screen

SCIC: Stable carbon isotope composition

MF: mass flow (gas flow and CH₄ content)

h: Efficiency approach: CMB: Carbon mass balance ([30]; PBE: profile based efficiency [31];

LMMB: local methane mass balance; TMMB: total methane mass balance;

TEMBA: Total CH₄ emission – before and after

A limited number of papers reports oxidation rates of several hundred g CH₄ per m² per day. These are usually point measurements representing peak oxidation rates rather than an annual average oxidation. When considering the median of all measurements (i.e. more representative for an annual average oxidation rate) the oxidation rate values typically range from 20 to 80 g CH₄ per m² per day.

Most experiences on methane oxidation are obtained on landfills in humid, temperate climates. Many developing countries have a warmer climate. It can therefore be anticipated (and calculated) that methane oxidation systems can reach higher oxidation rates in developing countries. In microbiology the so-called Q10-rule predicts that with every 10°C temperature increase microbial activity doubles. This would imply that oxidation rates from 40 to 160 g CH₄ per m² per day are conceivable, provided the other requirements for methane oxidising bacteria can be met (see Appendix 2).

It is expected that in more arid conditions potential methane oxidation activity will be reduced, compared to methane oxidation in humid, temperate climates. The main reason for this is a lack of moisture in the top-layer. However, few experiences available indicate that as a rule of thumb, whenever plants can grow, microbial activity is also possible. When the soils dry up, the methane oxidation zone seems to move downward, in a similar way as reported for European conditions during winter, when cool temperatures inhibit activity in the upper layers. Temperature and moisture conditions may regionally vary very much during a year. It is therefore necessary to observe monthly average temperature, rainfall and evapotranspiration data. The Methane Oxidation Tool provides a relatively simple approach to correct for temperature and moisture and consider monthly fluctuations over a year.

As moisture diminishes the pore system's capacity to transport gas, material for use in methane oxidation systems must contain an adequate share of pores with larger diameters (above 50 µm). These drain quickly, removing excessive moisture and remain available for gas transport. In very humid climates there is a possibility that the pores in the layers of the methane oxidation system are filled with water during long periods of time. Under those conditions sufficient oxygen cannot diffuse into the methane oxidation layer. Landfill gas cannot evenly migrate through the methane oxidation layer. When pressure builds up, the landfill gas might force a way out through a preferential pathway, where sufficient oxidation cannot occur. For the design of methane oxidation systems in humid climates it is important to find out how many litres per m² an average major rainfall event generates. It is not necessary to design for a '100-year rain event'. It is acceptable that during such an event methane is not oxidised. The average major rain event determines the soil drainage requirements. The required hydraulic conductivity of suitable materials will point at sandy soils. Soils suitable for methane oxidation systems also are predominantly sandy soils. In very humid climates it is however likely that the range of suitable sandy soils is limited to those soils with higher hydraulic conductivity and higher air-filled porosity. In addition to a higher hydraulic conductivity, it is important to make sure that infiltrating rain is drained away. The water drainage system is preferably situated below the gas distribution layer to prevent inhibition of gas distribution. To have good infiltration, the topsoil should not be crusted, it should be densely vegetated, and the vegetation should be well maintained to assure continued optimal infiltration.

APPENDIX 2: Layers in methane oxidation systems

This Appendix is based on:

- Gebert J., Huber-Humer M. and Cabral A.R. (2022) Design of Microbial Methane Oxidation Systems for Landfills (Front. Environ. Sci. 10:907562; doi: 10.3389/fenvs.2022.907562) and;
- Gebert, J., Huber-Humer, M. (eds) 2025: CLEAR Best Available Technology documents for Design, Operation and Monitoring of microbial methane oxidation systems to reduce landfill greenhouse gas emissions. Module 3: Quality control of materials and construction.
- More details are available in these documents.

The set-up and principle of the different layers within a methane oxidation system and the operational conditions for each option are briefly described in this appendix. Systems for microbial methane oxidation consist from bottom to top of the following layers:

- Levelling layer or remaining temporary cover
- Gas distribution layer
- (Intermediary layer)
- Methane oxidation layer subsoil
- Methane oxidation layer topsoil and vegetation.

Levelling layer

The levelling layer evens out any unevenness in the terrain. The levelling layer should be sufficiently permeable to not impede gas transport into the gas distribution layer. The nature of the material and the way it is constructed should furthermore allow sufficient carrying capacity and (slope) stability for the construction of the other layers of the methane oxidation system.

Gas distribution layer

The gas distribution layer facilitates horizontal distribution of the gas prior to its entry into the methane oxidation layer and hence harmonises the spatial methane load. The key aspect for the functioning of the gas distribution layer is that the difference in permeability between the methane oxidation layer and the gas distribution layer is maximized without compromising the air capacity of the methane oxidation layer. The exact dimensioning depends on the expected gas load, the pressure loss and the area to which this load should be distributed. The aim of the design should be to equalise the pressure loss over the area. Thicknesses of 20 cm to 50 cm have been proposed and constructed.

Intermediary layer

At the interface of two different layers filter stability and sufficient pore continuity to the underlying layer need to be observed. An intermediary layer can guarantee filter stability between gas distribution layer and methane oxidation layer. Capillary effects at the interface between gas distribution layer, intermediary layer and methane oxidation layer (and laterally to existing recultivation layer in case of windows or filters) are to be avoided as these hinder free water drainage, impair gas permeability and hence support the formation of preferential pathways.

Methane oxidation layer subsoil

Microbial oxidation of methane to carbon dioxide occurs in the methane oxidation layer, more particularly in the area where landfill gas mixes with atmospheric air. In methane oxidation systems that are optimised with respect to gas diffusivity atmospheric air can penetrate effectively into the soil. Under these conditions also the deeper layers in the subsoil can contribute to methane oxidation. This is desired since a larger thickness of the methane oxidation layer increases the effectiveness of methane oxidation. When the soil properties enable oxygen transport deeper into the soil, the oxidation process is better protected against unfavourable conditions that can occur closer to the surface, such as summer heat, winter frost, superficial drying, rainfall causing superficial water saturation etc..

Methane oxidation layer topsoil and vegetation

A humic topsoil of a methane oxidation layer improves water availability for the vegetation and microorganisms by increasing the plant available field capacity. It promotes aggregation of soil particles. It guarantees provision of nutrients for vegetation and microorganisms. Humic topsoil furthermore provides a good environment for soil organisms. Healthy vegetation in turn protects the soil against erosion and allows for optical integration of the methane oxidation system into the vegetated recultivation layer of the landfill.

Requirements on the physical properties of mineral materials

Materials intended for use in microbial methane oxidation systems should fulfil the requirements with respect to physical properties summarised in Table A2.1:

Table A2.1: Physical requirements on materials for MMOS.

Aspect	Motivation	Requirement
Long term stability	To sustain gas permeability and the functionality of methane oxidation systems, the materials should be characterised by mineral components.	MOL topsoil: 2-8% organic matter MOL subsoil: 1-3% organic matter
High air capacity	Oxygen ingress required for methane oxidation is strongly linked to the share of pores available for gas transport. Coarse pores drain water quickly, remove excess moisture and remain available for gas transport.	Sufficient pores > 50 µm
Available field capacity	In order to support a vegetation cover, the choice of material should always maintain an adequate climate-dependent available field capacity.	Air-filled porosity at field capacity water content >14 vol.-%
Compaction	Compaction impairs the air capacity and the continuity of the pore system.	E.g. moderate climate field capacity: > 140 mm
Crack formation	Cracks and clefts (resulting from soil aggregation and/or settlement) pose preferential pathways for gas and are a frequent cause of high local emissions.	Select insensitive textures and/or adequate construction techniques involving vehicles exerting low ground pressure.
Crack formation	Cracks and clefts (resulting from soil aggregation and/or settlement) pose preferential pathways for gas and are a frequent cause of high local emissions.	Fine-grained loamy textures are prone towards aggregation because of their clay content. They are not suitable for application in methane oxidation layers.

Table A2.2 summarizes textures that allow for an air-filled porosity of 13-14 vol.-%, depending on the bulk density of the soil, as determined for naturally grown soils. The data shows that with increasing compaction, the choice of suitable textures narrows down considerably. It must be noted that values can deviate for constructed soils.

Table A2.2: Soil textures with an air-filled porosity of 13-14 vol.-%, depending on the bulk density. Data apply to naturally developed soils

Bulk density	Value (g cm ⁻³)	Soil texture
Very low to low	< 1.4	< 65 % silt and < 17 % clay < 50 % silt and < 25 % clay < 15 % silt and < 35 % clay
Medium	1.4 to < 1.6	< 40 % silt and < 12 % clay < 15 % silt and < 25 % clay
High to very high	1.6 to > 1.8	< 25 % silt and < 8 % clay < 10 % silt and < 17 % clay

Requirements on the chemical properties of mineral materials

To provide a geochemical environment favourable to methanotrophic activity, materials intended for application in methane oxidation layer should meet the following criteria:

Table A2.3: Chemical requirements on materials for MOL.

Aspect	Motivation	Requirement
pH value	Optimum of methanotrophic bacteria.	pH 5.5 to 8.5
Organic matter content	To warrant nutrient supply for microorganisms and vegetation and enhance available field capacity.	<1 to 3% organic matter in the subsoil, 2% to 8% organic matter in the topsoil
Electric conductivity	At higher salt contents the methanotrophic activity declines due to osmotic stress.	< 4 mS/cm
Ammonium	Ammonium competes with methane for the central enzyme system of methanotrophs and can hence inhibit methane oxidation.	Ammonium containing substrates are to be avoided
Dissolvable iron	Iron may be mobilised and precipitate causing blockages.	< 1 g/kg
Carbonates	Methane oxidising bacteria produce carbon dioxide. In combination with calcium or magnesium this forms calcium and/or magnesium carbonate. This precipitates and can block pores that are vital for oxygen supply. In soils calcium in general is present as calcium carbonate with much smaller amounts of calcium hydroxide and calcium bicarbonate. The latter two are available for precipitation.	Calcium and magnesium are available in materials such as crushed concrete or waste incinerator bottom ash. These materials should be avoided. For 'normal' soils < 1% carbonate, which laboratories can easily determine, is a good proxy to avoid precipitation.

Gas distribution layer

Material for use in the gas distribution layer should largely be free of limestone as the increased partial pressure in carbon dioxide can result in precipitation of carbonates and hence in the reduction of pore volume available for gas transport. The gas distribution layer should also largely be free of dissolvable iron.

Organic materials

Organic materials such as compost are frequently used as amendment to mineral covers or as filter beds for methane oxidation filters and methane oxidation windows. Composts usually offer high nutrient supply and have a high potential for water retention. Due to the high share in coarse pores, composts have a low heat capacity and hence insulate well. Composts have been shown to exhibit high methane oxidation rates. The main disadvantage of organic materials lies in their microbial degradability leading to settlement and a subsequent reduction of gas permeability. Further, the aerobic degradation of organic matter competes with the high oxygen requirements of the methane oxidation process. The Austrian guideline on methane oxidation layers (ÖVA, 2008) therefore stipulates a maximum respiratory activity of $< 8 \text{ mg O}_2$

per g dry substance over 7 days. Under moist conditions, high organic matter content enhances the formation of anaerobic niches and can lead to the formation of methane. Overall, the use of organic materials requires an enhanced monitoring effort and possible treatment (loosening) or excavation and exchange of material. For mineral materials usually lower methane oxidation rates are reported, however, they provide increased long-term structural stability, can also support vegetation, serve as water balance layer or as area suitable for after-use.

Test methods for suitability assessment

To ensure that the requirements on material properties as explained above are met, candidate materials should be analysed for the parameters summarized in Table A2.5

Table A2.4: Proposed parameters to be analysed for assessment of suitability of candidate materials. Methods are suggested based on international standards.

Parameter and suggested methods	Methane oxidation layer: Mineral material	Methane oxidation layer: Organic material	Inter-mediary layer	Gas distribution layer
Particle size distribution Method: ISO 11277:2009	X	X	X	X
Standard Proctor compaction curve Method: ASTM D698 - 12e2	X			
Saturated hydraulic conductivity at three compaction levels, e.g. 80%, 85%, 90% of the maximum Proctor density ($\rho_{d,max}$) Method: ISO 17312:2005	X			
Water retention curve, giving also air capacity¹⁾ and plant-available field capacity²⁾ at three compaction levels, e.g. 80%, 85%, 90% of $\rho_{d,max}$. Method: ISO 11274:2019	X			
Gas conductivity (k_{Gas}) and effective diffusivity (D_{eff}) at three compaction levels, e.g. 80%, 85%, 90% of $\rho_{d,max}$; Method: Poulsen and Blendstrup, 2008; van Verveveld and Gebert, 2020	X	X ³⁾	X	X ³⁾
Organic matter, as loss on ignition (LOI) or total organic carbon (TOC); Method: ASTM D7348 – 13 or ISO 10694:1995	X	X	X	X
Respiratory activity (oxygen consumption) for organic-rich materials (e.g., composts) or mixtures with these materials; Method: e.g. ISO 16072:2002, CAN/BNQ 0413-220, ÖNORM S2027-4 or German DepV (2009)		X		

Parameter and suggested methods	Methane oxidation layer: Mineral material	Methane oxidation layer: Organic material	Inter-mediary layer	Gas distribution layer
NH₄⁺ content in materials with high organic matter content (>8 %DM) Method: ISO 11732:2005		X		
Carbonate content Method: ISO 10693:1995	X		X	X
Iron fractions Method: ISO 12782-1:2012 and ISO 12782-2:2012	X		X	
pH and electrical conductivity (EC) Method: ISO 10390:1994 and ISO 11265:1994	X	X		

- 1) Air capacity is air-filled porosity at field capacity (-6kPa suction)
2) Porosity between -6 kPa and -1500 kPa suction
3) Not compacted, to be tested on material as poured during construction

Test methods for quality control and quality assurance

Table A2.5: Proposed parameters to be analysed for assessment of a test field and quality of the final microbial methane oxidation system (MMOS) construction, methane oxidation layer (MOL). Methods are suggested based on international standards.

Parameter and suggested methods	Test field	Final MMOS
Bulk density, degree of compaction¹⁾ Field: Collection of undisturbed samples (ASTM D1587/D1587M) in combination with Laboratory: ISO 11272:2017. Also used in the field: Nuclear gauge (fast; ASTM 2015a), sand-cone (slow; ASTM 2007), or volumetric balloon procedure (slow; ASTM 2015b).	X	X
Water content Method: ISO 16586:2003	X	X
Air capacity²⁾ Method: ISO 11274:2019	X	X
Plant available field capacity³⁾ Method: ISO 11274:2019	X	X
Hydraulic conductivity Method field: ASTM 5126. Alternatively, it is recommended to use apparatus such as the Guelph permeameter or the Mini Disk infiltrometer (Meter Co.) Method lab: ISO 17312:2005	X	X

- 1) Requires obtainment of the Std. Proctor curve and pd_{max}
2) Air capacity is air-filled porosity at field capacity (-6kPa suction)
3) Porosity between -6 kPa and -1500 kPa suction (pore pressure)

APPENDIX 3: Minimisation of compaction before and during construction

Transport and storage of selected materials

Soils or composts used for methane oxidation systems should be produced, transported, and stored in a way that prevents pre-compression. Pre-compression negatively influences the materials' mechanical and physical behaviour. This includes minimising the height of storage heaps to below 2 m and preventing saturation of the materials during storage by ensuring that the materials drain well, or by storing them roofed or under a membrane. If soil is stored uncovered for a longer time, it is recommended to vegetate the soil heaps. The more finely-grained the soil, the higher the likelihood of undesired effects due to pre-compression.

The materials should only be transported and worked with when dry or slightly moist but never when very moist or wet. Construction should occur when the water content has been reduced to a level that the soil is semi-solid, meaning that the consistency index $I_c > 1.0$, i.e. the water content should be lower than the soil's plastic limit. When the soil water content leads to $I_c < 0.75$, the soil should be dried before construction.

To prevent formation of horizontal interfaces, the individual layers should preferably be constructed in one lift. This might however require machinery that is too heavy and will cause compaction during construction. In those cases, two lifts should be considered. The interface between the lift can be improved by means of a rotary cultivator.

Construction

Please observe that general civil engineering aspects such as required infrastructure, erosion control systems, stormwater management, drainage, etc. are not discussed in this document. This document focuses on methane oxidation. The need for these general civil engineering aspects varies a lot between climates and depends on site-specific wishes. They should not be forgotten. But it is beyond the scope of this document to present all the options in detail.

After construction, the layers of the methane oxidation system should not be overridden with machinery compacting the soil beyond the desired extent. To prevent erosion of the newly constructed system, the topsoil of the methane oxidation system should be vegetated as soon as possible.

For methane oxidation systems it is recommended that machines used to construct layers of a methane oxidation do not have soil pressures exceeding 36 kPa. For materials that are less prone to compaction a higher soil pressure may be considered on a case-to-case basis. The soil pressure of any machine can be determined by dividing its total weight, i.e. including blades, buckets and/or loads of material, by the surface of the wheels or tracks that is touching the soil. Some examples are provided in Table A3.1.

Bulldozers with sufficiently wide and long tracks can be used to construct soil layers with a bulk density between 1,300 and 1,900 kg per cubic meter. If according to the design a bulk density lower than 1,300 kg per cubic meter is required, a long stick excavator must be used. This situation should preferably be avoided. It is a cumbersome and therefore expensive construction method. The low density might result in a relatively high porosity possibly requiring a gas distribution layer with an impractically high porosity.

It is not recommended to construct layers thicker than 40 to 50 cm in one pass of the bulldozer. The topmost 10 to 20 cm of layer constructed with a bulldozer are compacted to a higher degree than the bottom 20 to 30 cm. The air capacity will be more evenly distributed if the top 10-20 cm are loosened by a e.g. a rotary cultivator. This equipment should be mounted on a tracked tractor and not on a wheeled tractor. The wheeled tractor has a too high soil pressure.

Table A3.1: Some examples of soil pressure of machines

	Mass	Surface	Pressure	Pressure
Item:	[kg]	[m ²]	[g/cm ²]	[kPa=kN/m ²]
Long stick excavator	52.000	4,77	1090	111
Idem on 4 dragline plates 1x6m	60.000	24	250	25
Midi excavator	8.000	1,99	402	41
Idem on 3 plates 1x3m	9.500	9	106	11
Bulldozer	18.300	5,50	332	34
Tracked tractor	12.000	3,90	308	31
Tracked dumper (5,7t + 3,7t load)	9.400	2,25	418	43
Tracked mowing machine	435	0,7	62	6
Tracked mowing robot	1.500	0,52	286	29
Wheeled mowing machine	375	0,075	500	51
Cagewheeled sowing machine	120	0,09	133	14
Person:				
70kg shoesize 41 / 7	70	0,015	467	48
90kg shoesize 45 / 10.5	90	0,017	529	54
70kg on 80 cm2 boards	70	0,08	88	9
90kg on 80 cm2 boards	90	0,08	113	11

Table A3.1 provides indicative examples of some machines. Please note that for any machine a contractor intends to use, the weight and the soil touching surface of the tracks needs to be compared and confirmed. Please also note that an average person on an average boot exerts a soil pressure that exceeds 36 kPa. Persons should only walk on layers after the roots of the vegetation provide sufficient cohesion to support boots without negative impact. If persons have to go into the methane oxidation system before the roots of the vegetation have sufficiently developed, they should have boards under their boots).

If tracks are narrow or short or the excavator is extremely heavy the machine cannot go onto the constructed layers. They should stay outside, unless they can drive on weight distributing plates that are moved around all the time.

The same applies to wheeled trucks, tractors or front-end loaders: they can only be applied outside the construction area or on weight distributing plates.

It is possible to construct methane oxidation layers in conditions where a suitable bulldozer is hard to obtain. Labour with wheelbarrows must however use pressure distributing boards for transport of material.

Shortly after construction and seeding it is not possible to go onto the methane oxidation systems and make the first cut of the grass with a standard tractor. The soil pressure would be too high and cause compaction. Only after 6 to 12 months, when the vegetation and the roots have developed, they can distribute the soil pressure of persons and machines.

APPENDIX 4: Cost estimates and cost-effectiveness

Table 4.1: Summary of survey responses

General aspects	Estonia	Estonia	Netherlands	Austria	Spain	Canada	Germany	Germany	Germany
Country of the biocover project: City or municipality:	Estonia Kudjape landfill, Kuressaare, Saaremaa island	Estonia Tallinn, Pääsküla landfill (1972-2003), active gas collection installed	Netherlands Province South Holland	Austria Anonymous	Spain Basque Country	Canada Region of Waterloo	Germany Anonymous	Germany Anonymous	Germany Anonymous
Type of technology:	Biocover	Biowindow	Biowindow	Biowindow	Biowindow	Biocfilter	Biocfilter	Biocfilter	Biocfilter
Size of the landfill [hectares]:	4,2 ha	25	7	4,5	30	100	100	100	100
Size of the section of the landfill treated [hectares]:	4,2 ha	25	7	10	4,5	~2 (system is supplied with landfill gas from 3 vertical passive gaswells located adjacent to the system)	33	33	33
Size of the biocover/window/filter [hectares]:	2,0 ha	six filters, total 1.3 ha	4 windows, total 0,276 ha	0,0964	0,35	0,0035 (10m x 3,5m)	0,14	0,21	0,21
Type of biocover:	One 2 ha large biocover	Biocfilters built on top of existing final cover layer	Windows built in the cover on a surface sealing, with 9 gas supply pipes through the sealing	10 biowindows replacing obsolete gas wells	Biowindow	Biocfilter - passive LFG supply	Passive biocfilter	Passive biocfilter	Passive biocfilter
Design based on expert judgement:	Described in project, approved by environmental impact assessment, Legal	Intended biowindows, because of legal reasons built as biocfilters. Design described in project, approved by environmental impact assessment, Legal	Yes, methane generation in 2012 below 25 m ³ STPH; active gas recovery not mandatory, but passive recovery and oxidation required.	Yes	Yes	Yes	Yes	Yes	Yes
Design based on tests of material properties:	Performed by Estonian University of Life Sciences, prof Kriipsalu	Material selected by Estonian University of Life Sciences, prof Kriipsalu	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Design method:		The volume of collected methane gradually dropped to 2.65 m ³ STPH/ha, which was the turning point where the owner had options either to cut off gas collection or to take responsibility and continue with passive methane oxidation system.	Methane Oxidation Tool		Methane Oxidation Tool	Brienne Nelson, et al. (2022) Mitigating fugitive methane emissions from closed landfills: A pilot-scale field study" Science of the Total Environments 851 (2022) 158351	Methane Oxidation Tool	Methane Oxidation Tool	Methane Oxidation Tool
Annual average methane load to the biocover [g CH ₄ per m ² and day]	Not measured	Not measured	7 (in 2012) declining to 2 (in 2025)	90	12	80	12,9	10,7	15,96
Method of measurement/estimation:			Alvalzorg Landfill Gas Model	gas extraction test (2013): 19/10 kg CH ₄ /a and assuming equal distribution over the windows	Alvalzorg Landfill Gas Model	Flow meter	MF	MF	MF
Annual average methane oxidation rate [g CH ₄ per m ² and day]	Annual rates not measured or calculated	Annual rates not measured or calculated	5	large spatial and seasonal variation	5	72 (90% oxidation)	11,7	9,7	13,26
Method of measurement/estimation:		GA5000 in situ, vacuum bottles ex-situ, flux chamber randomly	Methane Oxidation Tool	FC, PGP, MSS for regulatory purposes	Methane oxidation tool: assumption maximum = 40 gCH ₄ /per m ² and day	typical efficiency rate recorded during the operation of the PMOB	PBE	PBE	PBE
Total capital expenditure costs for construction of the biocover:	EUR 700.000	EUR 900.000	EUR 86.000	EUR 117.720	Estimate: EUR 70.000 (real CAPEX higher due to limited availability of suitable material)	USD 25.000	EUR 447.269	EUR 447.269	EUR 506.159
Year of capital expenditure costs:	2012 and 2013	2023 and 2024	Recalculated by indexation to 2025	2024	2017	2021, improvements 2023	2015	2015	2019
Annual costs for maintenance and monitoring:	Regular maintenance is mowing. Monitoring is water and gas sampling: presence of methane in 3 gas wells, 8 measurement levels. Several flux chamber measurements indicated: no methane emissions.	it is the first year, too soon to tell. Contract exists to mow biocfilters. Monitoring is gas sampling: presence of methane in 6 gas wells, 6 measurement levels. Gas observed in 3 filters and hardly anything in other 3.	Maintenance is mowing and covered by the aftercare provision for the entire landfill. Cost for the windows unknown. No monitoring required.	EUR 39.960	Estimate: year 1-5 EUR 23.000, year 6-15 EUR 12.000	USD 2.500	EUR 15.803	EUR 13.813	EUR 17.343
Year (pricelevel) of maintenance and monitoring costs:			NA	2024	2016	Maintenance and monitoring completed internally, costs for staff time only. Monitoring completed on a bi-weekly basis (~ one hour to complete)	2024	2024	2024
Construction aspects									
Thickness of the levelling layer [m]	None	None	None	-	NA	NA			
Material of the levelling layer	biocover on waste that was refilled and compressed	NA	NA	-	NA	NA			
Particle size range of the levelling layer [mm]	NA	NA	NA	-	NA	NA			
Thickness of the gas distribution layer [m]	0,5	0,5	0,2	0,5	0,25	0,2	0,2	0,2	0,2
Material of the gas distribution layer	Coarse shredded mineral C&D waste, fine material removed by sieving	Shredded concrete and bricks	Gravel and drainage pipes to gas supply openings through surface sealing	gravel	Crushed stone	Clean chipped gravel	gravel	gravel	gravel
Particle size range of the gas distribution layer [mm]		Estimated 32 to 64 mm	24 mm	32-64	2-16	19.05	2-8	2-8	2-8
Thickness of the intermediate layer [m]	None	None	None	-	0,05	NA	0,1	0,1	0,1
Material of the intermediate layer	NA	NA	NA	-	Sand	NA	gravel/sand	gravel/sand	gravel/sand
Particle size range of the intermediate layer	NA	NA	NA	-	1-2	NA	0-8	0-8	0-8
Thickness of the methane oxidation layer	1,5	approx 1.5 m	0,8	1,4	0,6	0,55	0,5	0,5	0,5
Material of the methane oxidation layer	Fine fraction from landfill mining 60%, matured sewage sludge compost 20 %, mineral soil 20%	Mature compost 70%, mineral soil 30%	95% drainage sand and 5% compost	compost	Sandy silt compost amended	compost / clean chipped gravel (1:1 ratio)	silty sand	silty sand	silty sand
Particle size range of the methane oxidation layer	Max 40 mm	Most compost was sieved 10 mm, last batches were unsieved. Compost contained some impurities, mineral soil contained some stones.	0,05-2	<25 mm	0,063-2	19.05 chipped stone, compost fine - 50mm	natural soil	natural soil	natural soil
Thickness of the top soil	None, biocover currently covered by vegetation, topsoil was not necessary	None	None	0.5-1 (cover surrounding the windows)	0,15	0,15	0,2	0,2	0,2
Material of the top soil	NA	NA	NA	soil/compost mixture	Sandy silt compost amended	Compost	silty sand with compost	silty sand with compost	silty sand with compost
Particle size range of the top soil	NA	NA	NA	-	0.063-2	Fine - 50mm	natural soil	natural soil	natural soil
Permanently installed measurement devices	Three gas wells up to 2 m deep, 8 levels,	One gas well per filter, total 6. Every gas well has 6 levels, between 0,25 m and 2,0 m. One well has an online temperature and pressure measurement system. Randomly gas concentration are measured with GA5000. One measurement campaign is required per year, from gas wells and from surface via flux chamber and vacuum bottles.	None	-	None	Soil gas probe, flux chamber	soil gas probes, soil moisture and water tension probes, temperature probe	soil gas probes, soil moisture and water tension probes, temperature probe	soil gas probes, soil water tension probes, temperature probe
Explanation:									
				Methods supporting performance evaluation e.g.:			Methods supporting efficiency evaluation e.g.:		
Biocfilters are self-contained fixed-bed reactors, built in to the landfill cover or stand alone and either with passive or active gas supply.				WLEM: whole landfill emission measurement using tracer dilution approach or other method			CMB: carbon mass balance		
Biowindows are open compartments integrated into the landfill cover that receive gas due to their increased permeability compared to the surrounding landfill cover.				FC: flux chamber measurements			PBE: profile based efficiency		
Biocovers use large parts of the landfill cover or the entire landfill cover as active methane oxidation layer.				PGP: Pore gas profiles			LMMB: local methane mass balance		
				MSS: methane surface screen			TMMB: total methane mass balance		
				SCIC: stable carbon isotope composition			TEMBA: total CH ₄ emission – before and after		
				MF: mass flow (gas flow and CH ₄ content)					

Table 4.2: Indicative costs of methane oxidation cover construction

Assumption: surface of methane oxidation system is 100.000 m²

Simple cover, cheap & compaction resistant materials	amount m ³ /m ²	unit cost \$/pc or \$/m ³	cost \$/ha
Surveying and plans	\$	2.000	\$ 200
Construction site set-up	\$	4.000	\$ 400
Transport of machines	\$	1.000	\$ 100
Profiling existing surface	\$	5.000	\$ 500
Purchase and storage of leveling material			
Construction of leveling layer			
Purchase and storage of gas distribution material	0,2 \$	5	\$ 10.000
Construction of gas distribution layer	0,2 \$	4	\$ 8.000
Purchase and storage of intermediary material			
Construction of intermediary layer			
Purchase and storage of methane oxidation material	0,4 \$	10	\$ 40.000
Construction of methane oxidation layer	0,4 \$	4	\$ 16.000
Loosen top of MOL (tracked rotary cultivator)			
Purchase and storage of topsoil material	0,2 \$	10	\$ 20.000
Construction of top soil layer	0,2 \$	4	\$ 8.000
Manually seed topsoil	\$	3.000	\$ 300
Assistance / supervision / unforeseen	\$	5.000	\$ 500
Total per hectare			\$ 104.000

Optimised cover	amount m³/m²	unit cost \$/pc or \$/m³	cost \$/ha
Surveying and plans		\$ 5.000	\$ 500
Construction site set-up		\$ 6.000	\$ 600
Transport of machines		\$ 2.000	\$ 200
Profiling existing surface		\$ 10.000	\$ 1.000
Purchase and storage of leveling material	0,1	\$ 3	\$ 3.000
Construction of leveling layer	0,1	\$ 5	\$ 5.000
Purchase and storage of gas distribution material	0,3	\$ 15	\$ 45.000
Construction of gas distribution layer	0,3	\$ 5	\$ 15.000
Purchase and storage of intermediary material	0,1	\$ 5	\$ 5.000
Construction of intermediary layer	0,1	\$ 5	\$ 5.000
Purchase and storage of methane oxidation material	0,5	\$ 10	\$ 50.000
Construction of methane oxidation layer	0,5	\$ 5	\$ 25.000
Loosen top of MOL (tracked rotary cultivator)		\$ 10.000	\$ 1.000
Purchase and storage of topsoil material	0,3	\$ 15	\$ 45.000
Construction of top soil layer	0,3	\$ 5	\$ 15.000
Loosen and seed topsoil (tracked rotary cultivator)		\$ 12.000	\$ 1.200
Installment of gas probes		\$ 10.000	\$ 1.000
Assistance / supervision / unforeseen		\$ 15.000	\$ 1.500
Total per hectare			\$ 220.000

Table 4.3: Operational costs

Assumption: surface of methane oxidation system is 100.000 m²

Inorganic cover, no performance monitoring	number per year		10 ha unit cost \$/pc		annual cost \$/ha
Inspection including report	4	\$	600	\$	240
Height (settlement) measurements	1	\$	4.000	\$	400
Repair of 0.1 hectare per year	0,1	\$	150.000	\$	1.500
Mowing	3	\$	5.000	\$	1.500
Sampling and analysing gasprobes including report	0	\$	2.000	\$	-
Surface screen including report	0	\$	1.000	\$	-
Flux box measurements including report	0	\$	4.000	\$	-
Whole site emission measurement including report	0	\$	5.000	\$	-
Data analysis and performance assessment	0	\$	6.000	\$	-
Reporting	1	\$	3.000	\$	300
Total per hectare				\$	3.940

Inorganic cover, some performance monitoring	number per year		10 ha unit cost \$/pc		annual cost \$/ha
Inspection including report	4	\$	600	\$	240
Height (settlement) measurements	1	\$	4.000	\$	400
Repair of 0.1 hectare per year	0,1	\$	150.000	\$	1.500
Mowing	3	\$	5.000	\$	1.500
Sampling and analysing gasprobes including report	4	\$	2.000	\$	800
Surface screen including report	4	\$	1.000	\$	400
Flux box measurements including report	0	\$	4.000	\$	-
Whole site emission measurement including report	0	\$	5.000	\$	-
Data analysis and performance assessment	1	\$	6.000	\$	600
Reporting	1	\$	3.000	\$	300
Total per hectare				\$	5.740

Organic cover, full performance monitoring	number per year		10 ha unit cost \$/pc		annual cost \$/ha
Inspection including report	4	\$	600	\$	240
Height (settlement) measurements	1	\$	4.000	\$	400
Repair of 1 hectare per year	1	\$	150.000	\$	15.000
Mowing	3	\$	5.000	\$	1.500
Sampling and analysing gasprobes including report	4	\$	2.000	\$	800
Surface screen including report	4	\$	1.000	\$	400
Flux box measurements including report	4	\$	4.000	\$	1.600
Whole site emission measurement including report	1	\$	5.000	\$	500
Data analysis and performance assessment	1	\$	6.000	\$	600
Reporting	1	\$	3.000	\$	300
Total per hectare				\$	21.340

CDM compliant cover and performance monitoring	number per year		10 ha unit cost \$/pc		annual cost \$/ha
Inspection including report	4	\$	600	\$	240
Height (settlement) measurements	1	\$	4.000	\$	400
Repair of 0.1 hectare per year	0,1	\$	150.000	\$	1.500
Mowing	3	\$	5.000	\$	1.500
Sampling and analysing gasprobes including report	12	\$	2.500	\$	3.000
Measuring gas temperatures	12	\$	2.000	\$	2.400
Surface screen including report	4	\$	1.500	\$	600
Flux box measurements including report	4	\$	5.000	\$	2.000
Whole site emission measurement including report	0	\$	5.000	\$	-
Data analysis and performance assessment	1	\$	8.000	\$	800
Reporting	1	\$	6.000	\$	600
Total per hectare				\$	13.040

Table 4.4: Cost effectiveness

Landfill accepting 150,000 tonnes MSW per year during 30 years

Waste density after disposal 1 tonne per cubic metre

Average waste height is 25 metres

Landfill surface is 18 ha

Methane generation was calculated separately with an IPCC compliant FOD model

Oxidation: maximum 35 g CH₄ per m² and day or 90% of the methane generation when less than 35g CH₄ per m² and day

		Simple biocover no performance monitoring	CDM compliant biocover & performance monitoring	Optimised biocover full performance monitoring
Construction costs depreciated in 10 years		\$ 1.881.000	\$ 4.608.000	\$ 4.608.000
Operational costs 10 years		\$ 709.200	\$ 2.347.200	\$ 3.841.200
Total costs over 10 years		\$ 2.590.200	\$ 6.955.200	\$ 8.449.200
CO₂eq emission reduction in 10 years	ton CO ₂ eq	400.000	480.000	550.000
Cost effectiveness	\$/ton CO₂eq	\$ 6,48	\$ 14,49	\$ 15,36

About the CCAC:

The Climate and Clean Air Coalition is a partnership of over 200 governments, intergovernmental organizations, and non-governmental organizations. The Coalition works to reduce powerful but short-lived climate pollutants (SLCPs) – methane, black carbon, hydrofluorocarbons (HFCs), and tropospheric ozone – that drive both climate change and air pollution.

Co-Chaired by the United Kingdom and Brazil, the Coalition aims to connect ambitious agenda setting with targeted mitigation action within countries and sectors. Robust science and analysis underpin all efforts, and bolstered by the CCAC Trust Fund, the Coalition has given rise to high-level political commitment, in-country support, and a range of tools that help make the case for action and support implementation.



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