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Chapter 2

BIOTIC LANDFILL CH_4 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 (CH_4) and carbon dioxide (CO_2). CH_4 has a global warming potential 23 times higher than CO_2, and the largest source of CH_4 emission is from landfill sites where it escapes through the landfill cover into the atmosphere. Thus even small reductions in landfill CH_4 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 CH_4 emission abatement can be achieved by CH_4 oxidizing bacteria (methanotrophs), which build up naturally very slowly in landfill cover soils, with low CH_4 oxidation rates resulting in high CH_4 surface fluxes from landfill soon after cover application. Bio-waste compost is investigated as an alternative landfill cover to maximize landfill CH_4 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 CH_4 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 biodegradeable 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 – CH_4 producing stage could last for 100 years. At near steady-state conditions, LFG is typically composed of approximately 55% CH_4, 40% CO_2, 5% N_2, with non CH_4 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].

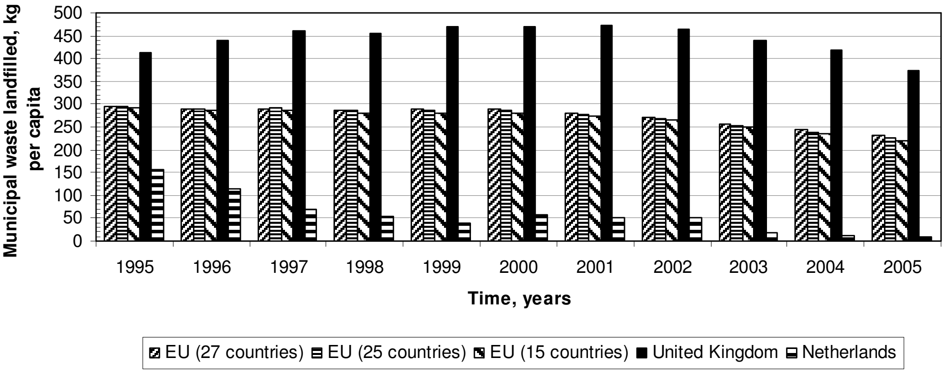

Figure 1. Municipal waste disposed of through landfill in Europe [6].

The composting process naturally produces some CH_4, CO_2, and nitrous oxide (N_2O). Information about N_2O emissions is presently limited. N_2O 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. CH_4 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 CH_4 is much higher than that of CO_2, 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 CH_4 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 CH_4 emissions and a long-term strategy in order to minimize LFG emissions is thus required.

Table 1. Ozone depletion and global warming potentials

Chemical	*CFC/HCFC no.*	*Ozone depleting potential*	*Global warming potential*
CO_2			1
CH_4			21
Chloroform			4
Nitrous oxide			310
DichloroCH_4(methylene chloride)			9
1-Chloro-1,1-difluoroethane	HCFC-142b	0.065	2300
ChlorodifluoroCH_4	HCFC-22	0.055	1900
ChlorofluoroCH_4	HCFC-31	0.020	
2-Chloro-1,1,1-trifluoroethane	HCFC-133a	0.060	
ChlorotrifluoroCH_4	CFC-13	1.0	14000
DichlorodifluoroCH_4	CFC-12	1.0	10600
DichlorofluoroCH_4	HCFC-21	0.040	
1,1,1,2-Tetrafluorochloroethane	HCFC-124	0.02–0.04	620
Trichlorofluoroethane (Freon 113)	HCFC-131	0.007–0.050	
TrichlorofluoroCH_4	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 CH_4 emissions have declined from 2.4×10^9 kg in 1990 to an estimated 9.3×10^8 kg in 2005, a reduction of 61% [11]. Despite these efforts and the resulting CH_4 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. CH_4 oxidation) interactions between the gas and the surrounding rocks and minerals. These processes can alter the relative concentration of CH_4 and CO_2, 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 CH_4 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 CH_4 that would otherwise escape from the landfill to the atmosphere, thereby reducing its impact on global warming. Biological CH_4 oxidation by methanotrophic bacteria (MTB) is ubiquitous in the environment. Some MTBs (gamma proteobacteria) predominate under atmospheric CH_4 concentrations (1.7 ppm), while others (alpha proteobacteria) are dominant under elevated CH_4 levels. These organisms have been well researched in landfill cover soils, rice paddies, wetlands, bogs etc., identifying their ability to oxidize CH_4 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 CH_4 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 CH_4

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.

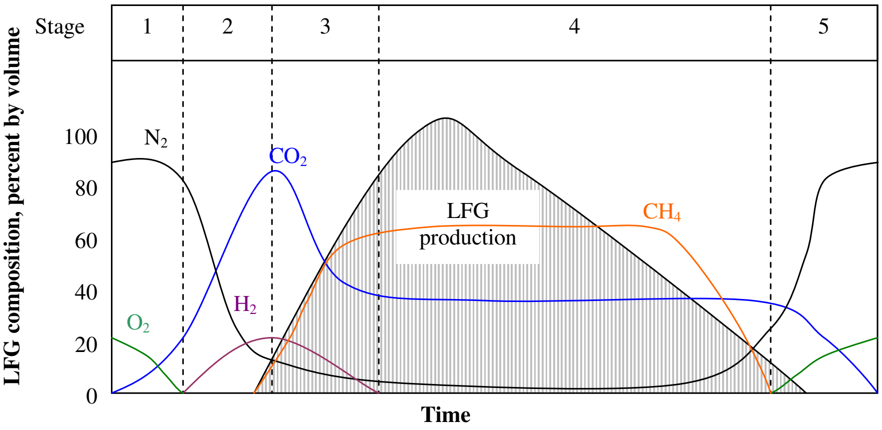

Figure 2. Idealized representation of landfill gas generation.

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.

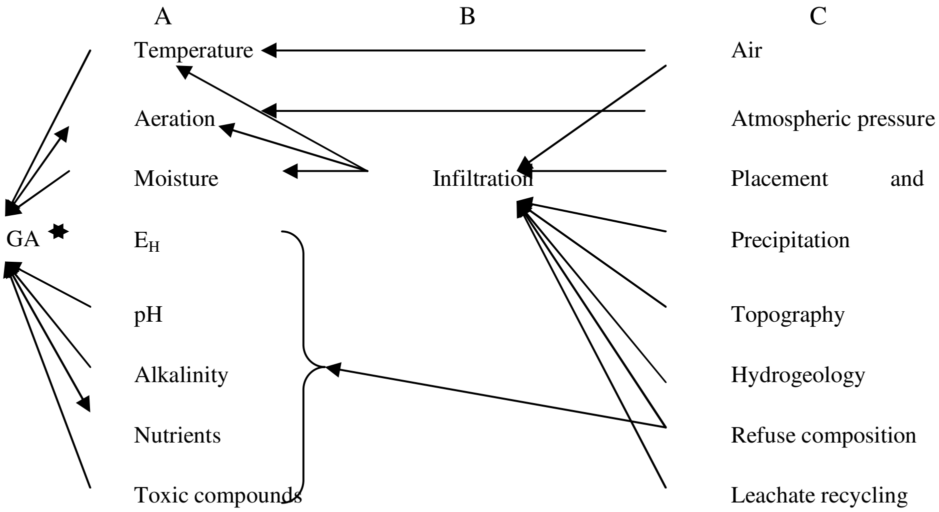

Figure 4. Factors influencing LFG production and composition in landfill sites.

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 m^3 ton^{-1} yr^{-1} and a waste density close to 1 m^3 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 - 90ºC can be encountered. In the majority of landfills, temperatures thereafter will subside, stabilizing at an optimum of 35 - 45ºC 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 - 15ºC. 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 CH_4 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 CH_4 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 CH_4 production.

C. Landfill CH_4 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 CH_4 is produced. CH_4 generated in landfills is partitioned into CH_4 recovered, emitted to the atmosphere, oxidized by CH_4 oxidizing bacteria (methanotrophs), laterally migrated, and internally stored in the landfill volume [21]. It has been reported that approximately 60% of the CH_4 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 CH_4 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 CH_4 in 2005 exceeds by far the natural range of the last 650000 years, as determined from ice cores. The latest global landfill CH_4 emissions estimates range from 16×10^{12} to 57×10^{12} g yr^{-1}, and global landfill CH_4 recovery estimates in 1996 was 3.8×10^{12} g yr^{-1} [24]. CH_4 has an atmospheric lifetime of about 10 yr and a global warming potential 23 times higher than CO_2 (mole basis, 100 yr timeframe) [25], thus even small reductions in landfill CH_4 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 CH_4 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. CH_4 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 CH_4 Abatement

Various approaches are currently being investigated to reduce landfill CH_4 emissions. When landfill gas extraction is economically not beneficial (i.e. from smaller and older landfills with low CH_4 generation rates), flaring is usually recommended [28]. Biotic CH_4 removal systems offer the same CH_4 conversion to CO_2 as flaring. However, unlike combustion, not every molecule of CH_4 consumed biotically is converted to CO_2. As much as 85% (mole/mole) of the CH_4 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 CH_4 oxidation indicated that soil microbes removed up to 10% of the CH_4 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].

CH_4 escaping from landfills can be oxidized by methanotrophic bacteria, which are ubiquitous in landfill soils [34-37], and can use CH_4 as their sole source of carbon and energy [36], functioning as the major biological sink for CH_4 in the environment and converting around half the carbon from its oxidation into biomass whilst respiring the rest as CO_2. 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 CH_4 and therefore predominate in a low CH_4 atmosphere. Type II methanotrophs are in the class Alpha-proteobacteria - have a low affinity for CH_4 and are prevalent under conditions of elevated CH_4 [36]. The highest CH_4 oxidation rates reported in the literature are up to 500 g CH_4 m^{-2} day^{-1} in laboratory studies and up to 150 - 200 g CH_4 m^{-2} day^{-1} in field studies [31,38,39]. These shifts in CH_4 oxidation rates, may be accompanied by shifts in the methanotroph populations in soils in response to environmental stimuli such as changes in concentrations of CH_4 and O_2, temperature, pH and nitrogen sources [36,40,41].

B. Effect of Environmental Factors on CH_4 Oxidation in Bio-Waste Compost

Several factors have been shown to influence the extent of CH_4 oxidation in landfill cover soils. Temperature and soil moisture are reported among the most important environmental variables for CH_4 oxidation [42], however other factors should also be considered.

CH_4 oxidation temperatures

Microbial CH_4 uptake shows seasonal temperature dependence, with an optimum temperature in the range of 15 - 35 ºC [39,43-45]. Above 40 ºC, CH_4 oxidation rates decline and drop to zero by 50ºC and slow noticeably at cooler temperatures of 2 – 5 ºC [39]. Table 2 gives values for methane oxidation rates. The timescale should also be considered, since exposure to temperatures exceeding 30ºC for long periods can lead to a loss of microbial activity due to enhanced cell decay [40].

Borjesson *et al.* [33] reported slightly different CH_4 oxidation capacities within the range of 1.17 and 1.57 µmol CH_4 (g dw soil)$^{-1}$ h^{-1} at 20 ºC in three soils. These capacities are similar to values for landfill covers consisting of mineral soils (0.998 [31], 1.62 [38], µmol CH_4 (g dw soil)$^{-1}$ h^{-1}), whereas cover soils rich in organic matter are known to have higher CH_4 oxidizing capacities (10.8 [46], 25 [47] µmol CH_4 (g dw soil)$^{-1}$ h^{-1}). Additionally the CH_4 consumption rates were markedly affected by shifts in temperature, and only type I methanotrophs grew at low temperatures (3 - 10 ºC), but both types grew at 20 ºC. Borjesson *et al.* [29] estimated microbial CH_4 removal using field comparisons of ^{13}C to ^{12}C isotope ratios, and trials at 0 ºC showed no evidence of microbial CH_4 consumption. Christophersen *et al.* [48] reported that in laboratory incubations of landfill soil under high headspace CH_4, 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 ºC, although the response was significantly less than the maximum at 15 ºC, which was 1.9×10^{-2} µg g^{-1} h^{-1}.

Table 2. Methane (CH_4) oxidation rates presented by different authors for samples from landfill cover soils.

Temperature, ºC	*Maximum CH_4 oxidation rate reported, µg CH_4 g^{-1} h^{-1}*	*Reference*
25	2.5 µg (g ww)$^{-1}$ h^{-1}	Whalen *et al.* [43] Humer and Lechner [64]
20	27.2 µg (g dw)$^{-1}$ h^{-1}	Kightley *et al.* [31]
15	0.01 µg (g dw)$^{-1}$ h^{-1}	Boeckx *et al.* [41]
25	152 µg (g dw)$^{-1}$ h^{-1}	Borjesson *et al.* [46]

Although Dunfield *et al.* [49] and Whalen *et al.* [43] reported that rates of CH_4 oxidation are controlled by temperature, Boeckx *et al.* [41] found that temperature only had a slight effect on CH_4 oxidation rates stating that the ideal temperature (20-30^{0}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 O_2 and CH_4 to the cells, and for CO_2 and waste products away from the cells. CH_4 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 CH_4 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 CH_4 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 CH_4 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 CH_4 oxidation rate reduction of 56% at moisture saturation. Low soil moisture content limits CH_4 oxidation in landfill soils. Adamsen and King [55] observed that decreasing the water content to 5% resulted in dramatic decreases in CH_4 oxidation rates. High soil moisture may lead to an inhibited aeration and thus high CH_4 production. CH_4 oxidation is fairly insensitive to oxygen concentration as long as it is above 3% v/v [32,56], however it is sensitive to CH_4 concentration [22,44,57]. Bender and Conrad [22] reported that four different incubated soils under elevated CH_4 concentration (> 100 μl CH_4 l^{-1}) showed a lag phase during which CH_4 concentration decreased only very slowly. However, the decrease of CH_4 concentration eventually accelerated, and reached a maximum after a certain time (induction of CH_4 oxidation). Without O_2 in the gas phase no CH_4 oxidation was detectable. The four soils investigated, which were different in texture, pH, Cu^{2+}, C content and water content (23 - 33% H_2O), showed different induction of CH_4 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 ºC temperature. Bender and Conrad [22] also observed that the induction process slowed down following an addition of Cu^{2+}, and when the soil aggregate size decreased from > 2 to < 0.05 mm diameter.

Water produced and released through CH_4 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 CH_4 oxidation horizon, presumably caused by a lack of oxygen at these depths.

Chandrakanthi *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 CH_4 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 CH_4 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. Methanothrops 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 CH_4 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 CH_4 uptake, but when amendments of KNO_3, vitamins, EDTA or $FeSO_4$ were added to landfill soil after the soil had been incubated for several thousand hours with CH_4, did not show stimulation over 2 - 3 day incubation periods [64]. Ammonium addition enhanced CH_4 uptake in short-term incubations [22,38], while in long-term incubations it inhibited CH_4 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 CH_4 oxidation, while addition of phosphate presented no effect [31].

Bender and Conrad [22] in a study of acidic peat samples found that CH_4 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 CH_4 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. CH_4 oxidation potential was 72 g CH_4 m^{-2} d^{-1} (at 20ºC), which was within the range of values given by other authors for the CH_4 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 CH_4 content increased steadily (up to 56%) while the O_2 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 CH_4 emission inversely correlated with absolute values of surface atmospheric pressure.

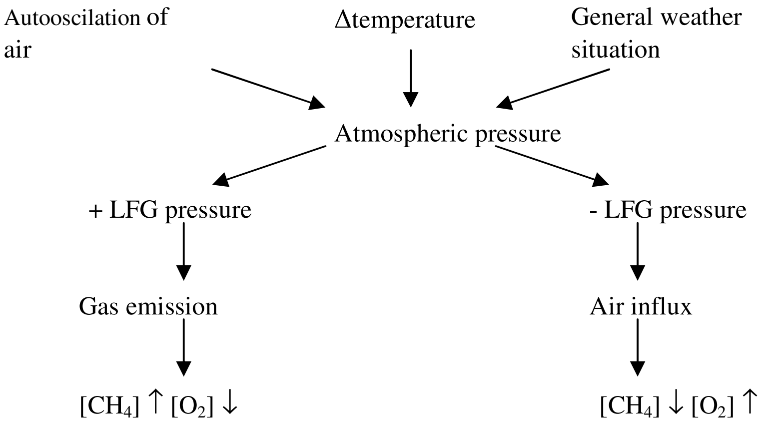

Figure 5. Conceptual diagram on the regulation on landfill gas emission on a landfill site

(Adapted from Gebert and Groengroeft [67]). Legend: Δ = difference, ↑ = increasing, ↓ = decreasing.)

Coupled Effects

Temperature and moisture are important environmental factor that may affect landfill CH_4 emission, but complex relationships exist between temperature, moisture, the CH_4 oxidizing capacity of cover materials, and their physical properties [69]. Additionally, a coupled effect on the extent of CH_4 oxidation may occur. Christophersen *et al.* [48] reported that CH_4 oxidation rates depend significantly on the organic matter content of he 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 ºC and 15 ºC 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 constrains.

CH_4 oxidation in conventional soil covers, typically of older landfills, has been reported to be effective in reducing the amount of CH_4 emitted [29,45,71]. However, one major limitation is that methanotroph communities build up very slowly in landfill cover soils [46], with low CH_4 oxidation rates resulting in high CH_4 surface fluxes from landfill, soon after cover application. CH_4 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]. CH_4 oxidation rate levels greater than 1,000 g CH_4 m^{-2} d^{-1} have been obtained in a thick compost amended engineered cover material [73].

Alternative cover materials with high initial CH_4 oxidizing capabilities (i.e. bio-waste compost) could reduce landfill CH_4 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 CH_4 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 CH_4 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

CH_4 oxidation rates in conventional soils have been extensively studied [18], but there are fewer studies on environmental factors influencing CH_4 oxidation in compost.

Humer and Lechner [14,73] studied MSW compost and sewage sludge compost as cover material to increase the oxidation of CH_4 and found that complete CH_4 oxidation is possible. They reported that CH_4 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 CH_4 flux equivalent to 400 – 550 l CH_4 m^{-2} d^{-1}. Working in CH_4 fed columns, sewage sludge compost was shown to support higher CH_4 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 CH_4 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 CH_4 oxidation layer [80]. Humer and Lechner [80] further investigated the effect of temperature on CH_4 oxidation using compost-filled columns in a climate-controlled chamber. The tests started at a temperature of 18 ºC, and after an adaptation time of about 6 days, all of the supplied CH_4 (approximately 150 l CH_4 m^{-2} day^{-1}) were removed. They reported that a constant and high CH_4 removal was obtained across a temperature range of 5 ºC to 30 ºC. When the temperature was reduced to approximately 4 ºC, the removal rates were 70 – 80% of those measured at 18 ºC. CH_4 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 O_2 g^{-1} dry matter

Streese and Stegmann [61] investigated CH_4 oxidation in two experimental plants, a bench-scale plant (total filter volume 5 l) and a pilot plant (total filter volume 4 m^3). 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 CH_4 m^{-3} d^{-1} using a constant inlet of 2.5% v/v CH_4 and compost as biofilter material. A mixture of compost, peat and wood fibres showed stable and satisfactory degradation rates approx. 480 g m^{-3} d^{-1} at mean inlet concentration of 3% v/v CH_4 over the period of one year. They demonstrated that bio-waste compost can successfully oxidize CH_4; 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 CH_4 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 CH_4 removal at a 14 ha operating landfill in Austria. Although a gas collection system was in place, CH_4 emissions of 0.58 g m^{-2} d^{-1} were detected. They further confirmed that landfill CH_4 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% CH_4 atmospheric capture as compared to 10 – 50 % estimates of CH_4 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 CH_4 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 CH_4 produced in the landfill reaching the bottom of the respective cover. They investigated the CH_4 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, the 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 CH_4 emissions. They concluded that following 33 weeks operation of an experimental plant, cover material showed an adequate microbial oxidation of CH_4 in landfill gas between 80% and 95% even under low temperatures (5ºC), and that aeration of the cover soil was the main influencing factor for CH_4 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 CH_4 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 CH_4 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 CH_4 oxidation in compost. Test bottles were injected with 10 ml of 100% CH_4, leading to an initial CH_4 concentration of about 5 - 10%. They reported that the influence of moisture content (29 -110%) and temperature (7 – 40^0C) on CH_4 oxidation was time-dependent (days). Optimal moisture content of two garden waste composts, G1 (31% organic matter) and G3 (52% organic matter) for CH_4 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 30ºC in the long term CH_4 oxidation, and much lower activity at 7ºC. 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 CH_4 concentrations normally > 30%

Abichou *et al.* [86] monitored CH_4 emissions at 15 cm thick non-vegetated intermediate cover soil overlying 1 yr old waste and a 45 cm thick vegetated intermediate cover soil overlaying 7 yr old waste. They reported that arithmetic means of the measured fluxes were 54 and 22 g CH_4 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 CH_4 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 CH_4 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 CH_4 m^{-2} d^{-1} and -0.389 to 22.2 g CH_4 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 CH_4 m^{-2} yr^{-1}). Percent oxidation of CH_4 was calculated from stable isotope data. Over the entire course of the experiment, the percent of CH_4 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 CH_4 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 CH_4 oxidation at landfills in warmer climates. Conservative estimates put the average annual percent CH_4 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% CH_4 oxidation [78]. These values are significantly higher than the average annual percent CH_4 oxidation of 10% for a landfill in New England [32], where CH_4 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 CH_4 oxidation. During summer, CH_4 oxidation was near 100%, while CH_4 oxidation could not be detected during the winter, once the temperatures dropped below 0ºC [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 CH_4 oxidation efficiency at different levels of microbe available N (NH_4^+ / NO_3^-). They found that inorganic beds were more effective supporters of microbial CH_4 oxidation than organic beds under conditions of elevated available N (> 0.25 g l^{-1}) at CH_4 concentration of 7000 - 7500 ppmv. CH_4 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 CH_4 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 CH_4 emission are available during the last ten years. Furthermore, efforts have focused on the effect of environmental factors on the rate of CH_4 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 CH_4 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 CH_4 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 CH_4 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 in 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	Landfill (Scotland) Regulations 2003 SI 2003 No. 235
	Pollution Prevention and Control (England and Wales) Regulations 2000, SI 2000 No. 1973
	Pollution Prevention and Control (Scotland) Regulations 2000, SI 2000 No. 323
	Air Quality (England) Regulations 2000, SI 2000, No. 928
	Air Quality (Wales) Regulations 2000, WSI 2000, No. 1940
	Air Quality (Scotland) Regulations 2000, SSI 2000, No. 97
	Air Quality (Scotland) Amendment Regulations 2002, SSI 2002, No. 297
	Air Quality Limit Values Regulations 2001, SI 2001 No. 2315
	Air Quality Limit Values (Wales) Regulations 2002, WSI 2002 No. 3183
	Air Quality Limit Values (Scotland) Regulations 2001, SSI 2001, No. 224
	Waste Management Licensing Regulations 1994, SI 1056 as amended
	Control of Substances Hazardous to Health Regulations 2002, SI 2002, No. 2677
	Contaminated Land (England) Regulations 2000, SI 2000, No. 227s
	Contaminated Land (Wales) Regulations 2001, WSI 2001, No. 2197
	Town and Country Planning General Development Order 1988, SI 1998, No. 1813
	Town and Country Planning (General Permitted Development) Order 1995, SI 1995, No. 418
	Town and Country Planning (General Development Procedure) Order 1995, SI 1995, No. 419
	Town and Country Planning (General Development Procedure (Scotland) Order 1992 (as amended)
	Town and Country (Environmental Impact Assessment) (England and Wales) Regulations 1999, SI 1999, No. 293
	Environmental Impact Assessment (Scotland) Regulations 1999, SSI 1999, No. 1
	Planning (Control of Major-Accident Hazards) (Scotland) Regulations 2000, SSI 2000, No. 179
Guidance	Planning Policy Guidance Note 10 Planning and waste management, 1999
	Planning Policy Guidance Note 22 Renewable energy, 1993
	Planning Policy Guidance Note 23 Planning and pollution control
	Planning Guidance (Wales) Planning policy, 1999 (under review)
	Technical Advice Note (Wales) 8 Renewable energy, 1996
	Technical Advice Note (Wales) 21 Waste, 2001
	National Planning Policy Guideline 6 Renewable energy, 2000 (applies in Scotland)
	National Planning Policy Guideline 10 Planning and waste management, 1996 (applies in Scotland)
	Planning Advice Note 51 Planning and environmental protection, 1997 (applies in Scotland)
	Planning Advice Note 58 Environmental impact assessment, 1999 (applies in Scotland)
	Planning Advice Note 63 Waste management planning, 2002 (applies in Scotland)
	Planning Advice Note 45 Renewable energy technologies (revised 2002) (applies in Scotland)

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 CH_4 and CO_2. The EC Landfill Directive 1999 [92] imposes strict engineering requirements on landfills, requiring landfill CH_4 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 CH_4 emission is from landfill sites where CH_4 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 CH_4 abatement. It is here suggested that in order to abate CH_4 emission from landfill sites, bio-waste compost obtained from waste management facilities could be applied as a landfill cover. By doing so, global CH_4 emissions will be reduced since composting is an aerobic process (although CH_4 emissions may occur due to anaereobic pockets) that produces mostly CO_2, landfilling the same BMSW fraction would in itself produce significantly larger quantities of CH_4. A posterior application of compost as a landfill cover will additionally reduce CH_4 emissions through increased levels of CH_4 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 CH_4 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 CH_4 oxidation represents an attractive alternative of the reduction of CH_4 coming out from landfills. Especially for those with lower gas emission rates (55 g CH_4 m^{-2} d^{-1}), like old landfills or landfills containing biological pretreated 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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