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Chapter 2

BIOTIC LANDFILL CH₄ EMISSION ABATEMENT USING BIO-WASTE COMPOST AS A LANDFILL COVER

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ABSTRACT

This chapter will provide a comprehensive review of research on the use of landfill covers for the minimization of the emissions of the greenhouse gas methane.

Traditionally, municipal solid waste has been buried in landfills, and its biodegradable fractions decomposed via a complex series of biotic and abiotic reactions, producing mainly methane (CH₄) and carbon dioxide (CO₂). CH₄ has a global warming potential 23 times higher than CO₂, and the largest source of CH₄ emission is from landfill sites where it escapes through the landfill cover into the atmosphere. Thus even small reductions in landfill CH₄ emission could lead to significant decreases of atmospheric concentrations and a corresponding reduction in anthropogenic forcing.

Recent regulatory changes moving waste management away from landfill towards more integrated, practical, sustainable and economic schemes demand the development of sustainable technologies, i.e. the composting industry. Landfill CH₄ emission abatement can be achieved by CH₄ oxidizing bacteria (methanotrophs), which build up naturally very slowly in landfill cover soils, with low CH₄ oxidation rates resulting in high CH₄ surface fluxes from landfill soon after cover application. Bio-waste compost is investigated as an alternative landfill cover to maximize landfill CH₄ emission abatement.

Thus, this chapter reviews the use of landfill cover soils and in particular recent investigations in the use of bio-waste compost for minimization of CH₄ emissions. Finally, it includes a discussion of regulatory and sustainable aspects.

I. INTRODUCTION

Traditionally, municipal solid waste (MSW) has been buried in landfills. In Europe, the overall amount of MSW disposed of through landfill has gradually decreased over the time span 1995-2005 from 293 kg per capita to 221 kg per capita in the European Union (EU) (15 countries) (Fig. 1) as a result of European legislative pressures (Directive 1999/31/EC) [1] aimed at minimizing waste disposal through landfill in the EU. Additionally, the amount of biodegradable municipal solid waste (BMSW) going to landfill must be reduced by 25% by 2010, 50% by 2013 and 65% by 2020 of 1995 levels (by weight) [2]. Although the recycling/composting rate in Europe has increased over the past 5 years still large percentages of BMSW are being sent to landfill. The BMSW fraction of UK waste, for example, is still as high as 60% of the total MSW sent to landfill [3].

Typical BMSW fractions include paper/card, kitchen waste, garden waste, textiles, and other materials that are not easily classified. These fractions decompose via a complex series of microbial and abiotic reactions, producing landfill gas (LFG). This process may continue for 20 to 50 years after initial burial of the MSW. Bozkurt *et al.* [4] suggested that a landfill's anaerobic – CH₄ producing stage could last for 100 years. At near steady-state conditions, LFG is typically composed of approximately 55% CH₄, 40% CO₂, 5% N₂, with non CH₄ organic compounds (benzene, vinyl chloride, chloroform, 1,1-dichloroethene, carbon tetrachloride) and non-organic species (hydrogen sulphide, vapour phase mercury) being present in LFG in much smaller amounts [5].

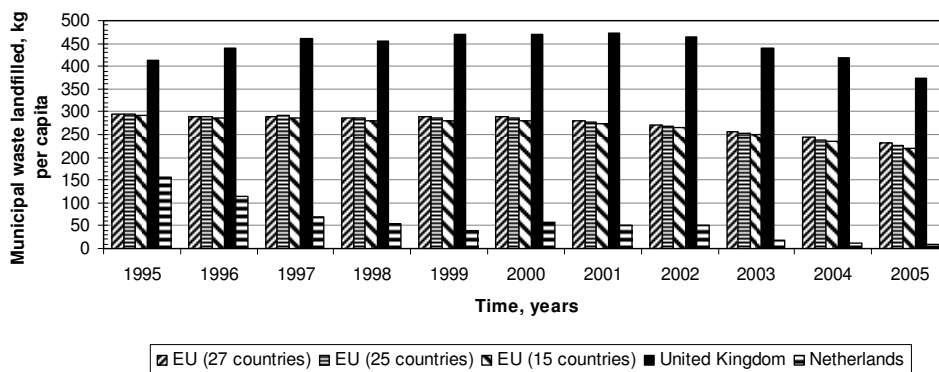


Figure 1. Municipal waste disposed of through landfill in Europe [6].

The composting process naturally produces some CH₄, CO₂, and nitrous oxide (N₂O). Information about N₂O emissions is presently limited. N₂O is a greenhouse gas (GHG) with an extremely high GWP (~310), it can also be generated in landfills through the processes of nitrification and denitrification [7], is linked to methanotrophic activity and therefore cannot be ignored when considering methods to reduce global warming. CH₄ emissions increase if the compost piles are too tall or too wet. Most composting occurs in open windrows without moisture control or means of collecting the gases released. The EU directive (Annex 1) [4] dictates that landfill operators must collect and combust LFG because the global warming potential (GWP) of CH₄ is much higher than that of CO₂, a product of its combustion (Table 1). Diverting biodegradable waste from landfills reduces the amount GHGs produced by

landfills, but also increases those released to the atmosphere from a much larger composting operation. It is therefore important that 'Best Composting Practice' should be developed to take these factors into account.

Within the European strategy for sustainable development, a long-term objective is to limit climate change, firstly by meeting the commitments of the Kyoto Protocol and then by reducing greenhouse gas emissions by an average of 1% per year over 1990 levels up to 2020 [8]. In 1998, the CH₄ emissions inventory for the UK totalled some 2.6 million tones, of which approximately 29% was derived from landfills [9]. LFG is therefore a major source of UK CH₄ emissions and a long-term strategy in order to minimize LFG emissions is thus required.

Table 1. Ozone depletion and global warming potentials

<i>Chemical</i>	<i>CFC/HCFC no.</i>	<i>Ozone depleting potential</i>	<i>Global warming potential</i>
CO ₂			1
CH ₄			21
Chloroform			4
Nitrous oxide			310
DichloroCH ₂ (methylene chloride)			9
1-Chloro-1,1-difluoroethane	HCFC-142b	0.065	2300
ChlorodifluoroCH ₂	HCFC-22	0.055	1900
ChlorofluoroCH ₂	HCFC-31	0.020	
2-Chloro-1,1,1-trifluoroethane	HCFC-133a	0.060	
ChlorotrifluoroCH ₂	CFC-13	1.0	14000
DichlorodifluoroCH ₂	CFC-12	1.0	10600
DichlorofluoroCH ₂	HCFC-21	0.040	
1,1,1,2-Tetrafluoroethane	HCFC-124	0.02–0.04	620
Trichlorofluoroethane (Freon 113)	HCFC-131	0.007–0.050	
TrichlorofluoroCH ₂	CFC-11	1.0	4600
Trichlorotrifluoroethane	CFC-113	0.8	6000
1,1,1-Trichlorotrifluoroethane	CFC-113	0.80	6000

CFC = chlorofluorocarbon; HCFC = hydrochlorofluorocarbon

Source: DETR *Climate change: draft UK program* [10].

Impermeable landfill caps combined with LFG extraction systems reduce emissions from both finished and not yet finished sections. In the UK, landfill CH₄ emissions have declined from 2.4 x 10⁹ kg in 1990 to an estimated 9.3 x 10⁸ kg in 2005, a reduction of 61% [11]. Despite these efforts and the resulting CH₄ emission reductions, a lot of LFG is still released

from landfill to atmosphere through (i) faults in the cap, (ii) temporarily covered areas, (iii) from the landfills' working faces and (iv) from old landfills.

Allen [12] stresses the high level of uncertainty relating to the long-term durability of artificial landfill liner systems. He points out that "the wisdom of placing such long-term reliance on an as yet unproven technology is short-sighted, and may ultimately be to our detriment". Purchase is expensive, installation needs to occur under favourable weather conditions and strict quality controls must be followed if its integrity is to be maintained. There is a risk that the liners will degrade through contact with corrosive leachates, hot and cold temperatures, ageing, physical stresses and the natural elements.

In order to apply the best available technology to reducing the harmful effects of landfill sites on the environment, it is important to understand how LFG characteristics and behaviour are influenced by a range of different factors. The composition of landfill gas will vary from one site to another, from one cell of a landfill to another, and will change over time. Some of these changes can be attributed to differences in waste composition, pre-treatment and storage, changes in the rate and predominant form of microbial activity, e.g. aerobic/anaerobic, the age of the emplaced wastes, gas management regime, the hydraulic characteristics of the site, the physiochemical properties of waste components, the differing properties of the components of landfill gas, e.g. solubility, landfill temperature. The composition of landfill gas can also vary within gas extraction and collection systems due to a mixture with air and gas/condensate and other interactions. The migration of landfill gas through sub-surface strata can also affect composition through physical (e.g. adsorption), chemical and biological (e.g. CH₄ oxidation) interactions between the gas and the surrounding rocks and minerals. These processes can alter the relative concentration of CH₄ and CO₂, and the trace chemistry of the gas as it moves further from the landfill source.

Because landfills and hence LFG are subject to such complex and varied conditions, suitable CH₄ emission reduction methods must work well across the range of potential conditions if they are to be effective. One approach - reviewed in this chapter - is to utilize the complex microbial communities present in a biowaste compost cover layer to oxidize the CH₄ that would otherwise escape from the landfill to the atmosphere, thereby reducing its impact on global warming. Biological CH₄ oxidation by methanotrophic bacteria (MTB) is ubiquitous in the environment. Some MTBs (gamma proteobacteria) predominate under atmospheric CH₄ concentrations (1.7 ppm), while others (alpha proteobacteria) are dominant under elevated CH₄ levels. These organisms have been well researched in landfill cover soils, rice paddies, wetlands, bogs etc., identifying their ability to oxidize CH₄ at a range of concentrations under different environmental conditions [13-16]. Interesting observations of Mandernack *et al.* [17] linked higher emissions of nitrous oxide with the increased activity of type II MTB. This suggests that reduction in CH₄ emissions due to biological oxidation could result in increased emissions of nitrous oxide – especially if the cover material has high levels of microbe-available N. Besides, MTB communities in compost have not been investigated in any great detail.

More biowaste compost production, in response to EU reductions in the landfilling of biodegradable waste, has increased compost availability. This has created the opportunity for its application as a landfill cover material, thereby encouraging more interest to develop. As well as covering MSW daily as it is placed in landfills to control blowing litter, odours, fire and vectors such as birds, rats and flies, landfill cells must be ultimately sealed when full. The functions of this final cover first included those of the daily cover but, in addition, to prevent

or minimize downward percolation of rainwater and therefore leachate, and to promote site reclamation and aesthetics [18]. In recent years, another function of the landfill cover considers LFG emission abatement.

Other benefits are realized as it replaces the need to purchase and transport large quantities of soil or silt for landfill cover. It also provides a useful application for large amounts of low-quality composts (glass and plastic contamination) that are produced on site without a suitable market.

II. LANDFILL CH₄

A. Landfill Gas Production

Biodegradable organic material present in landfilled MSW undergoes microbial degradation. This creates the gaseous intermediates and end-products that make up LFG. The idealized evolution of these components from waste with time (from the moment of deposit) was described by Farquhar and Rovers [19], and is shown in Fig. 2. Five stages were identified: (1) aerobic, (2) anaerobic non-methanogenic, (3) anaerobic methanogenic unsteady, (4) anaerobic methanogenic steady, (5) endogenous respiration.

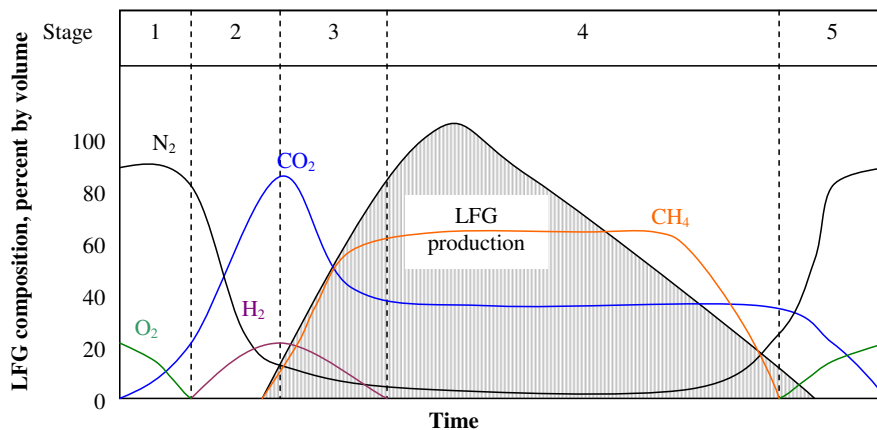


Figure 2. Idealized representation of landfill gas generation.

In practice, the idealized profiles described by the model (Fig. 2) are rarely achieved. Varying degrees of phase overlap, phase omission and, even, temporary cessation have been reported from the field. In addition, the duration of particular phases and the overall length of time taken for a body of waste to pass through the full degradation sequence vary considerably from one site to another. This reflects the influence of a wide range of factors controlling LFG production and composition.

B. Factors Controlling Landfill Gas Production and Composition

Farquhar and Rovers [19] developed a schematic representation of factors that affect LFG production. This is shown in Fig. 4 and illustrates how the various factors can interact ultimately affecting gas evolution from decomposing refuse. For instance, under the Group A factors, a lowering in temperature would reduce CH_4 production. This would lead to an accumulation of organic acids thus reducing alkalinity and pH. These conditions would further reduce CH_4 production. Considering the Group B factor, infiltration, its magnitude and composition can affect most of the factors in Group A. The factors in Group C (placement and cover, topography, hydrogeology, refuse composition, leachate recycling), several of which may be influenced by procedures during landfill design and operation, also interact with those in the other groups. Thus air temperature is a partial determinant of refuse temperature and may therefore influence infiltration and affect evaporation. Exchanges between air and gases within the refuse will be affected by atmospheric pressure. The movement of gases and water at the surface of the landfill will be affected by refuse placement and the materials and procedures used to cover the refuse. Precipitation, topography and hydrogeology will affect the magnitude of landfill infiltration and leachate recycling will affect its composition.

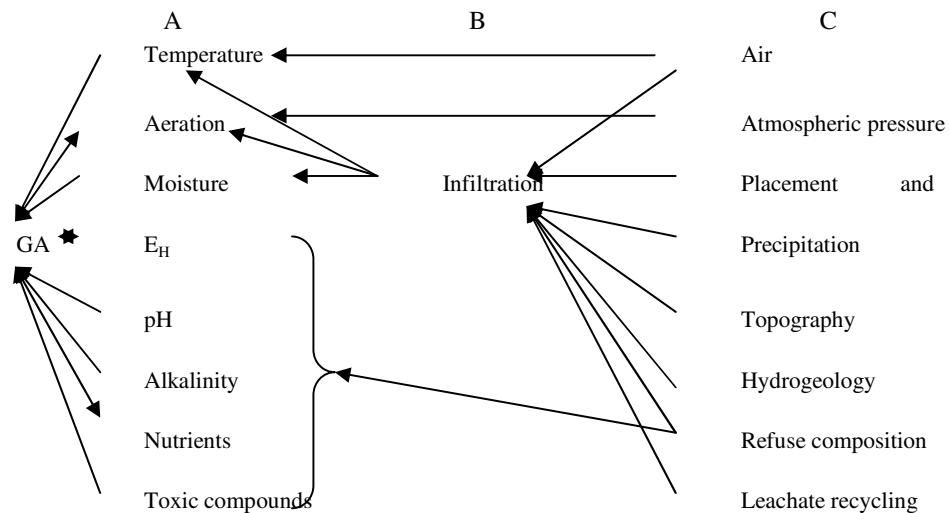


Figure 4. Factors influencing LFG production and composition in landfill sites.

The composition of the waste deposited within a landfill influences both the rate and the composition of the landfill gas generated. The biodegradable fraction of waste (which comprises approx. 25 – 30% by weight of municipal waste in the UK) is the portion which

under landfill conditions can undergo microbial degradation to produce gas and liquids. Currently 60% of the municipal waste produced in the UK is believed to be biodegradable waste [3]. Moisture content is one of the most significant factors influencing landfill gas production rates. High moisture content is normally associated with high rates of gas production, although rates do decline as saturation is approached. The hydraulic retention time of leachate in a landfill is typically of the order of several decades [20]. Gas retention times are usually orders of magnitude smaller, typically 2 - 4 weeks at gas generation rates of 5 - 10 m³ ton⁻¹ yr⁻¹ and a waste density close to 1 m³ ton⁻¹. Temperature is another important factor influencing the rate of landfill gas production. During the initial aerobic phases of waste degradation (Stage 1 in Fig. 2), temperatures as high as 80 - 90°C can be encountered. In the majority of landfills, temperatures thereafter will subside, stabilizing at an optimum of 35 - 45°C once methanogenesis is well established. Shallow landfills may be more sensitive to climatic conditions than deeper ones and landfill gas production will tend to drop below 10 - 15°C. Waste density is a function of the waste deposited, its particle size and the degree of compaction, and theoretically, the landfill gas yield per unit volume increases with waste density. However, increased waste densities generally reduce waste permeability, thereby inhibiting the free movement of the soluble nutrients required by bacteria. Hence, highly compacted waste at the base of a deep landfill may have a relatively low rate of CH₄ production. Waste degradation processes occur under a wider range of pH conditions than methanogenesis, which proceeds optimally between pH 6.5 and 8.5. Acidic conditions resulting from the rapid degradation of biodegradable wastes and an accumulation of breakdown products may inhibit or delay CH₄ generation. In addition, a low pH may promote the dissolution of metal ions within the waste mass, which may inhibit methanogenic activity. Methanogenesis can be inhibited completely or partially by chemical agents (commercial disinfectants, cleaning materials), which may be present in household waste deposited at landfills. Thus, landfill sites are complex and highly variable biological systems and, as presented in this section, many factors can lead to a wide variability in CH₄ production.

C. Landfill CH₄ Emission

In recent decades, better waste management has resulted in lined landfills and a cap of soil cover added regularly over newer landfills. This prevents fresh supplies of oxygen becoming available so the subsequent decay process is anaerobic and CH₄ is produced. CH₄ generated in landfills is partitioned into CH₄ recovered, emitted to the atmosphere, oxidized by CH₄ oxidizing bacteria (methanotrophs), laterally migrated, and internally stored in the landfill volume [21]. It has been reported that approximately 60% of the CH₄ produced from anthropogenic and natural sources is microbially oxidized adjacent to the zone of production or in soils functioning as atmospheric sinks [22,23]. According to the International Panel on Climate Change WGI Fourth Assessment Report, the global atmospheric concentration of CH₄ has increased from a pre-industrial value of about 715 ppb to 1732 ppb in the early 1990s, and is 1774 ppb in 2005. The atmospheric concentration of CH₄ in 2005 exceeds by far the natural range of the last 650000 years, as determined from ice cores. The latest global landfill CH₄ emissions estimates range from 16 × 10¹² to 57 × 10¹² g yr⁻¹, and global landfill CH₄ recovery estimates in 1996 was 3.8 × 10¹² g yr⁻¹ [24]. CH₄ has an atmospheric lifetime of about 10 yr and a global warming potential 23 times higher than CO₂ (mole basis, 100 yr

timeframe) [25], thus even small reductions in landfill CH₄ emission could lead to significant decreases of anthropogenic climatic forcing. Currently, estimates indicate that commercial landfill gas recovery projects recover more than 5×10^{12} g yr⁻¹ worldwide, thus reducing atmospheric CH₄ contributions from landfill sources [26]. In the United Kingdom (UK), there are approximately 4,000 licensed landfill sites [27], only ca. 150 engineered landfills [26].

Mitigation technologies can be encouraged in many ways through policies and regulations. First, governments can directly mandate certain approaches as a means of minimizing GHG emission or achieving other environmental benefits. CH₄ generation and thus, emission can be reduced through government policies or regulations for waste separation or recycling. To date, such policies have been motivated by the scarcity of suitable landfill capacity, and have had the secondary benefit of reducing greenhouse gas emissions. The landfill directives' primary goal is to reduce harmful effects on the environment.

III. BIO-WASTE COMPOST AS A LANDFILL COVER

A. Biotic Landfill CH₄ Abatement

Various approaches are currently being investigated to reduce landfill CH₄ emissions. When landfill gas extraction is economically not beneficial (i.e. from smaller and older landfills with low CH₄ generation rates), flaring is usually recommended [28]. Biotic CH₄ removal systems offer the same CH₄ conversion to CO₂ as flaring. However, unlike combustion, not every molecule of CH₄ consumed biotically is converted to CO₂. As much as 85% (mole/mole) of the CH₄ carbon may be incorporated into biomass and not released to the environment [29]. Therefore, any management technique or technology that can optimize this conversion is economically valuable.

Initial investigations of landfill CH₄ oxidation indicated that soil microbes removed up to 10% of the CH₄ gas fed continuously to a laboratory column filled with landfill soil [30]. Subsequent studies have shown that much higher uptake rates are possible in landfill soils [31-33].

CH₄ escaping from landfills can be oxidized by methanotrophic bacteria, which are ubiquitous in landfill soils [34-37], and can use CH₄ as their sole source of carbon and energy [36], functioning as the major biological sink for CH₄ in the environment and converting around half the carbon from its oxidation into biomass whilst respiring the rest as CO₂. Methanotrophs are traditionally divided into two main groups based on physiological and biochemical characteristics. Type I methanotrophs are members of the class Gamma-proteobacteria - they have a high affinity for CH₄ and therefore predominate in a low CH₄ atmosphere. Type II methanotrophs are in the class Alpha-proteobacteria - have a low affinity for CH₄ and are prevalent under conditions of elevated CH₄ [36]. The highest CH₄ oxidation rates reported in the literature are up to 500 g CH₄ m⁻² day⁻¹ in laboratory studies and up to 150 - 200 g CH₄ m⁻² day⁻¹ in field studies [31,38,39]. These shifts in CH₄ oxidation rates, may be accompanied by shifts in the methanotroph populations in soils in response to environmental stimuli such as changes in concentrations of CH₄ and O₂, temperature, pH and nitrogen sources [36,40,41].

B. Effect of Environmental Factors on CH₄ Oxidation in Bio-Waste Compost

Several factors have been shown to influence the extent of CH₄ oxidation in landfill cover soils. Temperature and soil moisture are reported among the most important environmental variables for CH₄ oxidation [42], however other factors should also be considered.

CH₄ oxidation temperatures

Microbial CH₄ uptake shows seasonal temperature dependence, with an optimum temperature in the range of 15 - 35 °C [39,43-45]. Above 40 °C, CH₄ oxidation rates decline and drop to zero by 50°C and slow noticeably at cooler temperatures of 2 – 5 °C [39]. Table 2 gives values for methane oxidation rates. The timescale should also be considered, since exposure to temperatures exceeding 30°C for long periods can lead to a loss of microbial activity due to enhanced cell decay [40].

Borjesson *et al.* [33] reported slightly different CH₄ oxidation capacities within the range of 1.17 and 1.57 μmol CH₄ (g dw soil)⁻¹ h⁻¹ at 20 °C in three soils. These capacities are similar to values for landfill covers consisting of mineral soils (0.998 [31], 1.62 [38], μmol CH₄ (g dw soil)⁻¹ h⁻¹), whereas cover soils rich in organic matter are known to have higher CH₄ oxidizing capacities (10.8 [46], 25 [47] μmol CH₄ (g dw soil)⁻¹ h⁻¹). Additionally the CH₄ consumption rates were markedly affected by shifts in temperature, and only type I methanotrophs grew at low temperatures (3 - 10 °C), but both types grew at 20 °C. Borjesson *et al.* [29] estimated microbial CH₄ removal using field comparisons of ¹³C to ¹²C isotope ratios, and trials at 0 °C showed no evidence of microbial CH₄ consumption. Christophersen *et al.* [48] reported that in laboratory incubations of landfill soil under high headspace CH₄, the maximum gas was consumed at a rate as high as 2.5 × 10⁻³ μg g⁻¹ h⁻¹ in soil at the lowest trial temperature of 2 °C, although the response was significantly less than the maximum at 15 °C, which was 1.9 × 10⁻² μg g⁻¹ h⁻¹.

Table 2. Methane (CH₄) oxidation rates presented by different authors for samples from landfill cover soils.

<i>Temperature, °C</i>	<i>Maximum CH₄ oxidation rate reported, μg CH₄ g⁻¹ h⁻¹</i>	<i>Reference</i>
25	2.5 μg (g ww) ⁻¹ h ⁻¹	Whalen <i>et al.</i> [43] Humer and Lechner [64]
20	27.2 μg (g dw) ⁻¹ h ⁻¹	Kightley <i>et al.</i> [31]
15	0.01 μg (g dw) ⁻¹ h ⁻¹	Boeckx <i>et al.</i> [41]
25	152 μg (g dw) ⁻¹ h ⁻¹	Borjesson <i>et al.</i> [46]

Although Dunfield *et al.* [49] and Whalen *et al.* [43] reported that rates of CH₄ oxidation are controlled by temperature, Boeckx *et al.* [41] found that temperature only had a slight effect on CH₄ oxidation rates stating that the ideal temperature (20-30°C) decreased with increased moisture content.

Moisture Contents and Oxygen Availability

Soil moisture provides a water film that acts as a protective layer against extreme concentrations and as a diffusion transport film for O₂ and CH₄ to the cells, and for CO₂ and waste products away from the cells. CH₄ oxidation activity occurs in a soil moisture content range from 8% up to 50% (w/w). Optimal moisture contents have been reported within the range 10 - 20% [43], between 20 - 30% for an unspecified type of soil [50], and between 11 and 32% in sandy soils [48]. A substantial decrease in CH₄ oxidation rates from 35% to 50% with a 10% moisture content increase (from 32% to 42%) has been observed in silty sand forest soils [51]. Figueroa [52] found that methanotroph activity was encouraged by relatively high moisture content, observing the highest CH₄ turnover rates in biowaste compost with moisture content of 25 - 50% (40 - 80% WHC). Poulsen *et al.* [53] reported some variation of the optimum moisture contents between four (unspecified) soil types. Additionally, Hanson and Hanson [36] reported that the rate of CH₄ oxidation in waterlogged landfill soil (41% by weight of water) was 6.1 mg d⁻¹, which was about the same as rates observed in oxic freshwater sediments, and was 116 mg d⁻¹ in soils with 11% water content. Nesbit [54] reported a CH₄ oxidation rate reduction of 56% at moisture saturation. Low soil moisture content limits CH₄ oxidation in landfill soils. Adamsen and King [55] observed that decreasing the water content to 5% resulted in dramatic decreases in CH₄ oxidation rates. High soil moisture may lead to an inhibited aeration and thus high CH₄ production. CH₄ oxidation is fairly insensitive to oxygen concentration as long as it is above 3% v/v [32,56], however it is sensitive to CH₄ concentration [22,44,57]. Bender and Conrad [22] reported that four different incubated soils under elevated CH₄ concentration (> 100 μl CH₄ l⁻¹) showed a lag phase during which CH₄ concentration decreased only very slowly. However, the decrease of CH₄ concentration eventually accelerated, and reached a maximum after a certain time (induction of CH₄ oxidation). Without O₂ in the gas phase no CH₄ oxidation was detectable. The four soils investigated, which were different in texture, pH, Cu²⁺, C content and water content (23 - 33% H₂O), showed different induction of CH₄ oxidation. Bender and Conrad [22] thus suggested that the induction process was affected by the soil properties. The induction process was highest between 28 - 35% soil water content, 6.7 - 8.1 pH, and 25 - 35 °C temperature. Bender and Conrad [22] also observed that the induction process slowed down following an addition of Cu²⁺, and when the soil aggregate size decreased from > 2 to < 0.05 mm diameter.

Water produced and released through CH₄ oxidation could enhance the growth of plants in a dry climate [84]. The authors also noted that the plant roots did not grow below the CH₄ oxidation horizon, presumably caused by a lack of oxygen at these depths.

Chandrankanthi *et al.* [58] reported that compost has become a popular alternative to using soil in biofiltration. It has ideal physical, chemical and biological characteristics. But, proper function of biofilters depends on maintaining conditions that promote the growth of methanotrophic bacteria. Mysliwiec *et al.* [59] identified lack of moisture and nutrient limitations (bacteria obtain their nutrients from the liquid phase) as having the greatest detrimental effect on how well biofilters performed. Microbial respiration creates thermal energy that produces an evaporation potential that can cause compost to dry [60]. In addition to this, drying within the media is not evenly distributed, causing the waste gas stream to short-circuit its previous path [59]. Thermal conductivity heat transfer and evaporation depends on such things as texture, organic content, water content and bulk density. In

addition to these factors, the compaction of compost increases the bulk density and so reduces the porosity of the media [58].

Different materials have different water holding capacities. A suitable material should be able to retain moisture without becoming waterlogged, good aeration depends on this. The pore-size distribution of the cover material plays an important role in the dynamics of LFG migration and CH₄ oxidation in the landfill cover. Water drains freely from larger diameter pores (> 50µm), but is bound to smaller pores (<10 µm) (Gebert *et al.* 2003) due to the cohesion between water molecules. Biofilter material needs to be well-structured and porous with sufficient specific surface area to promote mass transfer [61].

Soil Characteristics

Microbial CH₄ consumption may be influenced by soil type, presenting higher rates in coarse sand (61%) than in fine sand or clay (40 - 41%) [31], and on larger sized particles diameters of mineral soils such as clay, silt, and fine sand (0.5 - 2 mm) [22,62]. High soil organic content generally increases the oxidation rates, and increases the optimal soil moisture content [56]. While soils with organic contents of 1 to 10% show moderate oxidation potential, bio-waste compost and other materials with high organic content (up to 35% w/w) show 10 to 100 fold higher oxidation potentials. Moreover, those materials have higher moisture holding capacity and larger porosities. Methanotrophs optimal pH range is within 6.5 and 8.0, although oxidation activity may continue at higher pH values (8.5 - 9.0) [51]. Methanotrophs are tolerant to low pH values, down to 3.0. The effect of inorganic nitrogen on CH₄ oxidation is very complex and can be both stimulatory and inhibitive [63]. Short-term incubations have shown that nitrate, lime [64], ground wheat (high C:N) and sugar beet leaf amendment (low C:N) [41] added to fresh soil enhanced CH₄ uptake, but when amendments of KNO₃, vitamins, EDTA or FeSO₄ were added to landfill soil after the soil had been incubated for several thousand hours with CH₄, did not show stimulation over 2 - 3 day incubation periods [64]. Ammonium addition enhanced CH₄ uptake in short-term incubations [22,38], while in long-term incubations it inhibited CH₄ consumption in bare soil columns, and had no sustained inhibitory effect when the column surfaces were grass-covered [64]. Long-term incubations have shown that lime [64] and sewage sludge were stimulatory and enhanced CH₄ oxidation, while addition of phosphate presented no effect [31].

Bender and Conrad [22] in a study of acidic peat samples found that CH₄ oxidation rates were only slightly affected by pH at levels of between 4 and 6, declining rapidly below and above these points. Dedysh *et al.* [65] identified species of *Methylosinus* existing at a pH of 3.5 -5 in sphagnum peat but suggested that they may be dormant. Figueroa [52] reported optimum pH ranges to fall between 5.5 and 8.5 and that these preferred conditions remain fairly constant. Hanson and Hanson [36] were unable to find any examples of methanotrophic bacteria growing below a pH value of 5. These findings suggest that methanotrophic communities will adapt to different conditions and that optimum conditions will be largely species dependent.

Humer and Lechner [66] observed high density of MTB in the vicinity of plant roots growing in sewage sludge compost lysimeters. They attributed this phenomenon to a good supply of oxygen being available in these locations. A discreet band of CH₄ oxidizing activity was also present at a depth of 75-90 cm in the profile. High nutrient levels in bio-waste

compost result in nitrophile plant species enjoying a natural advantage at the expense of other species.

Atmospheric Pressure

Emission of landfill gas through a landfill cover soil in general follows the pressure gradient between landfill and atmosphere and is thus influenced by atmospheric pressure dynamics. Geber and Groengroeft [67] monitored a passively vented landfill site in Northern Germany for gas emission dynamics through high resolution measurements of landfill gas pressure, flow rate and composition as well as atmospheric pressure and temperature (Fig. 5). They reported a very low landfill gas pressure with a maximum value of 1.6 hPa. CH₄ oxidation potential was 72 g CH₄ m⁻² d⁻¹ (at 20°C), which was within the range of values given by other authors for the CH₄ oxidation potential of landfill soil covers [31,43]. Relative to LFG composition, Geber and Groengroeft [67] observed that with decreasing atmospheric pressure, subsequent increasing LFG pressure and positive gas fluxes, the CH₄ content increased steadily (up to 56%) while the O₂ content dropped to zero. They also observed that landfill gas pressure is a function of the gradient of atmospheric pressure (inverse), which corroborated the observations of Christophersen *et al.* [68]. Czepiel *et al.* [44] on the other hand, reported that landfill CH₄ emission inversely correlated with absolute values of surface atmospheric pressure.

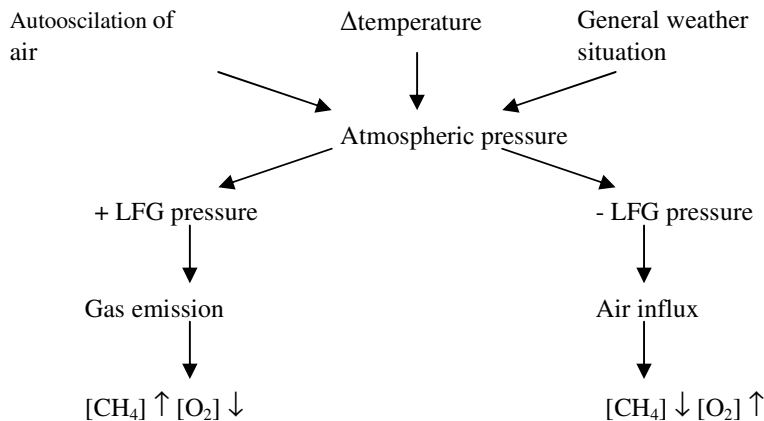


Figure 5. Conceptual diagram on the regulation on landfill gas emission on a landfill site

(Adapted from Gebert and Groengroeft [67]). Legend: Δ = difference, \uparrow = increasing, \downarrow = decreasing.)

Coupled Effects

Temperature and moisture are important environmental factor that may affect landfill CH₄ emission, but complex relationships exist between temperature, moisture, the CH₄ oxidizing capacity of cover materials, and their physical properties [69]. Additionally, a

coupled effect on the extent of CH₄ oxidation may occur. Christophersen *et al.* [48] reported that CH₄ oxidation rates depend significantly on the organic matter content of the soil, temperature, and soil moisture content, being the soil moisture the most important factor in their study. However their results also indicated that temperature was also important. Additionally, at increasing organic matter content (1 - 9% w/w), both the optimal soil moisture content and the maximum oxidation rate increased [56]. Zeiss [39] also reported that optimal soil moisture varies with soil type and porosity, with coarse sand showing the lowest optimal moisture content (10% w/w) and compost showing the highest optimal moisture content (over 30% w/w). Poulsen *et al.* [53] reported correlations between optimal soil moisture content and temperature. Between 2 °C and 15 °C lower temperatures correlate with slightly higher optimal moisture content (by 2 - 3% w/w).

C. Bio-Waste Compost

Conventionally, material suitable for use as daily cover has been sourced from waste generated by the construction and demolition industry. Recent regulatory changes moving waste management away from landfill towards more integrated, practical, sustainable and economic schemes demand the development of sustainable technologies, i.e. the composting industry. In the United Kingdom, composting is classified as a waste recovery operation under the Waste Framework Directive [70]. In addition, composting of waste is a vital component of meeting the Waste Strategy 2000 [10] targets for recycling and composting set at 25% by 2005, 30% by 2010, and 33% by 2015. In Europe, the EC Landfill Directive 1999 [1] sets a target for reduction of biodegradable waste to landfill of 25% by 2010, 50% by 2013, and 65% by 2020 of 1995 levels. It is therefore expected that large quantities of bio-waste composts will be produced to comply with current regulatory constraints.

CH₄ oxidation in conventional soil covers, typically of older landfills, has been reported to be effective in reducing the amount of CH₄ emitted [29,45,71]. However, one major limitation is that methanotroph communities build up very slowly in landfill cover soils [46], with low CH₄ oxidation rates resulting in high CH₄ surface fluxes from landfill, soon after cover application. CH₄ oxidation rates may be dependent on various physicochemical characteristics such as temperature, pH, soil composition, moisture holding capacity, pH, and nutrient content [31,38,40], and also biological characteristics such as the presence and also the diversity and function of methanotroph communities [72]. CH₄ oxidation rate levels greater than 1,000 g CH₄ m⁻² d⁻¹ have been obtained in a thick compost amended engineered cover material [73].

Alternative cover materials with high initial CH₄ oxidizing capabilities (i.e. bio-waste compost) could reduce landfill CH₄ emission. By definition, composting accelerates the processes involved in the biological transformation of organic matter under controlled aerobic conditions to produce a stabilized product, compost [74]. As such, bio-waste compost may be added as a landfill cover to mitigate landfill CH₄ emissions. Additionally, the ability of compost to remove organic contaminants (i.e. polycyclic aromatic hydrocarbons) [75,76] and odour [77] has been demonstrated. Bio-waste compost has more air-filled pore space than soils, on the order of 50% compared to 20 – 30% for soils. This allows more oxygen to penetrate for the oxidation of CH₄ and creates an extended aerobic zone in the cover. Another advantage of using bio-waste compost as a landfill cover is that it avoids the occurrence of

cracks in the landfill cover, reducing the risk of emission hot spots [78]. On the other hand, conventional soil covers consisting of a 1 m clay and a 0.3 m topsoil layer in the simplest configuration, often do not sufficiently reduce LFG emissions, because clay covers contain micro cracks and can develop larger cracks when desiccated.

It has been reported that the oxidation behaviour of laboratory biofilter columns changes with time with a short period of acclimatisation, a rapid oxidation rate increase reaching a peak before declining to a lower level [31,38]. Some researchers [64] suggested that this rate decline is due to the formation of exopolymeric substances (EPS) in the upper regions of the biofilter columns, thereby causing a reduction in the diffusion of gas through the media resulting in lower levels of methanotrophic activity. This does raise some issues of concern regarding the durability of a compost landfill cover material over the longer term.

D. Review of Current State of The Knowledge

CH₄ oxidation rates in conventional soils have been extensively studied [18], but there are fewer studies on environmental factors influencing CH₄ oxidation in compost.

Humer and Lechner [14,73] studied MSW compost and sewage sludge compost as cover material to increase the oxidation of CH₄ and found that complete CH₄ oxidation is possible. They reported that CH₄ uptake in laboratory incubations of compost from MSW and fully matured sewage sludge compost was superior to that in topsoil and humic garden soil. The more porous compost media permitted good gas penetration, so that a 60 cm column of MSW compost was able to remove a CH₄ flux equivalent to 400 – 550 l CH₄ m⁻² d⁻¹. Working in CH₄ fed columns, sewage sludge compost was shown to support higher CH₄ oxidation rates than a conventional soil [79]. Follow-up field-scale tests showed that both a municipal waste compost and a 50% (wt %) mixture of wood chips and sewage sludge compost would effectively oxidize fugitive CH₄ on a landfill with a gas collection system. Their studies work also demonstrated the importance of a gas distribution layer between the refuse and the CH₄ oxidation layer [80]. Hummer and Lechner [80] further investigated the effect of temperature on CH₄ oxidation using compost-filled columns in a climate-controlled chamber. The tests started at a temperature of 18 °C, and after an adaptation time of about 6 days, all of the supplied CH₄ (approximately 150 l CH₄ m⁻² day⁻¹) were removed. They reported that a constant and high CH₄ removal was obtained across a temperature range of 5 °C to 30 °C. When the temperature was reduced to approximately 4 °C, the removal rates were 70 – 80% of those measured at 18 °C. CH₄ oxidation occurs best in mature compost where the organic matter is almost completely stable with a 7-day respiratory activity value that is lower than 10 mg O₂ g⁻¹ dry matter

Streese and Stegmann [61] investigated CH₄ oxidation in two experimental plants, a bench-scale plant (total filter volume 5 l) and a pilot plant (total filter volume 4 m³). They used four different biofilters: one with pure yard waste compost, a second one with compost and intermittent additional gas distribution layers, a third one with the mixture of equal volumes of compost, peat, and wood fibres, and a fourth one with a mixture of two volumes of compost and one volume of wood fibres. After three months from the beginning of the experiment, the compost biofilters showed the highest degradation rates with values up to 1,512 g CH₄ m⁻³ d⁻¹ using a constant inlet of 2.5% v/v CH₄ and compost as biofilter material. A mixture of compost, peat and wood fibres showed stable and satisfactory degradation rates

approx. $480 \text{ g m}^{-3} \text{ d}^{-1}$ at mean inlet concentration of 3% v/v CH₄ over the period of one year. They demonstrated that bio-waste compost can successfully oxidize CH₄; however the mixture of compost, peat, and wood fibres produced more satisfactory results than the other biofilters investigated, especially with regard to long term stability. They hypothesized that differences in pH values or differences in microbial populations between the biofilters could explain the different CH₄ oxidation capacities. Besides, they pointed out that operational conditions (i.e. moisture, temperature) should be adjusted to the specific demands.

Hilger and Humer [28] investigated biotic CH₄ removal at a 14 ha operating landfill in Austria. Although a gas collection system was in place, CH₄ emissions of $0.58 \text{ g m}^{-2} \text{ d}^{-1}$ were detected. They further confirmed that landfill CH₄ abatement was feasible using bio-waste compost as a landfill cover. The greater air penetration, better temperature modulation, and nutrient supply offered by bio-waste compost resulted in a 100% CH₄ atmospheric capture as compared to 10 – 50 % estimates of CH₄ uptake efficiency measured in traditional soil landfill covers. The importance of a gravel support layer was evident, probably due to its functions to accumulate and distribute the gas into the compost. Hilger and Humer [28] also noticed that surface area and depth of compost interact with the effects of temperature, moisture content, and also gas penetration into the compost at various depths.

Barlaz *et al.* [78] compared emissions of CH₄ from landfill cells (1 m^2) covered with soil or with yard waste compost. They reported that the soil and biological cover were responsible for oxidation of 21% and 55% of the CH₄ produced in the landfill reaching the bottom of the respective cover. They investigated the CH₄ oxidation capacity when the gas collection system was turned off or active. They reported a 52% atmospheric uptake when the gas collection system was active or turned off in the compost cover. However, they reported a reduction from 54% to 12% atmospheric uptake when the gas collection system was active and turned off respectively in the soil cover. These results support the concept that a compost cover used as an intermediate cover can reduce emissions when no gas collection and control system is in place, when the gas collection system is not fully extended to a particular area of a landfill, and when the system is not operable. Barlaz *et al.* [78] concluded that bio-waste compost covers offer advantages to traditional soil covers due to their increased organic content, subsequent moisture holding capacity, and infiltration rates which make bio-covers less susceptible to cracking and erosion relative to a clay cover and translates into reduced maintenance costs.

Berger *et al.* [81] investigated the use of a system comprising a capillary barrier at the bottom and a soil layer above. Capillary barriers consisted of two-layer cover soil: a layer of fine material (capillary layer) which was built above a layer of coarse material (capillary block) on a slope. These capillary barriers are an alternative to conventional surface sealing systems [81] and may use bio-waste compost in the top layer. In Berger *et al.*'s design [81] the soil layer consisted of a layer of bio-waste compost mixed with sand (30 cm) over a layer of sand (90) to mitigate landfill CH₄ emissions. They concluded that following 33 weeks operation of an experimental plant, cover material showed an adequate microbial oxidation of CH₄ in landfill gas between 80% and 95% even under low temperatures (5°C), and that aeration of the cover soil was the main influencing factor for CH₄ oxidation.

Spokas *et al.* [82] investigated two experimental cells filled from 1994 to 1999, where the cover for the first cell consisted of 30 cm of organic soil overlain a geo-synthetic clay liner (GCL) overlain a sand layer, and the second cell consisted of 30 cm of organic soil overlaying a clay cover consisting of 1 m of compacted clay. They observed a 6 fold reduction in total

emissions and 1.8 times increase in recovery for the clay cover as opposed to the GCL cover. The total oxidation was higher above the GCL ranging from <10% to 50% due to the higher emission rate. However, both cells oxidized approximately 4% of the total emission through the cover. Spokas *et al.* [82] indicated that this low value of CH₄ oxidation was due to high soil moisture at the site during the field investigation which answers the concerns of Barlaz *et al.* [78]. Additionally the soil above the GCL cover was actively oxidizing CH₄ from the atmosphere.

Mor *et al.* [83] investigated at laboratory scale the effect of temperature and moisture and the time dependence of these variables on the CH₄ oxidation in compost. Test bottles were injected with 10 ml of 100% CH₄, leading to an initial CH₄ concentration of about 5 - 10%. They reported that the influence of moisture content (29 -110%) and temperature (7 - 40⁰C) on CH₄ oxidation was time-dependent (days). Optimal moisture content of two garden waste composts, G1 (31% organic matter) and G3 (52% organic matter) for CH₄ oxidation were 45 - 85% and >110% moisture on a dry weight basis, respectively. These values are higher than the optimal for mineral soils, which are typically around 15% [41,84]. They reported almost no influence of temperature between 15 and 30°C in the long term CH₄ oxidation, and much lower activity at 7°C. The maximum activity reported by Mor *et al.* [83] was 1.812 μmol kg_{dw}⁻¹, which was lower than that reported by others [85], maybe due to differences in the composition of the compost starting material or CH₄ concentrations normally > 30%

Abichou *et al.* [86] monitored CH₄ emissions at 15 cm thick non-vegetated intermediate cover soil overlying 1 yr old waste and a 45 cm thick vegetated intermediate cover soil overlying 7 yr old waste. They reported that arithmetic means of the measured fluxes were 54 and 22 g CH₄ m⁻² d⁻¹ from the thin and thick covers respectively. The peak flux was 596 g m⁻² d⁻¹ for the thin cover and 330 g m⁻² d⁻¹ for the thick cover. They reported that CH₄ oxidation through the cover was only partly responsible for the lower emission for the thicker cover. They suggested that mitigation of emissions from the thin intermediate cover can best be achieved by placing bio-waste compost cover on the entire area, while mitigation of emissions from the thick well-vegetated intermediate cover can be achieved by bio-waste compost placement limited to high emission zones.

Stern *et al.* [69] investigated the effect in oxidizing CH₄ of a thin (about 50 cm) biocover consisting of composted yard waste and woodchips (windrowed and turned for 3 yr) at the Leon County landfill (Florida, USA), compared to untreated landfill soils. The experiment was set up over waste that had been covered for 8 yr by 20 - 60 cm of sandy clay overlain by 20 - 50 cm of fine sandy loam. They reported the results of flux and oxidation field measurements for biocover and control cells for one annual cycle. Measured flux from the control cells and biocover cells ranged from -0.280 to 218 g CH₄ m⁻² d⁻¹ and -0.389 to 22.2 g CH₄ m⁻² d⁻¹, respectively. Over the entire study period, the mean flux from the control cells was significantly more than the flux from the biocover cells (10.6 compared to 1.2 g CH₄ m⁻² yr⁻¹). Percent oxidation of CH₄ was calculated from stable isotope data. Over the entire course of the experiment, the percent of CH₄ oxidation in the control and biocover cells were significantly different (p < 0.001), with a mean oxidation of 18% for the control cells and 38% for the biocover cells. The biocover cells contained significantly more soil moisture than the control, 0.74 ± 0.2 (w/w) compared to 0.22 ± 0.1 (w/w) for the soil. Similar effects were noted at the Outer Loop landfill [78], where the soil cover generally performed well, but occasionally released large quantities of CH₄ associated with desiccation cracks. No such cracks were observed in the biocover cells. Stern *et al.* [69] corroborated the results of Barlaz

et al. [78] concluding that biocovers serve to reduce emissions. Additionally, the study of Stern *et al.* [69] supports observations of higher percentages of CH₄ oxidation at landfills in warmer climates. Conservative estimates put the average annual percent CH₄ oxidation at the Leon County MSW landfill from 19% for untreated areas of the landfill to 38% for bio-waste compost treated areas. Similarly, a landfill in Kentucky had mean values of 21 - 55% CH₄ oxidation [78]. These values are significantly higher than the average annual percent CH₄ oxidation of 10% for a landfill in New England [32], where CH₄ oxidation was enhanced during the warmer months (20–30%) and near zero during winter. Studies conducted at two landfills in Sweden also indicate seasonal dependence of CH₄ oxidation. During summer, CH₄ oxidation was near 100%, while CH₄ oxidation could not be detected during the winter, once the temperatures dropped below 0°C [29]. Stern *et al.* [69] reported a distinctive inverse relationship between percent oxidation and flux for the bio-cover cells, and suggested an inverse relationship between oxidation and soil moisture and a positive relationship between soil temperature and oxidation, although the later was not reflected in averaged data.

Nikiema *et al.* [87] constructed lab-scale bio-filters (135 cm high, 15 cm diameter) to test CH₄ oxidation efficiency at different levels of microbe available N (NH₄⁺ / NO₃⁻). They found that inorganic beds were more effective supporters of microbial CH₄ oxidation than organic beds under conditions of elevated available N (> 0.25 g l⁻¹) at CH₄ concentration of 7000 - 7500 ppmv. CH₄ oxidation activity was however higher in the organic bed than the inorganic bed at low available N (0.14 g l⁻¹) levels. N was a limiting factor in the CH₄ oxidation capacity of the inorganic media, but had no influence in the organic material - presumably because adequate amounts of N were freely available.

In summary, laboratory, pilot-plant and field scale investigations of the use of bio-waste compost as a landfill cover to abate landfill CH₄ emission are available during the last ten years. Furthermore, efforts have focused on the effect of environmental factors on the rate of CH₄ oxidation. Results from these investigations are difficult to compare due to the different environmental conditions: (i) temperature, (ii) moisture, (iii) landfill site, (iv) bio-waste compost, etc.; and different scales of operation: laboratory vs. pilot scale. Regardless, most of the reviewed investigations, gave emphasis to temperature and moisture content.

IV. REGULATORY AND SUSTAINABLE ASPECTS OF BIO-WASTE COMPOST AS A LANDFILL COVER

A. Regulatory Aspects

In countries where solid waste landfilling is highly regulated, several initiatives have been undertaken to reduce landfill CH₄ emissions. In order to have an overview of the current legislation relevant to the control and management of landfill gas in the UK, a list is included in Table 3. In the UK and the EU, landfills are the first (48%) and second (31%) largest sources of anthropogenic CH₄ respectively [88,89]. Both entities have adopted the approach of increasing landfill gas collection and making systematic reductions in the quantity of biodegradable wastes that is buried. For instance, the EC Landfill Directive 1999 [1] imposes strict engineering requirements, in order to minimize CH₄ emissions from landfills.

The Landfill Directive (1999/31/EC) [1] has been established to reduce the negative environmental effects of landfill, including the pollution of soil, water and air, global warming and any other resulting risk to human health. It is implemented in England and Wales through the Landfill Regulations 2002 and through the Landfill [Scotland] Regulations 2003 in Scotland. It requires that landfill sites be classified according to the type of waste material that they accept: (i) hazardous, (ii) non-hazardous or (iii) inert. Operators are now required to submit detailed site plans. They also need to demonstrate their technical competence and commitment to raising both engineering and operating standards. The aforementioned directive sets challenging targets for the progressive diversion of biodegradable waste from landfill [90]. Article 5(2) states that the amount of BMSW that is sent to landfill should be reduced to 75% of 1995 levels by 2010, to 50% by 2013 and down to 75% by 2020. Although some of these targets can be met through Landfill Allowances Trading Schemes (LATS) between authorities, most will be delivered through the treatment (composting) and resulting diversion from landfill. If the UK fails to meet their targets, then they will be subject to a compliance fine of up to £0.5m per day after the first target date in 2010. In addition to this, a Landfill Tax for 2006/07 of £21 ton⁻¹ of active waste (rising by £3 ton⁻¹ year⁻¹ to £35 ton⁻¹) encourages operators to reduce the amount of biodegradable waste that they landfill.

Households in England produced an estimated 25.7 million tonnes of waste in the year 2004/05 (data from 'Best Value Performance Indicators' by LAs). Although waste inputs at material recovery and composting sites have tripled since 2001 to 5.3m tonnes, half of the waste sent to landfill in 2004/05 was estimated to consist of recyclable garden waste, kitchen waste and waste paper and board [91]. Although the amount of materials being composted is growing, there is still much potential for improvement.

Table 3. Current legislation relevant to the control and management of landfill gas in the UK.

EU Directives	75/442/EEC Waste Framework Directive and amendments 96/61/EC Integrated Pollution Prevention and Control 97/11/EC Environmental Impact Assessment 91/689/EEC Hazardous Wastes 99/31/EC Landfilling of Waste 96/62/EC on air quality assessment and management 1999/30/EC relating to limit values for sulphur dioxide, nitrogen dioxide and oxides of nitrogen, particulate matter and lead 2000/69/EC relating to limit values for benzene and carbon monoxide in ambient air
Acts	Environmental Protection Act 1990 Town and Country Planning (England and Wales) Act 1990 Town and Country Planning (Scotland) Act, 1997 Clean Air Act 1993 Environment Act 1995 Pollution Prevention and Control Act 1999 Statutory Landfill (England and Wales) Regulations 2002, SI 2002 No. 1559

Instruments	<p>Landfill (Scotland) Regulations 2003 SI 2003 No. 235</p> <p>Pollution Prevention and Control (England and Wales) Regulations 2000, SI 2000 No. 1973</p> <p>Pollution Prevention and Control (Scotland) Regulations 2000, SI 2000 No. 323</p> <p>Air Quality (England) Regulations 2000, SI 2000, No. 928</p> <p>Air Quality (Wales) Regulations 2000, WSI 2000, No. 1940</p> <p>Air Quality (Scotland) Regulations 2000, SSI 2000, No. 97</p> <p>Air Quality (Scotland) Amendment Regulations 2002, SSI 2002, No. 297</p> <p>Air Quality Limit Values Regulations 2001, SI 2001 No. 2315</p> <p>Air Quality Limit Values (Wales) Regulations 2002, WSI 2002 No. 3183</p> <p>Air Quality Limit Values (Scotland) Regulations 2001, SSI 2001, No. 224</p> <p>Waste Management Licensing Regulations 1994, SI 1056 as amended</p> <p>Control of Substances Hazardous to Health Regulations 2002, SI 2002, No. 2677</p> <p>Contaminated Land (England) Regulations 2000, SI 2000, No. 227s</p> <p>Contaminated Land (Wales) Regulations 2001, WSI 2001, No. 2197</p> <p>Town and Country Planning General Development Order 1988, SI 1998, No. 1813</p> <p>Town and Country Planning (General Permitted Development) Order 1995, SI 1995, No. 418</p> <p>Town and Country Planning (General Development Procedure) Order 1995, SI 1995, No. 419</p> <p>Town and Country Planning (General Development Procedure (Scotland) Order 1992 (as amended)</p> <p>Town and Country (Environmental Impact Assessment) (England and Wales) Regulations 1999, SI 1999, No. 293</p> <p>Environmental Impact Assessment (Scotland) Regulations 1999, SSI 1999, No. 1</p> <p>Planning (Control of Major-Accident Hazards) (Scotland) Regulations 2000, SSI 2000, No. 179</p>
Guidance	<p>Planning Policy Guidance Note 10 Planning and waste management, 1999</p> <p>Planning Policy Guidance Note 22 Renewable energy, 1993</p> <p>Planning Policy Guidance Note 23 Planning and pollution control</p> <p>Planning Guidance (Wales) Planning policy, 1999 (under review)</p> <p>Technical Advice Note (Wales) 8 Renewable energy, 1996</p> <p>Technical Advice Note (Wales) 21 Waste, 2001</p> <p>National Planning Policy Guideline 6 Renewable energy, 2000 (applies in Scotland)</p> <p>National Planning Policy Guideline 10 Planning and waste management, 1996 (applies in Scotland)</p> <p>Planning Advice Note 51 Planning and environmental protection, 1997 (applies in Scotland)</p> <p>Planning Advice Note 58 Environmental impact assessment, 1999 (applies in Scotland)</p> <p>Planning Advice Note 63 Waste management planning, 2002 (applies in Scotland)</p> <p>Planning Advice Note 45 Renewable energy technologies (revised 2002) (applies in Scotland)</p>

B. Sustainable Aspects

Traditionally biodegradable waste has not been source-segregated and it has been buried in landfills, decomposed via a complex series of microbial and abiotic reactions, producing mainly CH₄ and CO₂. The EC Landfill Directive 1999 [92] imposes strict engineering requirements on landfills, requiring landfill CH₄ to be captured and used. In UK there are more than 1,000 landfill sites [93], only ca. 150 engineered landfills [26], thus the largest source of CH₄ emission is from landfill sites where CH₄ escapes through the landfill cover into the atmosphere.

The biodegradable waste fraction previously buried in landfills, may now be considered an alternative sustainable source of bio-waste compost production. Thus, regulatory objectives and priorities relating to composting of biodegradable waste should also be considered. In the United Kingdom, composting is classified as a waste recovery operation under the Waste Framework Directive. In addition, composting of waste is a vital component of meeting the Waste Strategy 2000 [94] targets for recycling and composting set at 30% by 2010 and 33% by 2015.

This chapter has indicated that bio-waste compost can be applied as a landfill cover, and accomplish landfill CH₄ abatement. It is here suggested that in order to abate CH₄ emission from landfill sites, bio-waste compost obtained from waste management facilities could be applied as a landfill cover. By doing so, global CH₄ emissions will be reduced since composting is an aerobic process (although CH₄ emissions may occur due to anaerobic pockets) that produces mostly CO₂, landfilling the same BMSW fraction would in itself produce significantly larger quantities of CH₄. A posterior application of compost as a landfill cover will additionally reduce CH₄ emissions through increased levels of CH₄ oxidation, thereby reducing the effect that landfills have on global warming. Bio-waste compost is suggested as a highly available and a low-cost landfill cover to be used at modern landfills as an alternative soil cover to synthetic covers or washed gravel which may cost over \$10 m⁻² and \$12 m⁻² respectively [39]. Besides compost can be prepared from organic waste at the landfill site, and therefore there will be no extra cost in transporting soil from another place. Additionally, compost produced from municipal solid waste used as a fertilizer has been demonstrated to improve the quality of soil [95,96].

Therefore, the use of bio-waste compost as a landfill cover contributes to lower CH₄ greenhouse gas emission from traditional waste management practice. This approach agrees with the recent European Sustainable Development Strategy, which addresses seven key challenges as priorities until 2010, being climate change and clean energy, better management and natural resources among them [97].

V. FINAL REMARKS

Whilst more research on the use of bio-waste compost is still needed, the current state of the knowledge indicates that biotic landfill CH₄ oxidation represents an attractive alternative of the reduction of CH₄ coming out from landfills. Especially for those with lower gas emission rates (55 g CH₄ m⁻² d⁻¹), like old landfills or landfills containing biological pre-

treated waste. Bio-waste compost covers could also serve as both a polishing system for emissions not captured by a gas collection system and to minimize the potential for emissions associated with cracks. The use of bio-waste compost applied as a landfill cover will contribute to a sustainable development.

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REFERENCES

- [1] EC, Directive 1999/31/EEC Council Directive On The Landfill of Waste, L182/1, 16/07/99. European Commission, 1999.
- [2] EC, Directive 2003/30/EC Of The European Parliament and of the Council of 8 May 2003 on the promotion of the use of biofuels or other renewable fuels for transport, Official Journal of the European Union L 123 (2003) 42-46.
- [3] EA, Guidance on the management of landfill gas, Bristol, Environment Agency, 2004. www.environment-agency.gov.uk
- [4] S. Bozkurt, L. Moreno, I. Neretnieks, Long-term processes in waste deposits, *Sci. Total Environ.* 250 (2000) 101-121.
- [5] EPA, Guidance For Evaluating Landfill Gas Emissions From Closed Or Abandoned Facilities, EPA-600/R-05/123a. Washington, DC, United States Environmental Protection Agency, 2005.
- [6] EC, Municipal waste treatment, by type of treatment method, European Commission, Eurostat, 2006. <http://epp.eurostat.ec.europa.eu>.
- [7] J. Powell, P. Jain, H.D. Kim, T. Townsend, D. Reinhart, Changes in landfill gas quality as a result of controlled air injection, *Environ. Sci. Technol.* 40 (2006) 1029-1034.
- [8] EC, SCADPlus: Strategy for sustainable development, European Commission, 2005. <http://europa.eu/scadplus/leg/lvb/128117.htm>.
- [9] DEFRA, UK emissions of air pollutants 1970-2000. Report of the National Atmospheric Emissions Inventory compiled on behalf of Defra by the National Environmental Technology Centre (Netcen), Department for Environment, Food and Rural Affairs, 2002. <http://www.naei.org.uk/reports.php>
- [10] DETR, Waste Strategy 2000: England and Wales, London, Department of the Environment, Transport and the Regions: The Stationary Office, 2000.
- [11] DEFRA, Greenhouse Gas Inventories, for England, Scotland, Wales and Northern Ireland: 1990 - 2002, AEAT/ENV/R/1761. Department for Environment, Food and Rural Affairs, 2004. http://www.defra.gov.uk/science/Project_Data/DocumentLibrary/GA01026/GA01026_2280_FRP.doc
- [12] A. Allen, Containment landfills: the myth of sustainability, *Eng. Geol.* 60 (2001) 3-19.

- [13] T. Henckel, M. Friedrich, R. Conrad, Molecular analyses of the methane-oxidizing microbial community in rice field soil by targeting the genes of the 16S rRNA, particulate methane monooxygenase, and methanol dehydrogenase, *Appl. Environ. Microb.* 65 (1999) 1980-1990.
- [14] M. Humer, P. Lechner, Microbial methane oxidation for the reduction of landfill gas emissions, *J. Solid Waste Technol. Manag.* 27 (2001) 146-151.
- [15] S. Jensen, L. Ovreas, F.L. Daae, V. Torsvik, Diversity in methane enrichments from agricultural soil revealed by DGGE separation of PCR amplified 16S rDNA fragments, *Fems Microbiol. Ecol.* 26 (1998) 17-26.
- [16] J.L. Ross, P.I. Boon, P. Ford, B.T. Hart, Detection and quantification with 16S rRNA probes of planktonic methylotrophic bacteria in a floodplain lake, *Microbial Ecol.* 34 (1997) 97-108.
- [17] K.W. Mandernack, C.A. Kinney, D. Coleman, Y.S. Huang, K.H. Freeman, J. Bogner, The biogeochemical controls of N₂O production and emission in landfill cover soils: the role of methanotrophs in the nitrogen cycle, *Environ. Microbiol.* 2 (2000) 298-309.
- [18] D.J. Lisk, Environmental effects of landfills, *Sci. Total Environ.* 100 (1991) 415-468.
- [19] G.J. Farquhar, F.A. Rovers, Gas production during refuse decomposition, *Water Air Soil Pollut.* 2 (1973) 483-495.
- [20] K. Knox, The relationship between leachate and gas, in: *International landfill gas conference, Energy and Environment '90*, Technology Support Unit / Department of the Environment, ETSU, Harwell, 1990.
- [21] J. Bogner, K. Spokas, Landfill CH₄: rates, fates, and role in global carbon cycle, *Chemosphere* 26 (1993) 36-386.
- [22] M. Bender, R. Conrad, Effect of CH₄ concentrations and soil conditions on the induction of CH₄ oxidation activity, *Soil Biol. Biochem.* 27 (1995) 1517-1527.
- [23] W.S. Reeceburgh, S.C. Whalen, M.J. Alperin, The role of methylotrophy in the global methane budget. in: J.C. Murrell, D.P. Kelly (Eds.), *Microbial Growth of C1 Compounds*, Intercept Ltd., Andover, UK, 1993, pp. 1-14.
- [24] J. Bogner, E. Matthews, Global methane emissions from landfills: New methodology and annual estimates 1980-1996, *Global Biogeochem. Cycles* 17 (2003) 1065.
- [25] IPCC, *Climate Change 2001: The Scientific Basis. Technical summary*, ed., Cambridge University Press, Cambridge, 2001.
- [26] H. Willumsen, Landfill gas plants worldwide: number and types, in: *Sardinia '03 Waste Management and Landfill Symposium*, CISA, University of Cagliari, Sardinia, Italy, 2003.
- [27] DEFRA, *Operational Waste Facilities in England and Wales*, London, Department of Environment, Food and Rural Affairs, 2006.
- [28] H. Hilger, M. Humer, Biotic landfill cover treatments for mitigating methane emissions, *Environ. Monitoring Assessment* 84 (2003) 71-84.
- [29] G. Borjesson, J. Chanton, B.H. Svensson, Methane oxidation in two Swedish landfill covers measured with carbon-13 to carbon-12 isotope ratios, *J. Environ. Qual.* 30 (2001) 369-376.
- [30] R.L. Mancinelli, C.P. McKy, Methane-oxidizing bacteria in sanitary landfills, in: *First Symposium on Biotechnological Advances in Processing Municipal Wastes from Fuels and Chemicals*, Argonne National Laboratory Report ANL/CNSV-TM-167, Minneapolis, Minnesota, USA, 1985.

- [31]D. Kightley, D.B. Nedwell, M. Cooper, Capacity for methane oxidation in landfill cover soils measured in laboratory-scale soil microcosms, *Appl. Environ. Microb.* 61 (1995) 592-601.
- [32]P. Czepiel, B. Mosher, P. Crill, R. Harriss, Quantifying the effect of oxidation on landfill methane emissions, *J. Geophys. Res. Atmos* 101 (1996) 16721–16729.
- [33]G. Borjesson, I. Sundh, B. Svensson, Microbial oxidation of CH₄ at different temperatures in landfill cover soils, *Fems Microbiol. Ecol.* 48 (2004) 305-312.
- [34]P.F. Dunfield, M.T. Yimga, S.N. Dedysh, U. Berger, W. Liesack, J. Heyer, Isolation of a *Methylocystis* strain containing a novel pmoA-like gene, *Fems Microbiol. Ecol.* 41 (2002) 17-26.
- [35]J. Gebert, A. Groengroeft, M. Schloter, A. Gattinger, Community structure in a methanotroph by phospholipid fatty acid biofilter as revealed analysis, *Fems Microbiol. Lett.* 240 (2004) 61-68.
- [36]R.S. Hanson, T.E. Hanson, Methanotrophic bacteria, *Microbiol Rev* 60 (1996) 439-471.
- [37]M.G. Wise, J.V. McArthur, L.J. Shimkets, Methanotroph diversity in landfill soil: Isolation of novel type I and type II methanotrophs whose presence was suggested by culture-independent 16S ribosomal DNA analysis, *Appl. Environ. Microb.* 65 (1999) 4887-4897.
- [38]A. De Visscher, D. Thomas, P. Boeckx, O. Van Cleemput, Methane oxidation in simulated landfill cover soil environment, *Environ. Sci. Technol.* 33 (1999) 1854-1859.
- [39]C.A. Zeiss, Accelerated methane oxidation cover system to reduce greenhouse gas emissions from MSW landfills in cold, semi-arid regions, *Water Air Soil Pollut.* 176 (2006) 285-306.
- [40]A. De Visscher, M. Schippers, O. Van Cleemput, Short-term kinetic response of enhanced methane oxidation in landfill cover soils to environmental factors, *Biol. Fert. Soils* 33 (2001) 231-237.
- [41]P. Boeckx, O. VanCleemput, Methane oxidation in a neutral landfill cover soil: Influence of moisture content, temperature, and nitrogen-turnover, *J. Environ. Qual.* 25 (1996) 178-183.
- [42]R.S. Li, C. Zeiss, In situ moisture content measurement in MSW landfills with TDR, *Environ. Eng. Sci.* 18 (2001) 53-66.
- [43]S.C. Whalen, W.S. Reeburgh, K.A. Sandbeck, Rapid methane oxidation in a landfill cover soil, *Appl. Environ. Microbiol.* 56 (1990) 3405-3411.
- [44]P.M. Czepiel, J.H. Shorter, B. Mosher, E. Allwine, J.B. McManus, R.C. Harriss, C.E. Kolb, B.K. Lamb, The influence of atmospheric pressure on landfill methane emissions, *Waste Manage.* 23 (2003) 593-598.
- [45]J. Chanton, K. Liptay, Seasonal variation in methane oxidation in a landfill cover soil as determined by an in situ stable isotope technique, *Global Biogeochemical Cycles* 14 (2000) 51-60.
- [46]G. Borjesson, I. Sundh, A. Tunlid, B.H. Svensson, Methane oxidation in landfill cover soils, as revealed by potential oxidation measurements and phospholipid fatty acid analyses, *Soil Biol. Biochem.* 30 (1998) 1423-1433.
- [47]A.N. Nozhevnikova, A.B. Lifshitz, V.S. Lebedev, G.A. Zavarzin, Emission of methane into the atmosphere from landfills in the former USSR, *Chemosphere* 26 (1993) 401-417.
- [48]M. Christophersen, L. Linderod, P.E. Jensen, P. Kjeldsen, Methane oxidation at low temperatures in soil exposed to landfill gas, *J. Environ. Quality* 29 (2000) 1989-1997.

- [49]P. Dunfield, R. Knowles, R. Dumont, T.R. Moore, Methane production and consumption in temperate and sub-arctic peat soils - response to temperature and pH, *Soil Biol. Biochem.* 25 (1993) 321-326.
- [50]C. Scheutz, P. Kjeldsen, Environmental factors influencing attenuation of methane and hydrochlorofluorocarbons in landfill cover soils, *J Environ Qual* 33 (2004) 72-79.
- [51]B.K. Sitaula, L.R. Bakken, G. Abrahamsen, CH₄ Uptake by Temperate Forest Soil - Effect of N Input and Soil Acidification, *Soil Biol. Biochem.* 27 (1995) 871-880.
- [52]R. Figueroa, Methane oxidation in landfill top soils, in: T.H. Christensen, R. Cossu, R. Stegmann (Eds.), Ninth International Waste Management and Landfill Symposium, CISA-Environmental Sanitary Engineering Center: Cagliari, Italy, Sardinia, 2003.
- [53]T.G. Poulsen, M. Christophersen, P. Moldrup, P. Kjeldsen, Relating landfill gas emissions to atmospheric pressure using numerical modelling and state-space analysis, *Waste Manage. Res.* 21 (2003) 356-366.
- [54]S.P. Nesbit, G.A. Breitenbeck, A Laboratory Study of Factors Influencing Methane Uptake by Soils, *Agric. Ecosyst. Environ.* 41 (1992) 39-54.
- [55]A.P.S. Adamsen, G.M. King, Methane consumption in temperate and subarctic forest soils: rates, vertical zonation, and responses to water and nitrogen, *Appl. Environ. Microbiol.* 59 (1993) 485-490.
- [56]M. Christophersen, L. Linderoed, P. Jensen, P. Kjeldsen, Methane oxidation at low temperatures in soil exposed to landfill gas, *J. Environ. Qual.* 29 (2004) 1989-1997.
- [57]J.E. Bogner, K.A. Spokas, E.A. Burton, Kinetics of methane oxidation in a landfill cover soil: Temporal variations, a whole landfill oxidation experiment, and modeling of net CH₄ emissions, *Environ. Sci. Technol.* 31 (1997) 2504-2514.
- [58]M. Chandrakanthi, A.K. Mehrotra, J.P.A. Hettiaratchi, Thermal conductivity of leaf compost used in biofilters: An experimental and theoretical investigation, *Environ. Pollut.* 136 (2005) 167-174.
- [59]M.J. Mysliwicz, J.S. VanderGheynst, M.M. Rashid, E.D. Schroeder, Dynamic volume-averaged model of heat and mass transport within a compost biofilter: I. Modal development, *Biotechnol. Bioeng.* 73 (2001) 282-294.
- [60]D.E. Chitwood, J.S. Devinny, F.E. Reynolds, Evaluation of a two-stage biofilter for treatment of POTW waste air, *Environ. Prog.* 18 (1999) 212-221.
- [61]J. Streese, R. Stegmann, Microbial oxidation of methane from old landfills in biofilters, *Waste Manage.* 23 (2003) 573-580.
- [62]G. Borjesson, I. Sundh, A. Tunlid, A. Frostegard, B.H. Svensson, Microbial oxidation of CH₄ at high partial pressures in an organic landfill cover soil under different moisture regimes, *Fems Microbiol. Ecol.* 26 (1998) 207-217.
- [63]P.L.E. Bodelier, H.J. Laanbroek, Nitrogen as a regulatory factor of methane oxidation in soils and sediments, *Microbiol. Ecology* 47 (2004) 265-277.
- [64]H.A. Hilger, D.F. Cranford, M.A. Barlaz, Methane oxidation and microbial exopolymer production in landfill cover soil, *Soil Biol. Biochem.* 32 (2000) 457-467.
- [65]S.N. Dedysh, N.S. Panikov, J.M. Tiedje, Acidophilic methanotrophic communities from Sphagnum peat bogs, *Appl. Environ. Microbiol.* 64 (1998) 922-929.
- [66]M. Humer, P. Lechner, Effect of methane oxidation on the water balance of the landfill cover and the vegetation layer, in: T.H. Christensen, R. Cossu, R. Stegmann (Eds.), Ninth International Waste Management and Landfill Symposium, CISA-Environmental Sanitary Engineering Center: Cagliari, Italy, Sardinia, 2003.

- [67]J. Gebert, A. Groengroeft, Passive landfill gas emission - Influence of atmospheric pressure and implications for the operation of methane-oxidising biofilters, *Waste Manage.* 26 (2006) 245-251.
- [68]M. Christophersen, P. Kjeldsen, H. Holst, J. Chanton, Lateral gas transport in soil adjacent to an old landfill: factors governing emission and methane oxidation, *Waste Manage. Res.* 19 (2001) 595-612.
- [69]J.C. Stern, J. Chanton, T. Abichou, D. Powelson, L. Yuan, S. Escoriza, J. Bogner, Use of a biologically active cover to reduce landfill methane emissions and enhance methane oxidation, doi:10.1016/j.wasman.2006.07.018 (In press)
- [70]EC, Directive 2006/12/EC of the European Parliament and of the Council of 5 April 2006 on waste, 2006/12/EC. European Commission, 2006.
- [71]J. Bogner, M. Meadows, P. Czepiel, Fluxes of methane between landfills and the atmosphere: natural and engineered controls, *Soil Use Manage.* 13 (1997) 268-277.
- [72]J. Bogner, K. Spokas, E. Burton, R. Sweeney, V. Corona, Landfills as atmospheric methane sources and sinks, *Chemosphere* 31 (1995) 4119-4130.
- [73]M. Humer, P. Lechner, Alternative approach to the elimination of greenhouse gases from old landfills, *Waste Manag. Res.* 17 (1999) 443-452.
- [74]E. Epstein, *The Science Of Composting*, ed., Technomic Publishing Company, Lancaster, 1997.
- [75]B. Antizar-Ladislao, J.M. Lopez-Real, A.J. Beck, Bioremediation of polycyclic aromatic hydrocarbon (PAH)-contaminated waste using composting approaches, *Crit. Rev. Env. Sci. Technol.* 34 (2004) 249-289.
- [76]B. Antizar-Ladislao, J.M. Lopez-Real, A.J. Beck, Bioremediation of a PAH in an aged coal-tar contaminated soil using different in-vessel composting approaches, *J. Hazard. Materials B137* (2006) 1583-1588.
- [77]C. Hurst, P. Longhurst, S. Pollard, R. Smith, B. Jefferson, J. Gronow, Assessment of municipal waste compost as a daily cover material for odour control at landfill sites, *Environ. Pollut.* 135 (2005) 171-177.
- [78]M.A. Barlaz, R.B. Green, J.P. Chanton, C.D. Goldsmith, G.R. Hater, Evaluation of a biologically active cover for mitigation of landfill gas emissions, *Environ. Sci. Technol.* 38 (2004) 4891-4899.
- [79]M. Humer, P. Lechner, Methane Oxidation in Compost Cover Layers on Landfills, in: T.H. Christensen, R. Cossu, R. Stegmann (Eds.), *Seventh International Waste Management and Landfill Symposium*, Vol. 3, CISA-Environmental Sanitary Engineering Center: Cagliari, Italy, Sardinia, 1999.
- [80]M. Humer, P. Lechner, Design of a Landfill Cover Layer to Enhance Methane Oxidation Results From a Two Year Field Investigation, in: T.H. Christensen, R. Cossu, R. Stegmann (Eds.), *Eighth International Waste Management and Landfill Symposium*, Vol. 2, CISA-Environmental Sanitary Engineering Center: Cagliari, Italy, Sardinia, 2001.
- [81]J. Berger, L.V. Fornes, C. Ott, J. Jager, B. Wawra, U. Zanke, Methane oxidation in a landfill cover with capillary barrier, *Waste Manage.* 25 (2005) 369-373.
- [82]K. Spokas, J. Bogner, J.P. Chanton, M. Morcet, C. Aran, C. Graff, Y. Moreau-Le Golvan, I. Hebe, Methane mass balance at three landfill sites: What is the efficiency of capture by gas collection systems?, *Waste Manage.* 26 (2006) 516-525.

-
- [83]S. Mor, A. De Visscher, K. Ravindra, R.P. Dahiya, A. Chandra, O. Van Cleemput, Induction of enhanced methane oxidation in compost: Temperature and moisture response, *Waste Manage.* 26 (2006) 381-388.
- [84]S.C. Whalen, R.S. Reeburgh, Moisture and temperature sensitivity of CH₄ oxidation in boreal soils, *Soil Biol. Biochem.* 28 (1996) 1271-1281.
- [85]J.H. Wilshusen, J.P.A. Hettiaratchi, A. De Visscher, R. Saint-Fort, Methane oxidation and formation of EPS in compost: effect of oxygen concentration, *Environ. Pollut.* 129 (2004) 305-314.
- [86]T. Abichou, J. Chanton, D. Powelson, J. Fleiger, S. Escoriza, Y. Lei, J. Stern, Methane flux and oxidation at two types of intermediate landfill covers, *Waste Manage.* 26 (2006) 1305-1312.
- [87]J. Nikiema, L. Bibeau, J. Lavoie, R. Brzezinski, J. Vigneux, A. Heitz, Biofiltration of methane: An experimental study, *Chem. Eng. J.* 113 (2005) 111-117.
- [88]EC, Strategy paper for reducing methane emissions (Communication from the Commission to the Council and to the European Parliament), European Commission, 1996.
- [89]NETC, National Atmospheric Emissions Inventory 1970–1998, The U.K. National Air Quality Information Archive, National Environmental Technology Centre, U.K. Department of the Environment, 1999.
- [90]EA, The Landfill Directive: New rules on landfilling waste, Environment Agency, 2007. <http://www.environment-agency.gov.uk/business/444217/444663/landfill/>.
- [91]Defra, Municipal Waste Management, Department for Environment, Food and Rural Affairs, 2006. www.defra.gov.uk/environment/statistics/wastats/index.htm.
- [92]EC, Council Directive On The Landfill of Waste (1999/31/EEC), L182/1. European Commission, 1999.
- [93]DEFRA, Operational Waste Facilities in England and Wales., London, Department of Environment, Food and Rural Affairs, 2006.
- [94]DETR, Waste Strategy 2000: England and Wales, London, Department of the Environment, Transport and the Regions: The Stationary Office, 2000.
- [95]M. Negre, S. Zancolo, E. Malusa, G. Piccone, Fertilisation of an urban park soil with municipal solid waste compost. Effects on soil properties and plant growth, *Fresenius Environ. Bull.* 15 (2006) 200-206.
- [96]G.M. Zinati, Y.C. Li, H.H. Bryan, Utilization of compost increases organic carbon and its humin, humic and fulvic acid fractions in calcareous soil, *Compost Sci. Util.* 9 (2001) 156-162.
- [97]EC, The European Parliament and of the Council of 8 May 2003 on the promotion of the use of biofuels or other renewable fuels for transport (2003/30/EC), L 123/42-46. European Commission, 2003.