# EXPERIMENTAL INVESTIGATIONS OF MICROBIAL METHANE OXIDATION IN VEGETATED LANDFILL COVER SOIL OPERATED IN THE TROPICAL REGION

## INTRODUCTION

### 1. Background

Landfill is a conventional method for the disposal of municipal solid waste in many developing countries. Two main environmental impacts caused by landfilling the wastes which should be managed properly are leachate and landfill gases. The anaerobic decomposition of municipal solid waste in landfill generates landfill gas which composes of approximately 50-60% methane (by volume), 40-50% carbon dioxide and other trace gases including ammonia ($NH_3$), nitrogen ($N_2$), hydrogen ($H_2$), hydrogen sulfide ($H_2S$) and volatile organic compounds (VOCs) (Kightley *et al.*, 1995; Czepiel *et al.*, 1996). In conventional landfill operations, the leachate treatment process is partially managed while landfill gas management is normally disregarded, especially in small and medium landfills in which utilization of landfill gas for energy recovery purposes is not feasible. However, most landfill gases are recognized as greenhouse gases which cause the rising of ambient temperature; the so-called "greenhouse effect" or "global warming". Moreover, methane also has a global warming potential (GWP) of about 23 times higher than carbon dioxide in a 100-year time horizon (IPCC, 2001). Therefore, proper management of landfill gas, especially methane, is necessary for landfill operations.

One attractive way of minimizing methane emission from landfill relies on biochemical process in the final landfill cover soil. Specific microorganisms in this cover layer, methane-oxidizing bacteria or methanotrophs, are able to use methane as their sole carbon and energy sources and completely degrade methane to carbon dioxide through their metabolism under aerobic condition, known as "microbial methane oxidation" (Hanson and Hanson, 1996). Many studies demonstrated the performance of landfill cover soil in reducing methane through methane oxidation. However, this reaction is influenced by many factors such as type of soil, soil depth, temperature, porosity, moisture content, oxygen availability, organic and nutrient content, etc (Whalen *et al.*, 1990; Kightley *et al.*, 1995; Boeckx and Cleemput, 1996; Visvanathan *et al.*, 1999; Humer and Lechner, 2001a; Park *et al.*, 2002). Moreover, water and oxygen contents in soil are very important factors for methane oxidation. Consequently, proper design and management of final landfill cover soil under the appropriate conditions is necessary if this low-cost option for effective methane minimization is to be adopted.

Recently, introduction of compost as final cover soil has been reported as an alternative landfill operation for effective methane oxidation due to its properties of loose texture and high porosity encouraging oxygen penetration into soil pores, high water retention capacity supporting adequate moisture content for methanotrophs, and supplemental organic matters and nutrients stimulating methanotrophic activity (Christophersen *et al.*, 2001; Humer and Lechner, 2001a; Humer and Lechner, 2001b;

Streese and Stegmann, 2003; Wilshusen *et al.*, 2004; Mor *et al.*, 2006). These properties of compost possibly provide favorable conditions for methane oxidation in final landfill cover soil.

Furthermore, the provision of vegetation on landfills is also attributed to an increase of soil oxygen content by transporting oxygen through plant vascular systems (Schütz *et al.*, 1991; Chanton, 2005) and then stimulating methane oxidation. In addition, some researches also notice that the plant rhizosphere provides a beneficial environment for methanotrophs (Curl and Truelove, 1986; Maurice, 1998; Hilger *et al.*, 2000b).

This study proposes to investigate the enhancement of methane oxidation in the combined options of landfill operation, namely introduction of compost as landfill cover soil and application of vegetation practice on the top soil. Furthermore, simulation of tropical climate is also performed in this study with wet (rainy season) and dry (summer and winter) condition operations. Besides rainwater irrigation, leachate is also applied to landfill cover soil for simulating wet condition in order to maintain proper moisture content for methanotrophic activity and presumably provide some beneficial effects directly to methane oxidation. Moreover, this application of leachate also substantially reduces leachate volume which needs to be treated and discharged to the environment.

This study is examined in three phases including (1) methane oxidation study in various landfill cover materials, (2) methane oxidation study in the vegetated landfill cover system, and (3) methane oxidation study under wet and dry conditions. First, the effect of compost is investigated in comparison with sandy loam soil and the mixture of compost and soil. Secondly, effect of vegetation (tropical grasses) in compost cover is studied. These two experiments are examined under wet condition of tropical climate with rainwater or leachate irrigation to investigate the effect of leachate on methane oxidation and also on plant growth. Finally, effect of seasonal variation in tropical regions is considered by comparison of methane oxidation under wet and dry conditions. This experiment also studies the landfill cover systems both with and without vegetation.

## 2. Objectives of the Study

This study focuses on improvement of final landfill cover system for enhancement and sustenance of methane oxidation, as summarized in the following objectives:

1) To investigate effects of compost as landfill cover material on methane oxidation in comparison with different cover materials.
2) To investigate effects of vegetation on methane oxidation.
3) To investigate effects of leachate irrigation on methane oxidation and plant growth.
4) To investigate methane oxidation efficiency over a year duration in the tropics with seasonal variation of wet (rainy season) and dry (summer and winter) conditions.
5) To determine the moisture variation and water balance in simulated landfill cover systems under wet and dry conditions.

## 3. Scope of the Study

This study is performed through laboratory-scale experiments as follows:

1) Column experiments are conducted to simulate final landfill cover systems by purging with synthetic landfill gas ($CH_4$:$CO_2$ = 60:40).
   1.1) Three types of landfill cover materials, i.e. sandy loam, sandy loam/compost mixture and compost, are used in the study of methane oxidation efficiency in different cover materials.
   1.2) Two species of tropical grasses, dixie grass (*Sporobolus virginicus*) and torpedo grass (*Panicum repens*), are employed in the study of methane oxidation efficiency in simulated landfill cover soil with vegetation.
   1.3) The operated conditions with and without irrigation are performed according to simulation of wet and dry conditions in the tropics. Leachate and rainwater are used in the wet condition experiment.
   1.4) Parameters observed in these column experiments are
      - Gas parameters in terms of gas concentrations (determined by GC technique), and methane oxidation rate
      - Microbiological parameters in terms of methanotrophic types and populations (identified by FISH technique), and EPS production
      - Soil physical and chemical properties
      - Plant growth indexes
      - Soil permeate characteristics
2) Batch experiments are conducted to investigate methanotrophic activity by incubating soil samples in serum bottles. Soil samples used in these experiments include:
   2.1) Soil samples from the column experiments
   2.2) Soil samples with nitrogen and organic amendments

# LITERATURE REVIEW

## 1. Introduction

### 1.1 Greenhouse effect

The earth's climate is fueled by the sun. Most of the sun's energy, called solar radiation, is absorbed by the earth, but some is reflected back into space. Clouds and a natural layer of atmospheric gases absorb a portion of earth's heat and prevent it from escaping into space. This keeps the earth warm enough for life and is known as the natural greenhouse effect. Without the natural greenhouse effect, the earth's average temperature would be much colder, and the earth would be uninhabitable. The greenhouse effect is being increased by the release of certain gases into the atmosphere that absorbs the thermal infrared radiation emitted by the surface of the earth and then causes the rising of ambient temperature. This is called global warming and the certain gases contributing to this global warming are greenhouse gasses.

Changes in the atmospheric concentrations of these greenhouse gases can alter the balance of energy transfers between the atmosphere, space, land, and oceans. A gauge of these changes is called radiative forcing, which is a simple measure of changes in the energy available to the earth-atmosphere system. Figure 1 shows the phenomena of greenhouse effect.

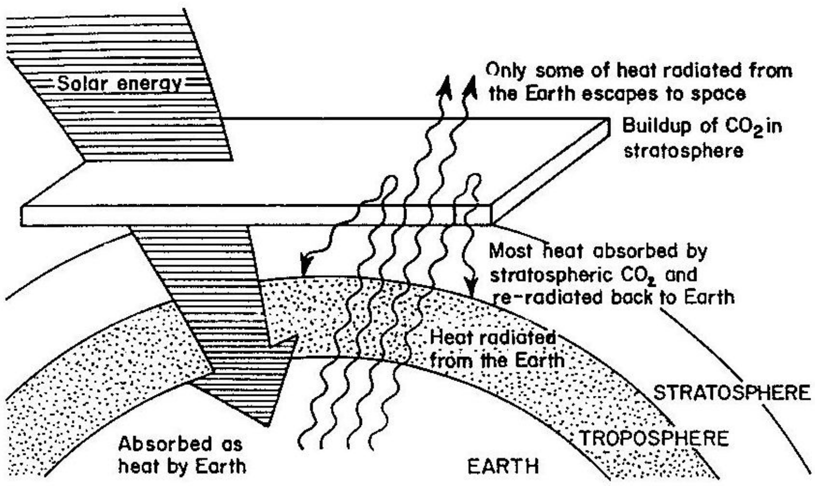



**Figure 1** Phenomena of greenhouse effect

Source: Pokherl (1998)

Naturally occurring greenhouse gases include water vapor ($H_2O$), carbon dioxide ($CO_2$), methane ($CH_4$), nitrous oxide ($N_2O$), and ozone ($O_3$). Moreover, there are a number of entirely anthropogenic greenhouse gases in the atmosphere, namely several classes of halogenated substances that contain fluorine, chlorine, or bromine (i.e. hydrofluorocarbons, HFCs; perfluorocarbons, PFCs; chlorofluorocarbons, CFCs; sulphur hexafluoride, $SF_6$; perfluoromethane, $CF_4$). The literature reviews have clear evidences that human activities have affected concentrations, distributions and life cycles of these gases (shown in Table 1). Furthermore, greenhouse gases vary in atmospheric life time and in radiative effects, also known as global warming potential (GWP) which defines the warming effects caused by an emission of 1 kg of a greenhouse gas relative to that of 1 kg of carbon dioxide, over a fixed time horizon. The global average surface temperature of the earth has increased by between 0.45 ± 0.15°C over the 20$^{th}$ century (IPCC, 2001).

**Table 1** Global atmospheric concentration (ppm), rate of concentration change (ppb/yr), atmospheric life time (years) and global warming potential (GWP) of greenhouse gasses

| Atmospheric Variable | $CO_2$ | $CH_4$ | $N_2O$ | $SF_6$ [(1)] | $CF_4$ [(1)] |
|---|---|---|---|---|---|
| Pre-industrial atmospheric conc. | 278 | 0.700 | 0.270 | 0 | 40 |
| Atmospheric conc.(1998) | 365 | 1.745 | 0.314 | 4.2 | 80 |
| Rate of conc. change [(2)] | 1.5 [(3)] | 0.007 [(3)] | 0.0008 | 0.24 | 1.0 |
| Atmospheric lifetime | 50-200 [(4)] | 12 [(5)] | 114 [(5)] | 3,200 | >50,000 |
| 100-year GWP | 1 | 23 | 296 | 22,200 | 5,700 |

Note: [(1)] Concentrations in ppt and rate of concentration change in ppt/yr
[(2)] Rate is calculated over the period 1990 to 1999
[(3)] Rate has fluctuated between 0.9 and 2.8 ppm/yr for $CO_2$ and between 0 and 0.013 ppm/yr for $CH_4$ over the period 1990 to 1999
[(4)] No single lifetime can be defined for $CO_2$ because of the different rates of uptake by different removal processes
[(5)] This lifetime has been defined as an adjustment time that takes into account the indirect effect of the gas on its own residence time
Source: IPCC (2001)

The characteristic of greenhouse gases as shown below:

1) Carbon dioxide ($CO_2$): In nature, carbon is cycled between various atmospheric, oceanic, land biotic, marine biotic and mineral reservoirs. The largest fluxes occur between the atmosphere and terrestrial biota, and between the atmosphere and surface water of the oceans. In the atmosphere, carbon predominantly exists in its oxidized form as carbon dioxide. The carbon dioxide is one of the greenhouse gas chemical compounds, accumulating in the atmosphere as a result of human activities, animal respiration, in the decay or combustion of animal, vegetable matter natural. The emission of carbon dioxide increases, due to the rising of sea water temperature, the increasing of oxidation reaction from organic matters, the decreasing of photo-oxidation from plants, and the combustion from human activities.

2) Methane ($CH_4$): Methane is primarily produced through anaerobic decomposition of organic matters in biological systems. Agricultural processes such as wetland, rice cultivation, enteric fermentation in animals and decomposition of animal wastes emit methane, as does the decomposition of municipal solid wastes. Table 2 lists the global source and sink of methane emission. Methane is removed at

the atmosphere (troposphere) by reacting with the hydroxyl radical ($OH^{\bullet}$) and is ultimately converted to carbon dioxide which has much less GWP than methane. Minor removal processes also include a soil sink and stratospheric reactions.

**<u>Table 2</u>** Estimation of the global source and sink of methane emission

| Reference: | Fung *et al.* (1991) | Hein *et al.* (1997) | Lelieveld *et al.* (1998) | Houweling *et al.* (1999) | Olivier *et al.* (1999) |
|---|---|---|---|---|---|
| Base year: | 1980s | - | 1992 | - | 1990 |
| Natural sources | | | | | |
| Wetlands | 115 | 237 | 225 | 145 | |
| Termites | 20 | - | 20 | 20 | |
| Ocean | 10 | - | 15 | 15 | |
| Hydrates | 5 | - | 10 | - | |
| Anthropogenic sources | | | | | |
| Energy | 75 | 97 | 110 | 89 | 109 |
| Landfills | 40 | 35 | 40 | 73 | 36 |
| Ruminants | 80 | 90[1] | 115 | 93 | 93[1] |
| Waste treatment | - | [1] | 25 | - | [1] |
| Rice agriculture | 100 | 88 | [2] | - | 60 |
| Biomass burning | 55 | 40 | 40 | 40 | 23 |
| Other | - | - | - | 20 | |
| Total source | 500 | 587 | 600 | | |
| Sinks | | | | | |
| Soils | 10 | - | 30 | 30 | |
| Tropospheric OH | 450 | 489 | 510 | | |
| Stratospheric loss | - | 46 | 40 | | |
| Total sink | 460 | 535 | 580 | | |

Note: [1] Waste treatment included under ruminants
[2] Rice included under wetlands
Source: IPCC (2001)

3) Nitrous oxide ($N_2O$): Anthropogenic sources of nitrous oxide emissions include agricultural soils (especially the use of synthetic and manure fertilizers) and fossil fuel combustion (especially from mobile combustion). Nitrous oxide is primarily removed from the atmosphere by the photolytic action of sunlight. The nitrous oxide is an inert gas in troposphere (15 km from earth), but reacts with ozone in stratosphere (> 15 km from earth).

4) Chlorofluorocarbons (CFCs) and Freons include potent global warming gases. Their net radiative forcing effect on the atmosphere is reduced because they cause stratospheric ozone depletion, which is itself an important greenhouse gas in addition to shielding the earth from harmful levels of ultraviolet radiation.

Greenhouse gases significantly impact on temperature rising or global warming. The harmful effect depends on its lifetime in the atmosphere and GWP. Thus, low content of greenhouse gas with long lifetime and high GWP, more affects the global warming than high content of other gases with short lifetime and low GWP.

## 1.2 Landfill method of solid waste disposal

Landfills are the physical facilities used for the disposal of residual solid wastes in the surface soils of the earth. Historically, landfills have been the most common methods of waste treatment in a manner that protects the environment. The modern landfills are also classified according to the types of waste material disposed into them (Tchobanoglous *et al.*, 1993).

1) Sanitary landfills: These landfills are also called modern or engineered landfills which usually have physical barriers such as liners and leachate collection systems and procedures to protect the public from exposure to the disposed wastes. In the past, the term sanitary landfill was used to denote a landfill in which the waste placed in the landfill was covered daily. Nowadays, sanitary landfill refers to an engineered facility for the disposal of municipal solid waste designed and operated to minimize public health and environmental impacts. A sanitary landfill is also sometime identified as a solid waste management unit.

2) Hazardous waste landfills: These landfills are generally constructed to be secure repositories for hazardous waste which is harmful to human health and environment, such as high-level radioactive waste. Landfills for the disposal of hazardous wastes are also called secure landfills. Double liner systems are the norm for these landfills.

3) Inert waste landfills: These landfills receive wastes which are chemically and physically stable and do not undergo decomposition, such as sand, bricks, concrete or gravel.

4) Dumps: They are also called non-engineered landfills without the protective layers required by sanitary landfills. Rodents, odor, air pollution and insects are, therefore, found at the dump surroundings which result in serious public health and aesthetic problems (Vesilind *et al.*, 2002).

Landfilling is the process by which residual solid waste is placed in a landfill. It includes monitoring of the incoming waste stream, placement and compaction of the waste, and installation of landfill environmental monitoring and control facilities. Within the landfill, the biological, chemical, and physical processes are occurred to promote the degradation of wastes and result in the production of leachate (the polluted water emanating from the base of the landfill) and gases.

### 1.3 Landfill gas generation

In general, solid waste in landfill can be decomposed under anaerobic condition to be the emission forms of landfill gas and leachate. This biodegradation process in landfill sites depends on the characteristics of landfill and solid waste, soil oxygen content, temperature, moisture content and nutrient content. Landfill gases usually consist of methane ($CH_4$), carbon dioxide ($CO_2$), nitrogen ($N_2$), oxygen ($O_2$), hydrogen sulfide ($H_2S$), ammonia ($NH_3$), hydrogen ($H_2$) and carbon monoxide (CO). Table 3 shows the quantitative and physical property data of landfill gases in municipal solid waste (MSW) landfill.

**Table 3** Typical constituents found in MSW landfill and their characteristics

| Landfill gases | % (dry volume basis) | Molecular weight | Density [(1)] (g/L) | Specific weight [(1)] ($lb/ft^3$) |
|---|---|---|---|---|
| Methane ($CH_4$) | 45-60 | 16.03 | 0.7167 | 0.0448 |
| Carbon dioxide ($CO_2$) | 40-60 | 44.00 | 1.9768 | 0.1235 |
| Nitrogen ($N_2$) | 2-5 | 28.02 | 1.2507 | 0.0782 |
| Oxygen ($O_2$) | 0.1-1.0 | 32.00 | 1.4289 | 0.0892 |
| Hydrogen sulfide ($H_2S$) | 0-1.0 | 34.08 | 1.5392 | 0.0961 |
| Ammonia ($NH_3$) | 0.1-1.0 | 17.03 | 0.7708 | 0.0482 |
| Hydrogen ($H_2$) | 0-0.2 | 2.016 | 0.0898 | 0.0056 |
| Carbon monoxide (CO) | 0-0.2 | 28.00 | 1.2501 | 0.0781 |
| Trace constituents | 0.01-0.6 | - | - | - |

Note: [(1)] at standard condition (0°C, 1 atm)
Source: Adapted from Tchobanoglous *et al.* (1993)

From Table 3, methane and carbon dioxide are the major landfill gases from biodegradation process under anaerobic condition. The biochemical reaction can be written as (Tchobanoglous *et al.*, 1993)

$$\text{Organic matter (solid waste)} + H_2O \xrightarrow{\text{Bacteria}} \text{Biodegraded organic matter} + CH_4 + CO_2 + \text{Other gases} \quad (1)$$

Figure 2 also shows the degradation of organic matter under anaerobic condition. Typical anaerobic waste digestion processes include (1) Hydrolysis, (2) Fermentation or Acidogenesis, and (3) Methanogenesis.

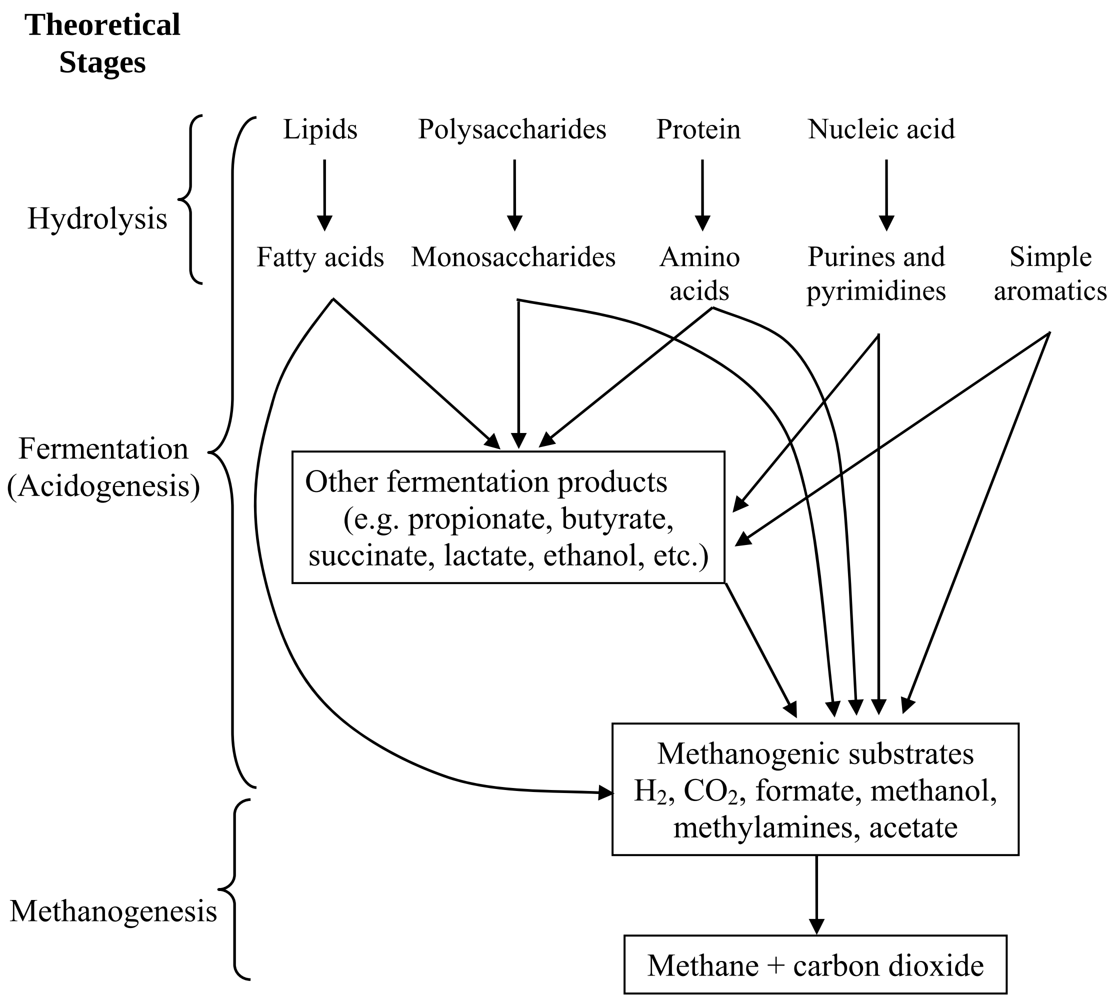



**Figure 2** Biodegradation processes under anaerobic condition

Source: Metcalf and Eddy (2003)

Furthermore, landfill gas generation from the anaerobic digestion process can be divided into five phases (Tchobanoglous *et al.*, 1993; Christensen *et al.*, 1996), as illustrated in Figure 3.

Phase I: Initial adjustment phase. Biological decomposition occurs under aerobic conditions (trapped air in the landfill).

Phase II: Transition phase. Oxygen is depleted and anaerobic conditions begin to develop.

Phase III: Acid phase. This phase involves two steps in the three-step biodegradation process (Figure 2), namely hydrolysis and acidogenesis. Fermentative and acidogenic bacteria (acidogen or acid former) produce volatile fatty acids (VFA), carbon dioxide and hydrogen under anaerobic conditions. The presence of these gases reduces the content of nitrogen.

Phase IV: Methane fermentation phase. This phase is the last step in the three-step biodegradation process (Figure 2), namely methanogenesis. Methanogenic bacteria (methanogen or methane former) start to grow converting the acetic acid and hydrogen gas formed by acid former in acid phase to methane and carbon dioxide.

Phase V: Maturation phase. This phase occurs after the readily available biodegradable organic material has been converted to methane and carbon dioxide in Phase IV. The rate of landfill gas generation significantly diminishes because the available nutrients have been removed with the leachate and the remaining substrates in landfill are slowly biodegraded.

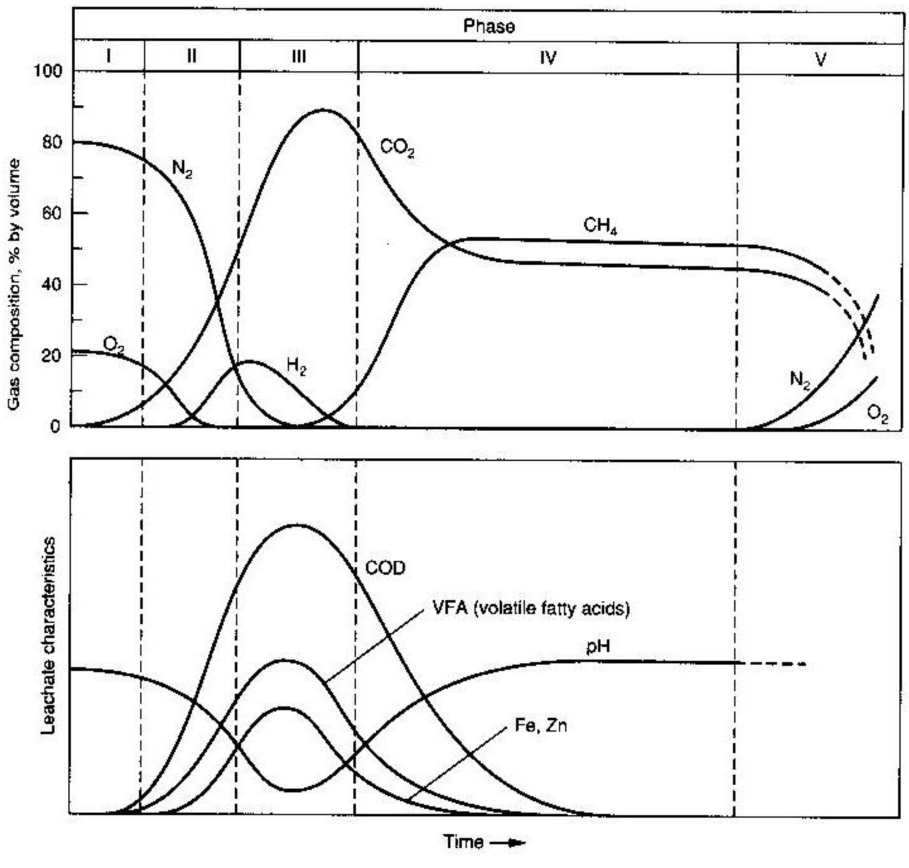



**Figure 3** Generalized phases in the generation of landfill gases

Note: I = initial adjustment phase, II = transition phase, III = acid phase, IV = methane fermentation phase, and V = maturation phase

Source: Tchobanoglous *et al.* (1993)

Production rate of landfill gases, especially methane gas, are different based upon age of landfill, depth of solid waste and type of solid waste. High production rate is usually obtained from mature landfill while old landfill provides with low rate of production. Comparison of methane production rate from different landfills is given in Table 4. It can be seen that methane emission from various landfills are in the range of 72-274 L/m$^2$.d. Hence, this value can be calculated for methane flow rate operated in the simulated landfill cover column experiment. In column area of 0.0177 m$^2$, methane flow rate of 1-4 mL/min can be used.

**Table 4** Methane production rate from various landfills

| Landfill name | Year fill began | Year fill completed | Waste load (kg×10$^9$) | Surface area (m$^2$×10$^4$) | Ave. thickness of waste (m) | Annual $CH_4$ production per kg waste (L/kg.yr) | $CH_4$ production rate [(1)] (L/m$^2$.d) |
|---|---|---|---|---|---|---|---|
| Azura Western Azura, CA | 1953 | - | 6.0 | 22 | 37 | 2.5 | 187 |
| Bradley Sun Valley, CA | 1960 | - | 7.5 | 24 | 37 | 2.5 | 216 |
| Coyote Canyon Irvine, CA | 1964 | 1981 | 19.6 | 162 | n.a. | 2.5 | 86 |
| Hewitt Los Angeles, CA | 1962 | 1975 | 5.6 | 24 | 31 | 2.5 | 158 |
| Mountain View Mountain View, CA | 1975 | 1975 | 0.7 | 8 | 12 | 7.5 | 173 |
| Palos Verdes Rolling hills estates, CA | 1957 | 1975 | 3.4 | 13 | 31 | 3.1 | 216 |
| Scholl Canyon Glendale, CA | 1963 | 1974 | 4.3 | 18 | 27 | 1.2 | 72 |
| Sheldon Arleta Los Angeles, CA | 1962 | 1974 | 2.7 | 15 | 26 | 5.6 | 274 |

Note: [(1)] from calculation
n.a. = not analyzed
Source: Adapted from Emcon (1980)

## 1.4 Landfill cover system

Normally, landfill cover can be divided into two types: (1) interim or intermediate cover and (2) final cover. The interim cover layers are used to cover the wastes as daily cover to control disease vectors and rodents, to minimize odor, litter, and air emission, to minimize leachate production, and to enhance the aesthetic appearance of the landfill site (Vesilind *et al.*, 2002). The primary purposes of the final landfill cover are to minimize infiltration of rain into the soil, to limit uncontrolled release of landfill gases into the atmosphere, to suppress the proliferation of vectors, and to facilitate landscaping of the site to provide a reasonable appearance (Koerner and Daniel, 1997). There are six basic components of a final cover system (Figure 4): (1) surface layer, (2) protection layer, (3) drainage layer, (4) hydraulic/gas barrier layer, (5) gas collection layer, and (6) foundation layer.

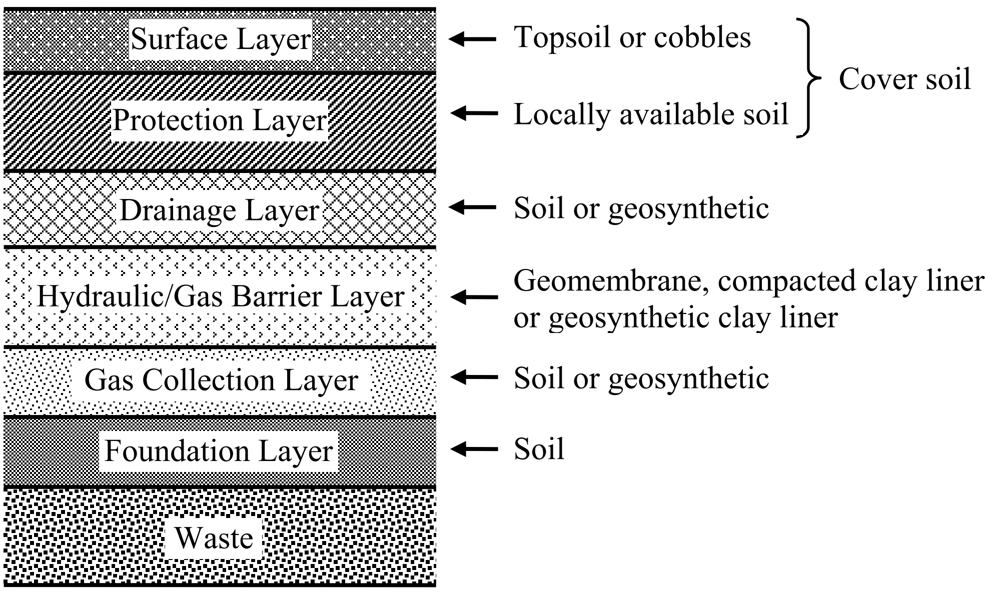



**Figure 4** Typical layers used for final landfill cover

Source: Koerner and Daniel (1997)

Not all components are needed for all final covers. For example, a drainage layer may not be needed in an arid region, or a gas collection layer may be required for some covers but not others, depending upon the requirement of gas collection and management. Additionally, some of cover layers may be combined, such as the surface layer and protection layer are commonly combined into a single layer of soil (cover soil). Likewise, the gas collection layer is often combined as a single layer with the foundation layer. Details of each cover component are noted in Table 5.

**<u>Table 5</u>** Details of general components of final cover systems

| Components | Functions | Materials | Thickness |
|---|---|---|---|
| Surface layer | - Minimize erosion and promote transpiration of water back to the atmosphere<br>- Reduce water infiltration into soil<br>- Increase water runoff at soil surface | - Soil<br>- Cobbles<br>- Asphaltic concrete | - Minimum 150 mm<br>- 450-600 mm (soil)<br>- 75-150 mm (asphaltic concrete) |
| Protection layer | - Store infiltrated water in the cover until evapotranspiration<br>- Physically separate the underlying drainage and barrier layer components and buried waste from burrowing animals and plant<br>- Protect underlying layers from excess wetting/drying and freezing | - Native soil<br>- Cobbles | - 450-900 mm |
| Drainage layer | - Reduce the water head on the barrier layer and infiltration<br>- Drain the overlying protection layer and increase its water storage capacity<br>- Reduce and control pore water pressures in the cover soil, and improve slope stability | - Cohesionless soils e.g. sand or gravel<br>- Geosynthetic materials e.g. geotextile filter and geonet drainage | - Minimum 300 mm |
| Hydraulic/Gas barrier layer | - Directly minimize water percolation through cover and indirectly promote water storage or drainage in the overlying layers<br>- Prevent landfill gases from escaping into the atmosphere | - Geomembranes (GMs)<br>- Geosynthetic clay liners (GCLs)<br>- Compacted clay liners (CCLs) | - Minimum 300-460 mm<br>- 600 mm (clay) |
| Gas collection layer | - Collect gases or VOC from waste decomposition<br>- Allow gases flowing into periodically-spaced collection pipes or vents | - Native soil<br>- Sand, gravel, geonet, geotextile or geocomposite | - Minimum 300 mm (soil) |
| Foundation layer | - Support the overlying layers | - Soil | - Minimum 300 mm |

Source: Data from Koerner and Daniel (1997) and Vesilind *et al.* (2002)

## 2. Methane Oxidation in Landfill Cover Soil

Based on the global methane budget reported by IPCC (2001), the main global methane sinks are chemical reactions in the troposphere and microbial methane oxidation in soils by methane oxidizing bacteria. However, microbial methane oxidation is very important process which reduces methane emission before released to the atmosphere and further accounts for about 80% of global methane consumption (Kighley *et al.*, 1995).

### 2.1 Microbial methane oxidation

Microbial methane oxidation in upland soil is considered to be mainly performed by the specific microorganisms, namely methane-oxidizing bacteria or methanotrophs or methanotrophic bacteria, through their metabolism. These bacteria can use methane as their sole source of carbon and energy for growth by oxidizing methane to carbon dioxide, water and biomass under aerobic condition (Visscher and Cleemput, 2003a) as shown in Eq.(2):

$$CH_4 + 1.5\,O_2 \xrightarrow{\text{Methanotroph}} 0.5\,CO_2 + 1.5\,H_2O + 0.5\,CH_2O \qquad (2)$$

where $CH_2O$ represents biomass. However, in a long time period it can be assumed that biomass will die, decompose, and eventually convert to carbon dioxide and water under aerobic condition. Therefore, the over-all reaction can be summarized as the following stoichiometry.

$$CH_4 + 2\,O_2 \xrightarrow{\text{Methanotroph}} CO_2 + 2\,H_2O \qquad (3)$$

This methane oxidation reaction is exergonic reaction which releases energy 780 kJ/mol (Ribbons *et al.*, 1970) or 210.8 kcal/mol (Croft and Emberton, 1989). Moreover, Eq.(3) also illustrates an ideal $O_2$ :$CH_4$ ratio of 2:1 which correlates with the oxygen requirement of 2 L $O_2$/L $CH_4$ or 4 g $O_2$/g $CH_4$ . However, if biomass is accumulated, less oxygen requirement for methane oxidation is observed. Mennerich (1986) indicates that 3.6-4.0 g $O_2$/g $CH_4$ is actually needed for methane oxidation, in addition, Kjedsen *et al.* (1997) also indicate that 3.5 g $O_2$/g $CH_4$ is required.

Metabolism pathways of methanotrophs for methane oxidation and assimilation of formaldehyde are shown in Figure 5. Methanotrophs produce enzymes known as methane monooxygenases (MMOs) to catalyze the oxidation of methane ($CH_4$) to methanol ($CH_3OH$) under aerobic condition. Following reaction, dehydrogenation is employed for the synthesis of formaldehyde (HCHO), formate (HCOOH) and finally carbon dioxide ($CO_2$) by enzymes of methanol dehydrogenase (MDH), formaldehyde dehydrogenase (FADH) and formate dehydrogenase (FDH), respectively (Hanson and Hanson, 1996). Moreover, two pathways of formaldehyde assimilation into the cells are used to classify methanotrophs into two groups. Type I methanotrophs utilize the ribulose monophosphate (RuMP) pathway for formaldehyde assimilation while type II methanotrophs assimilate formaldehyde via the serine pathway (Bowman *et al.*, 1993).

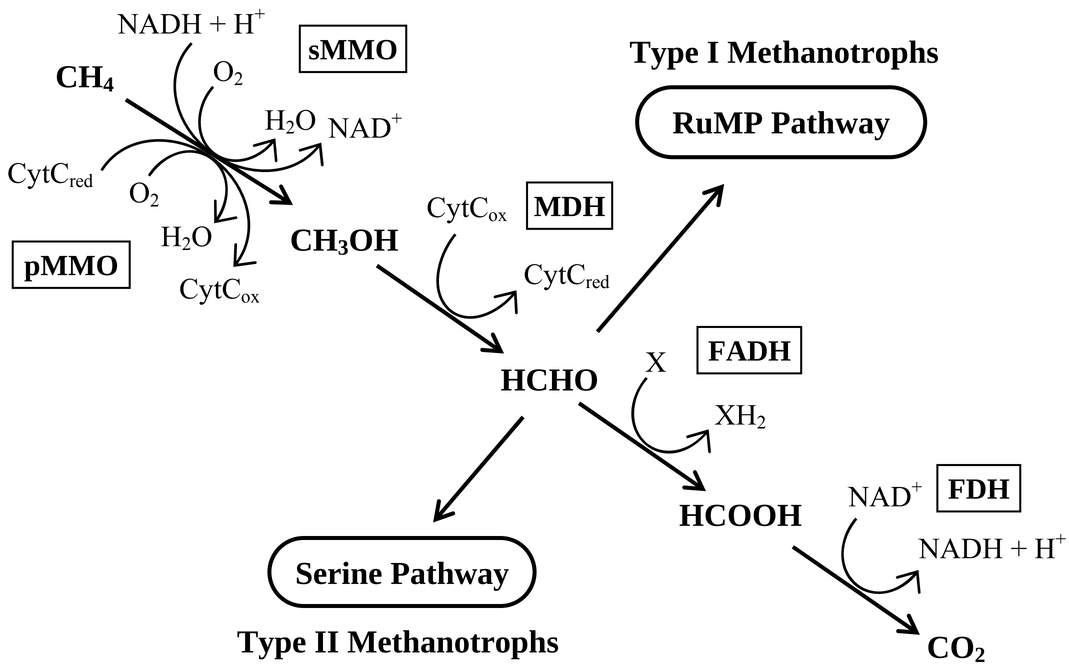



**Figure 5** Pathways for methane oxidation and assimilation of formaldehyde

Source: Hanson and Hanson (1996)

Furthermore, methane monooxygenases (MMOs) which initiate the oxidation of methane are classified into two forms. One form is a soluble MMO (sMMO) which utilizes NADH + $H^+$ as an electron donor while another form is a particulate MMO (pMMO). Forming different MMOs by methanotrophs depend upon the presence of copper in soil (Hanson and Hanson, 1996). However, these enzymes are non-specific catalyst for methane oxidation, they can also oxidize ammonium ($NH_4^+$) and other organic compounds (e.g. halogenated hydrocarbons) through co-oxidation process (Humer and Lechner, 2001a). Thus, ammonium or other organic compounds is recognized as competitive inhibitor to methane oxidation which its products can not be used by methanotrophs or may even negatively impact ambient conditions.

2.2 Influencing factors on methane oxidation

Factors that affect methane oxidation in soil are related to the environmental conditions for methanotrophic bacteria as described below.

2.2.1 Temperature

In general, methane oxidation increases with the increasing of soil temperature. However, most methanotrophs can exist at temperature ranging from 15 to 30°C (mesophilic culture). Whalen *et al.* (1990) have reported that increase of temperature from 15 to 25°C causes methane oxidation rate to almost double, however, the optimum temperature with the highest methane oxidation of 70 μg $CH_4$/g soil.d is 31°C. Moreover, Boeckx and Cleemput (1996) indicate that the temperature range of 25-30°C is suitable for methane oxidation in landfill cover soil studied in European countries. Otherwise, the study in tropical region (Visvanathan *et al.*, 1999) has found rather high optimum temperature for methane oxidation (30-36°C) as shown in Figure 6.

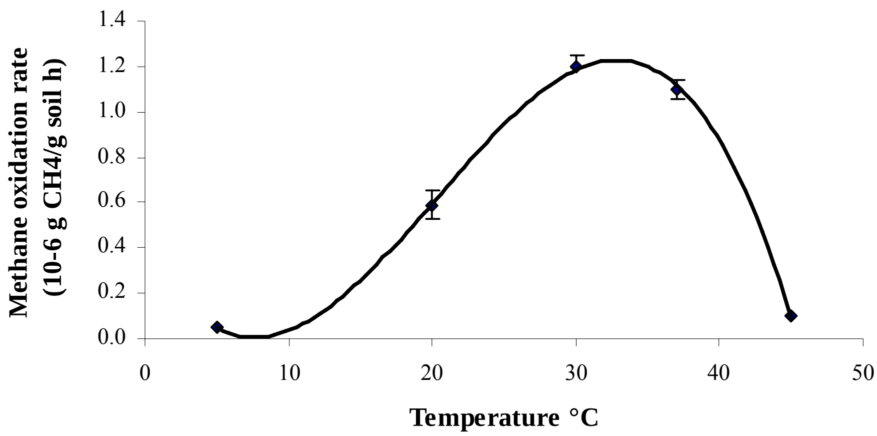



**Figure 6** Methane oxidation rate as function of soil temperature

Source: Visvanathan *et al.* (1999)

2.2.2 Water content

Water content is a very important factor of methane oxidation in soil. Water has two main functions on methane oxidation. One is to offer the optimum environment for methanotrophs. Another function is to influence on oxygen penetration into the soils. As the water content increases, the oxygen diffusion into the soil decreases. Many studies remark that soil has optimum moisture content for methane oxidation. Below this moisture content (Figure 7), methane oxidation rate will increase with the increasing of soil moisture. On the other hand, above this moisture content, methane oxidation rate will decrease with the increasing of soil moisture. The optimum soil water content will be different in various soil types. Humer and Lechner (2001a) and Park *et al.* (2002) report that optimum water content for loamy sand is 13% and also notice that below this content, methanotrophic bacteria tend to become inactive. In addition, moisture content of 15% is reported as optimum content for high capacity of methane oxidation at 2.36 ng $CH_4$/h. g soil (Boeckx and Cleemput, 1996). Similar to the study of Boeckx *et al.* (1996) and Visvanathan *et al.* (1999), the optimum moisture content is stated in range of 15.6-

18.8% and 15-20%, respectively. Figure 8 also shows the influence of soil moisture and temperature on methane oxidation.

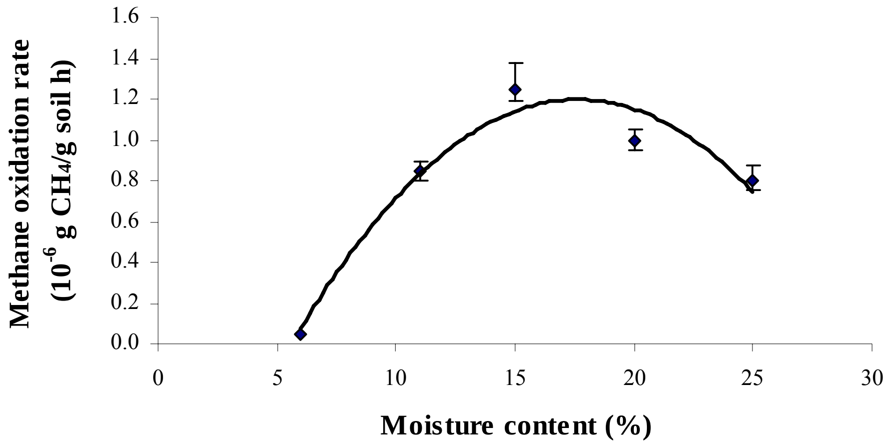



**Figure 7** Methane oxidation rate as function of soil moisture

Source: Visvanathan *et al.* (1999)

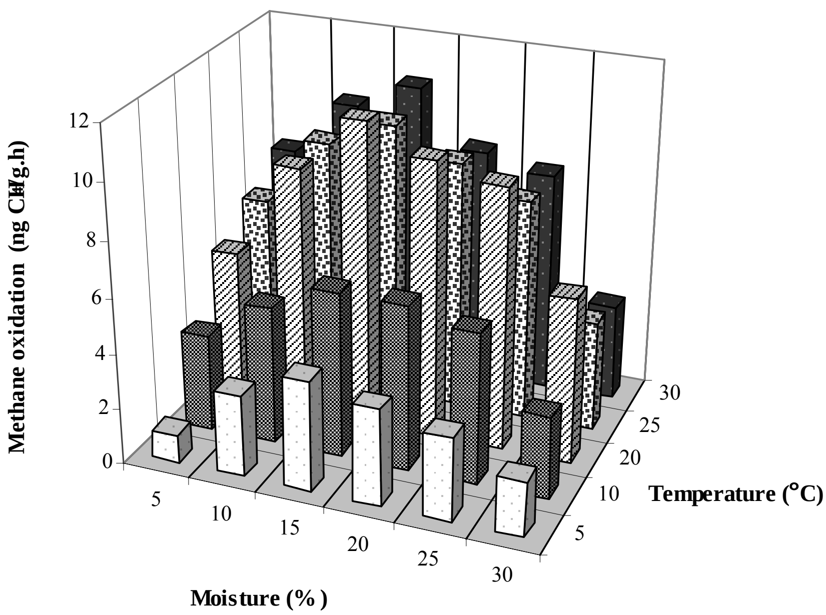



**Figure 8** Methane oxidation rate as function of soil moisture and temperature

Source: Boeckx *et al.* (1996)

2.2.3 Oxygen supply

Oxygen availability in soil pores is the main factor driving methane oxidation process with high rate of oxidation at high concentration of available oxygen. However, the actual oxygen requirement for methane oxidation is reported as 3.6-4.0 g $O_2$/g $CH_4$ by Mennerich (1986) and 3.5 g $O_2$/g $CH_4$ by Kjedsen *et al.* (1997). Additionally, Humer and Lechner (2001a) also indicate that methanotrophic activity is significantly reduced when oxygen concentration is below 2%v/v in gaseous phase. Likewise, the rapid decrease of methane oxidation to zero at oxygen level below 3% has been observed by Bender and Conrad (1994).

2.2.4 Soil porosity

The porosity of soil directly affects oxygen diffusion into the soil. Porosity can provide a channel for oxygen penetration into deeper soil layer and a contact surface area for methanotrophs. High porosity of soil also helps to retain methane and oxygen in the cover soil for methane oxidation process before leaking to the atmosphere.

2.2.5 Organic matter and nutrient supply

Organic content in substrate and nutrient supply are essentially important in methane oxidation. Organic matter mainly supports as a carrier for methanotrophs and improves soil properties, whereas nutrient supply is necessary for methanotrophic growth (Humer and Lechner, 2001a). Nevertheless, nutrient nitrogen source in term of $NH_4^+$ can inhibit methane oxidation while $NO_3^-$ does not significantly affect methane oxidation as shown in Table 6 (Boeckx and Cleemput, 1996; Boeckx *et al.*, 1996; Park *et al.*, 2002). Many studies demonstrate strong inhibitory effects of $NH_4^+$ on methane oxidation in batch experiments of many types of soils, such as arable soil, paddy soil and forest soil (Hutsch, 1998; Cai and Yan, 1999; Whalen, 2000). Addition of $NH_4^+$ in terms of $NH_4Cl$ 25 µg/g soil can inhibit 78-89% of methane oxidation (Bronson and Mosier, 1993) and further $NH_4NO_3$ 2 g N/kg soil also decrease 64% of methane oxidation (Kightley *et al.*, 1995).

**Table 6** Effect of ammonium ($NH_4^+$) and nitrate ($NO_3^-$) additions on methane oxidation

| $NH_4^+$ addition | | $NO_3^-$ addition | |
|---|---|---|---|
| mg $NH_4^+$-N/kg | $CH_4$ oxidation rate (ng $CH_4$/g.h) | mg $NO_3^-$-N/kg | $CH_4$ oxidation rate (ng $CH_4$/g.h) |
| 4 | 2.36 | 0 | 1.82 ± 0.14 |
| 29 | 2.01 | 25 | 1.86 ± 0.02 |
| 54 | 1.52 | 50 | 1.81 ± 0.21 |
| 79 | 0.78 | 75 | 1.84 ± 0.06 |
| 104 | 0.53 | 100 | 1.73 ± 0.07 |

Source: Data from Boeckx and Cleemput (1996)

Despite the fact that MMOs enzymes produced by methanotrophs can oxidize other organic and inorganic substances, especially $NH_4^+$ which has similar chemical structures and almost equal molecular weight to methane (Anthony, 1982). Therefore, methane oxidation is negatively impacted by this $NH_4^+$ co-oxidation. Moreover, the intermediate and end products of $NH_4^+$ co-oxidation ($NO_2^-$ and hydroxylamine) are also toxic to methanotrophs (Whittenbury *et al.*, 1970b; Schnell and King, 1995). Some hydrocarbon compounds, namely acetylene ($C_2H_2$) at 0.001%v/v, ethylene ($C_2H_4$) at 0.1%v/v and methyl fluoride ($CH_3F$) at 0.1%v/v, almost completely inhibit methane oxidation (Chan and Parkin, 2000).

Different observations of $NH_4^+$ addition stimulating methane oxidation are found by Cai an Moiser (2000) and Visscher *et al.* (2001). At high $NH_4^+$ content, nitrifying bacteria ($NH_4^+$ oxidizers) could increase their amount and activity which helped to decrease the negative effect of $NH_4^+$ co-oxidation on methane oxidation. In addition, these active $NH_4^+$ oxidizers could also oxidize methane simultaneously.

Furthermore, some inhibitory effect of $NO_3^-$ addition on methane oxidation is also found by Chiemchaisri (2001b) and Wang and Ineson (2003). Addition of $NO_3^-$ is causing restriction of nitrite ($NO_2^-$) oxidation via nitrification and thus accumulation of $NO_2^-$ which inhibited methanotrophic activity.

### 2.2.6 Extracellular polysaccharides (EPS) production by methanotrophs

Methanotrophs produce and secrete extracellular polysaccharides (EPS) on their cell walls in forms of capsules, slime or gums for protecting some unfavorable conditions such as high temperature, desiccation, predation and a carbon-rich environment besides serving as soil anchorage (Smith, 1982; Hilger *et al.*, 1999, 2000a; Chiemchaisri *et al.*, 2001a).

The nature of EPS production varies widely across the microbial community and different environmental conditions. Moreover, it is often produced in excess degree which has been linked to nutrient imbalance and oxygen deficiency (Wrangstadh *et al.*, 1986), but nevertheless Chiemchaisri *et al.* (2001a) remarks that high oxygen content also correlates with acceleration in the production of EPS.

Excess EPS slime can trap soil particulates, clog soil pores, restrict oxygen penetration into soil and thus reduce methane oxidation (Hilger *et al.*, 1999, 2000a; Chiemchaisri *et al.*, 2001a). In addition, EPS biofilm that coats bacteria cell also acts as a barrier to substrate and oxygen diffusion into embedded bacteria (Hilger *et al.*, 2000a; Wilshusen *et al.*, 2004a, 2004b) and there is evidence that diffusivity decreases with increasing film age (Matson and Characklis, 1976) which eventually restricts methanotrophic activity.

## 2.3 Methane oxidation studies in actual landfill cover soil

Methane oxidation studies in actual landfill cover soil at various regions are individually associated with different factors such as types of soil, soil depth, all environmental conditions which affect soil temperature and water content, or landfill ages which correlate with production rate of landfill gas etc.

Table 7 illustrates a summary of the previous studies of methane oxidation in actual landfill cover soil. Characteristics of landfill (e.g. type of soil, soil depth, pH, temperature and moisture content), methane oxidation rate and the optimum condition for methane oxidation are listed.

## 2.4 Methane oxidation studies in laboratory-simulated landfill cover soil

Methane oxidation studies in simulated landfill cover soil column can be controlled to perform in the optimum conditions. Consequently, methane oxidation rates reported in the soil column studies are normally higher than those in actual landfill studies.

Table 8 also shows a summary of the previous studies of methane oxidation in laboratory scale. All experiments perform in soil columns with similar optimum conditions such as soil type (sandy loam), soil moisture (10-20%), rate of landfill gas supply (5-10 mL/min) etc.

**Table 7** Summary of methane oxidation studies in actual landfill cover soil

| Descriptions | Whalen *et al.* (1990) | Boeckx *et al.* (1996) | Börjesson and Svensson (1997) | Bogner (1997) |
|---|---|---|---|---|
| Landfill characteristics | | | | |
| Location | U.S.A. | Belgium | Sweden | U.S.A. |
| Soil type | Sand mixed with clays | Sandy loam | Sandy loam | Silt clay |
| Depth (cm) | 150-300 | 30 | 10-80 | 100 |
| pH | 5.4 | 7.3 | - | - |
| Density ($g/cm^3$) | 1.88 | - | 1.4-1.6 | - |
| Moisture (%) | 11 | 3.8-33.1 | 5.0-39 | 10-35 |
| Temperature (°C) | 25 | 8.0-24.5 | 0.4-22.6 | 5-30 |
| $NH_4^+$-N (mg/kg) | - | 8.6 | - | - |
| $NO_3^-$-N (mg/kg) | - | 4.0 | - | - |
| Organic matter (%) | 4 | 1.0 | 0.66-4.1 | 3 |
| Methane oxidation rate (MOR) | 45 $g/m^2.d$ | 10.86 ng $CH_4$/g.h | 120-390 mmol $CH_4$/ $m^2.h$ | 48 $g/m^2.d$ |
| Unified MOR (mol $CH_4/m^3.d$) | 1.4 | - | 3.6-11.7 | 3 |
| Experimental results | | | | |
| Depth with max MOR (cm) | 3-6 | - | 50-60 | 25 |
| Temp. with max MOR (°C) | - | - | - | - |
| Optimum temperature (°C) | 31 | 20-30 | - | - |
| Moisture with max MOR (%) | 11 | - | - | - |
| Optimum moisture (%) | - | 15.6-18.8 | - | - |

**Table 8** Summary of methane oxidation studies in landfill cover soil columns

| Descriptions | Kightley *et al.* (1995) | Visvanathan *et al.* (1999) | Visscher *et al.* (1999) | Hilger *et al.* (1999) |
|---|---|---|---|---|
| Column characteristics | | | | |
| Size of column | ∅ 15 cm height 1 m | ∅ 20 cm height 120 cm | ∅ 14.1 cm height 60 cm | ∅ 15 cm |
| Soil type | 1) coarse sand<br>2) clay topsoil<br>3) fine sand | 1) sandy loam<br>2) sandy clay loam | 1) loamy soil<br>2) sandy loam | sandy loam |
| Depth (cm) | 90 | 90 | 50 | 30 |
| Study period | 6 months | 150 days | 28 days | 1000-4000 hrs |
| pH | 6.6, 6.4, 5.3 | - | 6.2, 5.2 | - |
| Moisture (%) | 40, 55, 45 | 11-18 | 16.5 | 15 ± 0.5 |
| Temperature (°C) | 19 ± 3 | 28-36 | - | - |
| $NH_4^+$-N (mg/kg) | - | - | 3.2 | - |
| $NO_3^-$-N (mg/kg) | - | - | 32.6 | - |
| Organic matter (%) | - | - | 1.0, 1.7 | - |
| Gas ratio | > 99% $CH_4$ | 60%$CH_4$, 40%$CO_2$ | 50%$CH_4$, 50%$CO_2$ | 50%$CH_4$, 50%$CO_2$ |
| Gas flow rate (mL/min) | 5 | 5-9 | 7 | 10 |
| Methane oxidation rate | 10.4, 6.8, 6.9 mol $CH_4/m^2.d$ | 100 g $CH_4/m^2.d$ | 12, 18.1 mol $CH_4/m^2.d$ | 1.625 x $10^{-7}$ g $CH_4/cm^2.s$ |
| Unified MOR (mol $CH_4/m^3.d$) | 11.6, 7.6, 7.7 | 6.9 | 24, 36.2 | 29.25 |
| Experimental results | | | | |
| Depth with MOR (cm) | 30, 45, 55 | 15-40 | 30 | 15 |
| Opt. temperature (°C) | - | 30-36 | - | - |
| Opt. moisture (%) | - | 15-20 | - | - |

**Table 8** (Cont'd)

| Descriptions | Chiemchaisri *et al.* (2001b) | Stein and Hettiaratchi (2001) | Park *et al.* (2002) | Kettunen *et al.* (2006) |
|---|---|---|---|---|
| Column characteristics | | | | |
| Size of column | ∅ 19 cm height 90 cm | ∅ 6 in. height 1 m | ∅ 10 cm height 37.5 cm<br>∅ 10 cm height 67.5 cm | ∅ 30 cm height 50 cm |
| Soil type | sandy loam | 1) Springbank landfill loam<br>2) Rockyview dark soil<br>3) Sedge peat moss | sandy loam | 1) compost + waste + sand<br>2) compost + waste + bark chips |
| Depth (cm) | 60 | 80 | 30, 60 | 30 |
| Study period | 10 months | 300 days | 90 days | 65 days |
| pH | 7.1 | 8.45, 7.6, 6.5 | 8.8 | 6.8, 6.5 |
| Moisture (%) | 11.07 | 9.4, 10.0, 316 | 5-20 | 57, 164 |
| Temperature (°C) | - | -36 - 34 | 25 ± 5 | 4-23 |
| $NH_4^+$-N (mg/kg) | 5.51 | - | 1.0 | - |
| $NO_3^-$-N (mg/kg) | 87.47 | - | 3 | - |
| Organic matter (%) | 0.12 | 3.1, 4.7, 79 | 0.4 | - |
| Gas ratio | 60%$CH_4$, 40%$CO_2$ | 99%$CH_4$ | - | 50%$CH_4$, 50%$CO_2$ |
| Gas flow rate (mL/min) | 5 | 0.02 | 2-4 | 4-6 |
| Methane oxidation rate | 6.16 g $CH_4$/$m^2$.d | 100 g $CH_4$/$m^2$ d | 27.2 mol $CH_4$/$m^2$ d | 0.18, 0.25 g $CH_4$/kg.d |
| Unified MOR (mol $CH_4$/$m^3$.d) | 0.64 | 7.8 | 45.3 | 11.25, 14.06 |
| Experimental results | | | | |
| Depth with MOR (cm) | 0-40 | 66 | 30, 60 | 30 |
| Opt. temperature (°C) | 30 | 30 | 25 | 21-23 |
| Opt. moisture (%) | 15 | 15.4 | 13 | - |

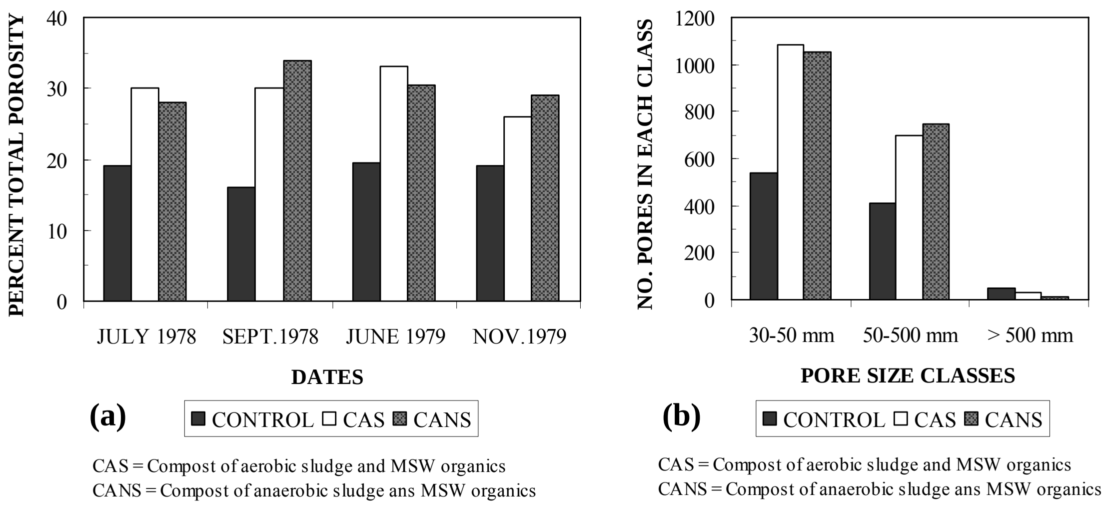
## 3. <u>Compost as Landfill Cover Material</u>

### 3.1 Effect of compost application on soil properties

Compost application influences on soil properties both physical (soil structure, bulk density and water retention) and chemical (cation exchange capacity, pH, electrical conductivity and nitrogen availability) characteristics as discussed below.

#### 3.1.1 Soil structure

Soil porosity directly affects aeration and water movement in the soil matrix. Compost application significantly increases total soil porosity (Figure 9(a)) and also affects the distribution of soil pore size (Figure 9(b)). Compost increases the number of pores in small (0.5-50 μm) and medium-sized (50-500 μm) classes which help to retain water necessary for plant growth and microorganisms, and transports water and air into the soil (Pagliai *et al.*, 1981). However, compost causes the reduction of large pores (>500 μm) which are fissures and play a relatively small part in water movement and retention.




**<u>Figure 9</u>** Effect of compost application on (a) soil porosity and (b) soil pore size distribution

Source: Data from Pagliai *et al.* (1981)

#### 3.1.2 Soil bulk density

The addition of compost generally results in a decrease of soil bulk density especially in cases of clays and other dense soils. Jacobowitz and Steenhuis (1984) find that at higher rates of sludge compost application (50, 200 and 500 t/ha), the soil bulk density significantly decreases. Figure 10 shows the effect of compost application on the soil bulk density for two types of soils (sandy loam and silt loam). Compost mainly decreases bulk density at the upper layer (3-6 cm depth) and this effect is more pronounced for the silt loam soil than for the sandy loam soil. Similar result is also found by Tester (1990), the addition of biosolids compost also reduces bulk density of sandy loam soil.

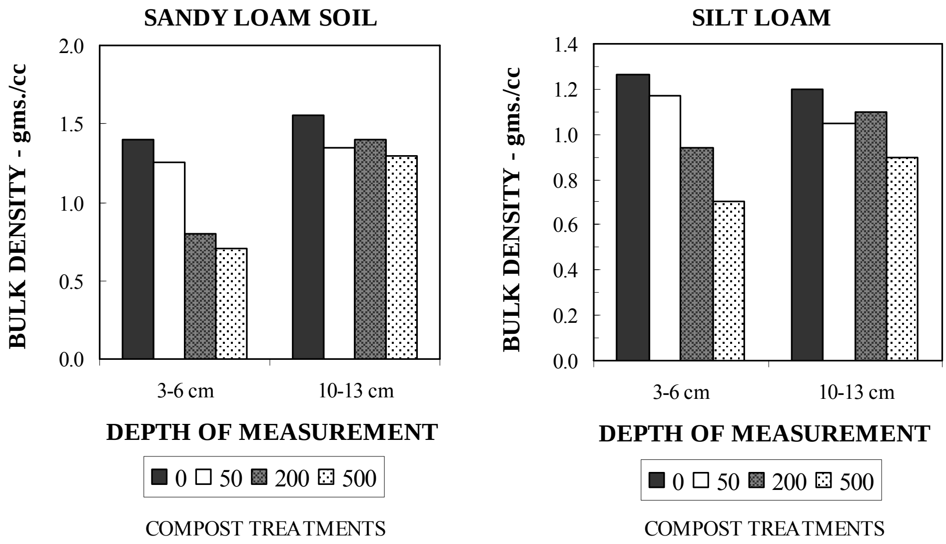



**Figure 10** Effect of compost application at different rates (0, 50, 200 and 500 ton/ha) on soil bulk density

Source: Jacobowitz and Steenhuis (1984)

### 3.1.3 Soil water retention

Compost application increases the water-holding capacity of soils and consequently provides higher available water content (Mays *et al.*, 1973; Epstein *et al.*, 1976; Jacobowitz and Steenhuis, 1984). Figure 11 shows that adding higher biosolids compost to sandy soil results in increasing of water retention (saturation and available water). Tester (1990) also reports that increasing rates of compost increase the soil water content of loamy sand soil (Figure 12). The upper soil layer (5 cm depth) is more impacted by adding compost than the lower layer. Soil water retention significantly increases when amend with compost.

Furthermore, application of compost to soil also increases water infiltration and improves the permeability in soils. Increased infiltration will, in turn, lead to increased soil moisture content while reduce the potential for runoff and erosion at the soil surface.

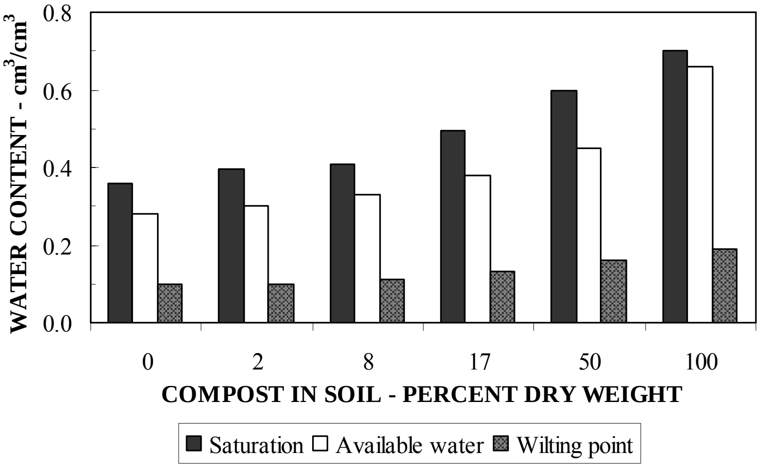



**Figure 11** Effect of compost additions on soil water retention

Note: Available water was calculated as the difference between saturation and the wilting point.
Source: Jacobowitz and Steenhuis (1984)

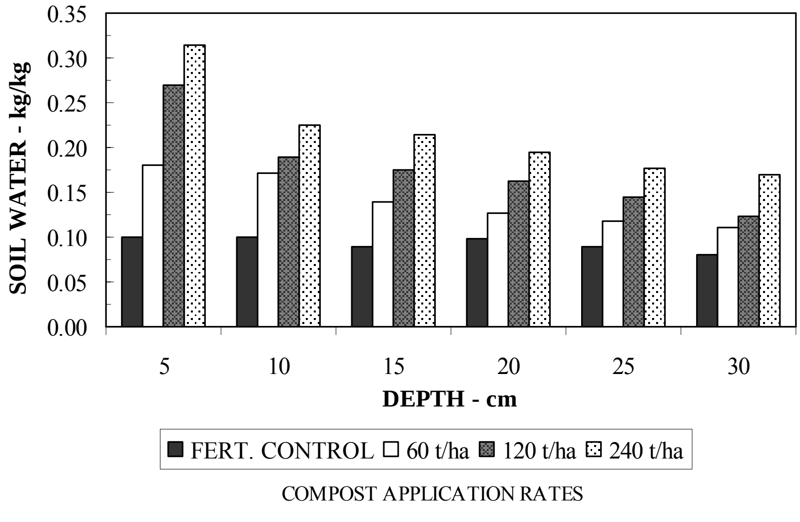



**Figure 12** Effect of compost application on soil water content

Source: Data from Tester (1990)

### 3.1.4 Cation Exchange Capacity (CEC)

Cation Exchange Capacity (CEC) is the sum total of exchangeable cations that a soil, soil constituent, or other materials can adsorb at specific pH. It is usually expressed in centimoles of charge per kilogram of exchanger ($cmol_c$/kg).

CEC is obtained from the attachment of positively charged cations (e.g. $K^+$, $Ca^{2+}$) to the negative charges of soil particles. Therefore, CEC provides the retention of plant nutrient and prevents the potential for leaching of cations into groundwater or lower soil layers. The two major soil constituents that affect CEC are clay minerals and organic matters. Stevenson (1994) and MacCarthy *et al.* (1990) state that CEC of soil organic matters is higher than that of soil clay mineral.

Application of compost (e.g. biosolids compost and MSW compost) relates to adding of organic carbon and thus increases CEC of soil (Epstein *et al.*, 1976; Epstein and Wu, 1994).

### 3.1.5 Soil pH

Most stable composts have pH in range of 6.5-7.5. Application of compost (e.g. MSW compost) can increase soil pH from 5.4 to 6.8 (Mays *et al.*, 1973). Increases of soil pH are also reported by Epstein *et al.* (1976), Jacobowitz and Steenhuis (1984) and Tester (1990) for biosolids compost.

### 3.1.6 Electrical Conductivity (EC)

Electrical Conductivity (EC) is a measure of salt content of the soil solution which represents salinity of soil in units of micromhos per centimeter (mmhos/cm) or decisiemens per meter (dS/m). Salinity affects germination and plant growth both directly and indirectly. Moreover, high salt content also inhibits soil microbial activity.

Different types or feedstocks of compost may cause different EC values and EC will be increased with composting time (Grebus *et al.*, 1994) due to extending decomposition period of organic matters and then resulting in high salt concentration (Manios and Syminis, 1988). Epstein *et al.* (1976) and Shiralipour *et al.* (1992) report that the use of compost (biosolids compost and MSW compost) can result in an increase in soil EC.

### 3.1.7 Nitrogen availability in soil

Nitrogen in compost is predominantly in the organic form which is not soluble and does not leach through the soil. For nitrogen to be available to plants or soil microorganisms, it needs to be converted to the inorganic soluble form (i.e. ammonium and nitrate) via mineralization process.

## 3.2 Effect of compost on methane oxidation

As stated by Kightley *et al.* (1995), soil with porous, coarse and organic-rich characteristics are responsible for the greatest methane oxidation. Therefore, further experiments are carried out to determine the degree to which the types of organic materials can regulate the capacity of methane oxidation as described in the following studies.

Humer and Lechner (1999) find that sewage sludge compost and MSW compost are a suitable substrate for methane oxidation. Under optimum ambient conditions, a layer of MSW compost of 60 cm in depth is able to entirely oxidize the amount of methane which is usually released from a MSW landfill (about 20-180 $m^3$ $CH_4/m^2$.yr).

Humer and Lechner (2001a) indicate that high methane oxidation rate is achieved in coarse, ripe waste compost, mature compost or activated compost, such as sewage sludge compost or MSW compost. In addition, methane oxidation in these composts is also higher than in natural soils. They propose that the structure of compost must have long-term stability and an adequate porosity even at high water content, in order to maintain appropriate permeability of oxygen and methane.

Streese and Stegmann (2003) demonstrate high methane oxidation rate of 63 g $CH_4/m^3$.h in the fine-grained compost at the third-month beginning of the experiment, however, decrease in the fifth-month of the experiment due to the accumulation of exopolymeric substances (EPS) formed by methanotrophs. Furthermore, they also suggest that a mixture of compost, peat and wood fibers provided stable and satisfactory methane oxidation rates about 20 g $CH_4/m^3$.h over a period of one year. Monitoring of methane oxidation rate or degradation rate is shown in Figure 13.

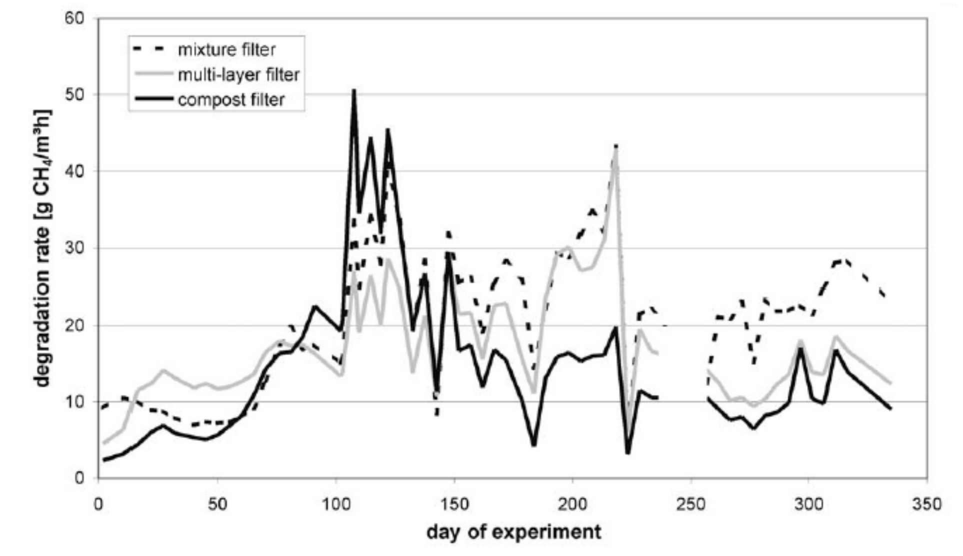



**Figure 13** Methane oxidation rates observed in three biofilters over 340 days

Source: Streese and Stegmann (2003)

Wilshusen *et al.* (2004a) find that leaf compost has the highest methane oxidation efficiency compared with woodchip compost and MSW compost. Compost characteristics with media homogeneity and fineness in particle size seem to give positive impacts on methane oxidation performance.

Mor *et al.* (2004) also recommend that effective compost for high methane oxidation should be stable and has low respiration rate. Methanotrophic activity found in their studies is substantially higher in compost than the activity normally found in soils. Compost possesses more air-filled pore space (50%) than soils (20-30%). Thus, it will support more oxygen diffusion for methane oxidation and also extend the active aerobic zone for methanotrophs.

From these literatures, compost is used as landfill cover soil for the purpose of stimulating methane oxidation. Its beneficial properties are responsible for the favorable conditions supporting methane oxidation; (1) loose texture and high porosity promoting oxygen diffusion into soil pores, (2) high water retention capacity supporting adequate moisture content for methanotrophs, and (3) supplemental organic matters and nutrients stimulating methanotrophic activity.

## 4. Vegetated Landfill Cover Soil

### 4.1 Characteristics and species of plants growing on landfill cover soil

Based on the biodegradation in the waste layer of landfill, landfill gases (methane and carbon dioxide) are produced and penetrate to the upper soil layers which may impact on the cover plants at the top soil. Hence, plant species applied on landfill cover soil should resist to high content of landfill gases and low available oxygen in soil. Moreover, plants with extensive root characteristic are preferred to prevent soil erosion. In addition, it should be a local plant which normally grows on landfill site. In this study, tropical grasses are considered to apply for landfill cover as listed below.

#### 4.1.1 *Cynodon dactylon*

Common names: Bermuda grass, Giant Bermuda grass, Devil grass, Couch grass, Indian doab, Grama, Devilgrass, Couchgrass, Balama grass

Origin and geographic distribution: Pacific Islands (e.g. American Samoa, Cocos Islands, Commonwealth of the Northern Mariana Islands, Volcanic Marianas, Cook Islands, etc.), Pacific rim (e.g. Australia, New Zealand, Japan, Korea, Taiwan, China, Thailand, Cambodia, Vietnam, etc.) and Indian Ocean Islands (e.g. Chrismas Island, Mauritius, etc.)

Natural habitat: Grassland, lawns and pastures and as a weed in cultivation

Botany: A variable perennial, creeping by means of stolons and rhizomes penetrating the soil to a depth of 1 m or more. Culms 8-40 cm high (rarely to 90 cm) and 0.5-1 mm in diameter. Leaf-blade linear-lanceolate, 1-16 cm × 2-5 mm, glabrous or hairy on upper surface. Spike two to six, usually 3-6 cm long and in one whorl (Skerman and Riveros, 1990; Tudsri, 1997).

Soil requirements: There are varieties adapted for a wide range of soils. It prefers well-drained, fertile soils, especially heavier clay and silt soils not subject to flooding, well supplied with lime and high nitrogen mixed fertilizers. It also grows on sandy loams. It has proved very drought resistant and its rhizomes survive drought well. It also has good tolerance to salinity, but makes only slow growth (Skerman and Riveros, 1990).


**Figure 14** Bermuda grass (*Cynodon dactylon*): (a) spikelet, and (b) ligule

Source: Mannetje and Jones (1992)

4.1.2 *Cynodon plectostachyus*

Common names: Naivasha star grass, Estrella, Bermuda mejorado, Haeaiiano

Origin and geographic distribution: East Africa, e.g. Ethiopia, Kenya, Uganda, Tanzania, etc. It was imported into Thailand by Kasetsart University since 1961.

Natural habitat: Dry lake beds.

Botany: A large, robust, non-rhizomatous grass. Culms robust to fairly slender, 30-60 cm high and 1-3 mm in diameter at the base. Leaf-blade flat, linear-lanceolate, 10-15 cm × 4-5 mm, with or without scattered hairs (Skerman and Riveros, 1990; Tudsri, 1997).

Soil requirements: It has a wide range of tolerance from sandy loams to alluvial silts and clays, and black cracking clay soils, but prefers soil of high fertility. It is tolerant to alkaline soils and very good tolerant to drought. Furthermore, it prefers to grow in full sunlight and can spread rapidly under good conditions (Skerman and Riveros, 1990).

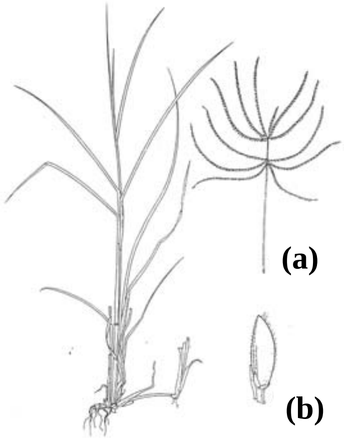



**Figure 15** Star grass (*Cynodon plectostachyus*): (a) inflorescence, and (b) spikelet

Source: Skerman and Riveros (1990)

4.1.3 *Sporobolus virginicus*

Common names: Dixie grass

Origin and geographic distribution: Along coasts in tropical Africa, western seaboard of India, Sri Lanka, Australia and the United States.

Natural habitat: Sand dunes just above high-water mark, and behind mangrove swamps.

Botany: Rhizomatous perennial with lanceolate, spin-tipped leaf-blades growing 15-40 cm high, erect, from creeping, hard, scaly rhizomes. Inflorescence dense, spikelike, up to 15 mm wide with short appressed branches and pale spikelets. The panicle is not more than 7.5 cm long (Skerman and Riveros, 1990).

Soil requirements: It has a wide range, from clays to sands. It can grow on highly saline marsh soils. Furthermore, it is tolerant to flooding, especially at the water level 5-15 cm above the soil surface (Skerman and Riveros, 1990).

4.1.4 *Panicum repens*

Common names: Torpedo grass (in Thai: Yah Chanagard)

Origin and geographic distribution: Indonesia, Malaysia, Thailand and other South-East Asian countries. Wetter areas throughout the tropical and subtropical regions of the world (Mannetje and Jones, 1992).

Natural habitat: Lake shores, and seasonal and permanent swamps.

Botany: A perennial grass with long, sharp pointed rhizomes and often also surface stolons. Culms erect or decumbent, up to 120 cm high, often from a knotty base. Leaf-sheath 4-7 cm long, hairy at the margins near the throat. Leaf-blade linear-acuminate, 7-25 cm × 2-8mm, flat or rolled when dry (Mannetje and Jones, 1992).

Soil requirements: Generally found on sandy soils, but some strains grow on heavy clay. The soils are always wet and of alluvial origin. It is useful on copper-deficient soils. It is also very good in tolerance to salinity and grows well even after several days in standing water. It is frequent on lake edges, edges of dams and in swamps throughout the tropics. Moreover, it tolerates to drought, as the rhizomes remain alive in long dry periods (Skerman and Riveros, 1990).

**Figure 16** Dixie grass (*Sporobolus virginicus*)

Source: Skerman and Riveros (1990)

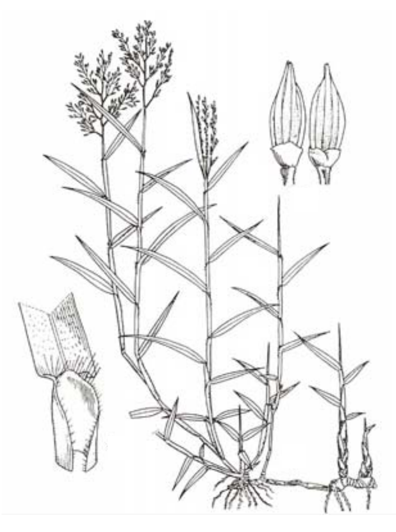


**Figure 17** Torpedo grass (*Panicum repens*)

Source: Mannetje and Jones (1992)

According to the previous studies (Yodsang, 2003; Chittanukul, 2004), *Cynodon dactylon*, *Cynodon plectostachyus* and *Sporobolus virginicus* could grow under the landfill cover operation with leachate irrigation. Nevertheless, *Sporobolus virginicus* also provided the highest methane oxidation capacity in comparison with other grass species. In addition, *Panicum repens* is a local grass which is found in the tropical landfill site of Thailand (Sai Noi Lanfill, Nontaburi Province). Thus, both *Sporobolus virginicus* and *Panicum repens* are used in this study to investigate their effect on methane oxidation.

4.2 Effect of vegetation on methane oxidation

Vegetation on landfill cover soil contributes to the change of soil structure and further increases soil oxygen content by plant root system. Thus, it can imply that the provision of vegetation gives preferable impacts on methane oxidation. Several studies also prove the positive effect of vegetation on methane oxidation as follows.

Maurice (1998) remarks that plant photosynthesis which mainly occurs in the chloroplast of leaves helps producing more available oxygen. On the other hand, plant respiration also consumes oxygen and releases carbon dioxide. However, plants also help transporting oxygen from the atmosphere through their leaves, stems and roots into soils and then enhance methane oxidation.

Hilger et at. (2000b) study the effect of vegetation on methane oxidation by using grasses, namely Kentucky 31 (*Festuca arundinacea*). They found that vegetation causes the increase of methane oxidation capacity from 37% to 47%. Furthermore, the presence of grasses also reduces the inhibitory effect of ammonium on methane oxidation.

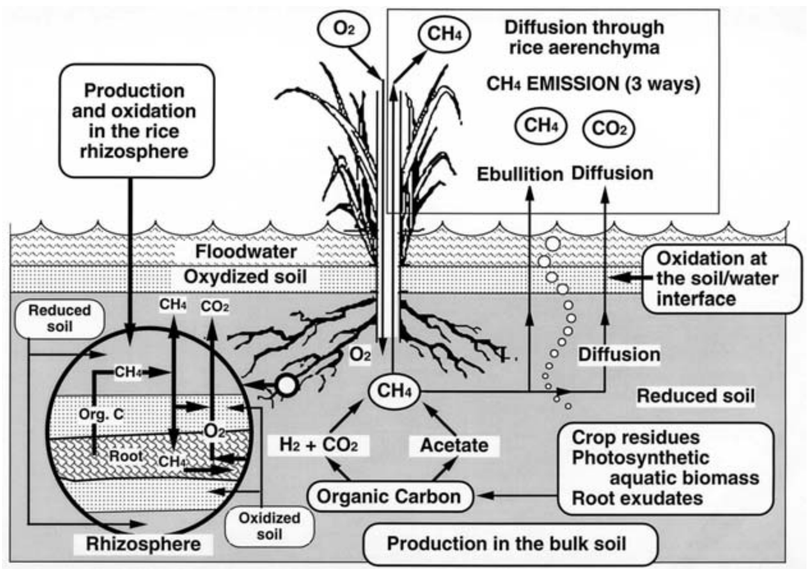



**Figure 18** Production, oxidation and transfer of methane to the atmosphere

Source: Mer and Roger (2001)

In addition to oxygen transportation through the aerenchyma of vascular plant, methane is also transported through this vascular system (Schutz *et al.*, 1991; Mer and Roger, 2001; Chanton, 2005). In submerged soil systems (wetland and rice paddy), other two options of methane emission include molecular diffusion through the sediment-water and water-air interfaces, and ebullition through gas bubble formation (Figure 18).

According to the literatures, the provision of vegetation positively affects methane oxidation in two options; (1) increasing available oxygen content in soil by enhancing transport action of oxygen via plant vascular, and (2) increasing amount of methanotrophic bacteria and their activity by providing exudates at rhizosphere which serve as supplemental nutrients.

## 5. Proposed Scope of this Study

In sanitary landfill, biodegradation of solid waste in the waste layer produces landfill gases, mainly methane and carbon dioxide. As methane penetrates to upper layers, cover soil plays an important role in reducing the emission of methane via methane oxidation reaction. Methanotrophic bacteria are able to oxidize methane to carbon dioxide and water under aerobic condition.

As shown in Figure 19, methane oxidation or methanotrophic activity in the top soil depends on the existence of methanotrophs, oxygen supply and suitable substrates (both organic matters and nutrients). To encourage methane oxidation, it will be associated with the design and operation of final cover soil; (1) application of compost as landfill cover soil presumably provides organic matters to soil microorganisms and improves soil structure as a result of increasing oxygen penetration and water retention, (2) practice with vegetation can support oxygen transfer via plant vascular system and provide favorable root surroundings for methanotrophs, and (3) leachate irrigation helps to maintain proper water content and provide nutrient supplement for methanotrophs.

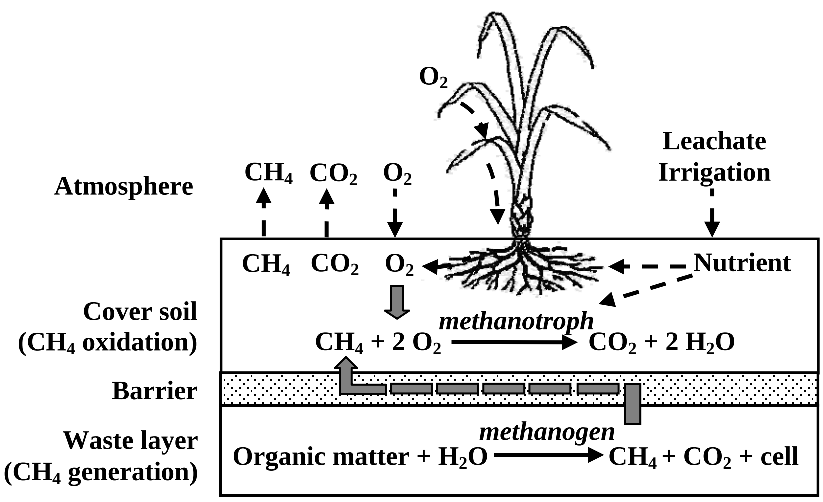



**Figure 19** Biochemical mechanisms in landfill

# MATERIALS AND METHODS

## 1. Materials

### 1.5 Experimental columns

The acrylic columns with 15 cm diameter, 5 mm thickness and 100 cm height were used to simulate landfill cover system. These open-ended columns had 5 rubber septum ports each for gas sampling along its depth (i.e. 5, 15, 30, 50 cm from soil surface, and gas inlet at the bottom). At the bottom of column, there was also gas inlet for artificial landfill gas ($CH_4$:$CO_2$ = 60:40) and effluent outlet for irrigated leachate or rainwater. In each column, landfill cover material of 60-cm depth was prepared and supported by a 5 cm layer of gravel (average size of 1-2 cm) which helped distributing the gas upflow into the upper cover layer and also facilitate the water downflow to the bottom space (10 cm depth) of column. The total landfill cover volume was 0.0106 $m^3$. Figure 20 illustrates the laboratory soil column used for this study.

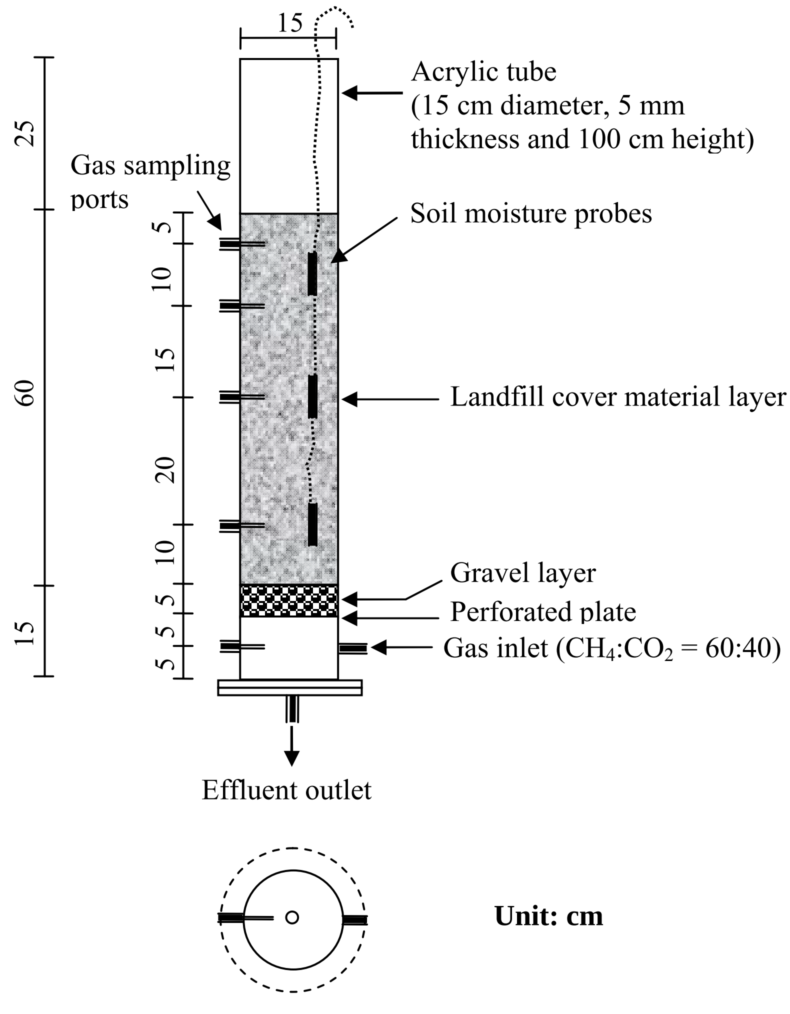



**Figure 20** Schematic of laboratory soil column

1.6 Landfill cover materials

Three types of landfill cover materials (i.e. sandy loam, compost, and mixture of sandy loam and compost) were used in this study for investigating the effect of their properties on methane oxidation.

Sandy loam was prepared from natural soil and coarse sand in ratio of 1:2. Natural soil was obtained from a field crops research station of Kasetsart University, Nakhonratchasrima Province, Thailand. This prepared sandy loam consisted of 80% sand, 8% silt and 12% clay (by dry weight basis). Compost, another material, was commercial grade of leaf compost for garden usage (product of Dinsida, Thailand). It was sieved through 4.75 mm mesh sieve (no.4) to obtain homogeneous texture before using the experiment. And the last one, mixture of sandy loam and compost was prepared in ratio of 1:1 (by wet weight basis).

The physical and chemical properties of these materials were determined according to "Tropical soil biology and fertility: a handbook of methods" (Anderson and Ingram, 1993). Their characteristics are presented in Table 9.

**Table 9** Characteristic of landfill cover materials

| Properties | Unit | Sandy Loam | Mixture (1:1) | Compost |
|---|---|---|---|---|
| pH (1 : 2.5) | - | 7.30 | 6.86 | 6.36 |
| EC (1 : 2.5) | dS/m | 0.24 | 3.40 | 7.15 |
| CEC | $cmol_c/kg$ | 4.8 | 11.8 | 22.3 |
| Moisture content | %d.w. | 14.48 | 25.07 | 51.73 |
| Bulk density | $kg/m^3$ | 1,250 | 802 | 566 |
| Porosity | % | 52.83 | 69.74 | 78.64 |
| Total organic matter | % | 1.05 | 11.47 | 21.07 |
| Total organic carbon | % | 0.61 | 6.65 | 12.22 |
| TN | mg/kg | 1,880 | 4,728 | 9,645 |
| $NH_4^+$ - N | mg/kg | 13.26 | 26.84 | 34.06 |
| $NO_3^-$ - N | mg/kg | 16.93 | 132.20 | 120.41 |
| Available P | mg/kg | 8 | 2,655 | 5,845 |
| Available K | mg/kg | 39 | 2,195 | 5,780 |

Furthermore, other soil physical properties (field capacity and evaporation) which related to soil water status were also analyzed as follows.

Field capacity (FC) of each cover material was determined by gravimetric method (Cassel and Nielsen, 1986). PVC tube with similar size to that of acrylic column was used in this determination. The water content of each cover material was observed within 1 to 2 days of drained condition after wetting (saturated condition) with no evapotranspiration. Field capacity is defined as the constant water content at natural drainage after saturation.

Evaporation was evaluated by weighing method or lysimetric method (Boast, 1986). Similar to field capacity analysis, PVC tube (0.0177 $m^2$ surface area) was also used for measuring evaporation of water from bare cover materials. Water loss was determined occasionally or continuously by weighing. Table 10 shows field capacity and evaporation of each cover material.

**Table 10** Field capacity and evaporation of landfill cover materials

| Landfill Cover Materials | Field Capacity (% dry weight basis) | Evaporation ($L/m^2.d$) |
|---|---|---|
| Sandy Loam | 19.80 | 1.02 |
| Mixture (1:1) | 44.39 | 1.25 |
| Compost | 72.28 | 2.21 |

1.7 Tropical grasses

Two tropical grasses (Figure 21), *Sporobolus virginicus* and *Panicum repens*, were used for evaluating the effect of plant on methane oxidation. These two species were a local grass in the tropics with high salt tolerant characteristics and ability to growth under both flooding and drought conditions. Moreover, Chittanukul (2004) also stated that *Sporobolus virginicus* gave some beneficial effects on methane oxidation in the column study. In addition, *Panicum repens* was also found in the natural landfill site of Sai Noi Landfill, Nontaburi Province, Thailand. Both grasses were grown for about two weeks in nursery pots before being transferred into the experimental columns. Their initial heights were set at 20 cm.

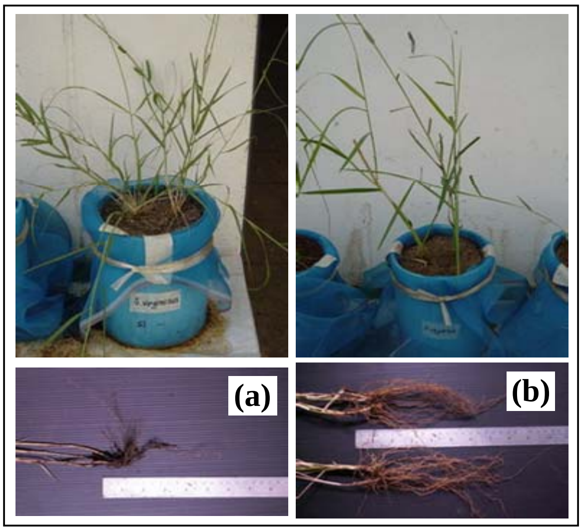



**Figure 21** Tropical grasses and their roots used in vegetated cover systems: (a) *S. virginicus* and (b) *P. repens*

1.8 Leachate and rainwater

Leachate and rainwater were used in this study for the purpose of maintaining soil moisture content and also simulating rainy season in tropical region. Stabilized leachate with low ratio of BOD/COD (approximately 0.1) was prepared by diluting with rainwater to a final concentration of approximately 500 mg COD/L before being used. At this concentration, the stabilized leachate was expected to provide low oxygen consumption for heterotrophic bacteria and less competition with methanotrophic bacteria. The characteristics of leachate were continually examined at the scheduled time following standard method for the examination of water and wastewater (APHA, 1992). Table 11 shows the average value of leachate characteristics. Rainwater was collected between June and October 2004 at Department of Environmental Engineering, Faculty of Engineering, Kasetsart University, Bangkok, Thailand and stored in plastic tank until use.

**Table 11** Characteristics of leachate

| Parameters | Unit | Value |
|---|---|---|
| pH | - | 8.01 ± 0.43 |
| EC | dS/m | 11.3 ± 3.6 |
| Temperature | °C | 28.4 ± 1.9 |
| BOD | mg/L | 31.3 ± 6.1 |
| COD | mg/L | 494 ± 40 |
| TKN | mg/L | 647 ± 38 |
| $NH_4^+$ - N | mg/L | 584 ± 44 |
| $NO_2^-$ - N | mg/L | n.d. |
| $NO_3^-$ - N | mg/L | 0.22 ± 0.02 |
| TP, mg/L | mg/L | 4.08 ± 1.01 |
| BOD/COD | - | 0.07 ± 0.02 |
| COD/TKN | - | 0.76 ± 0.11 |
| Color | - | Yellow* |

Note: n.d. = not detected
*visual observation

## 2. Experimental Systems and Operation Procedures

An overall experimental set-up can be drawn in Figure 22. Details of each part are given below.

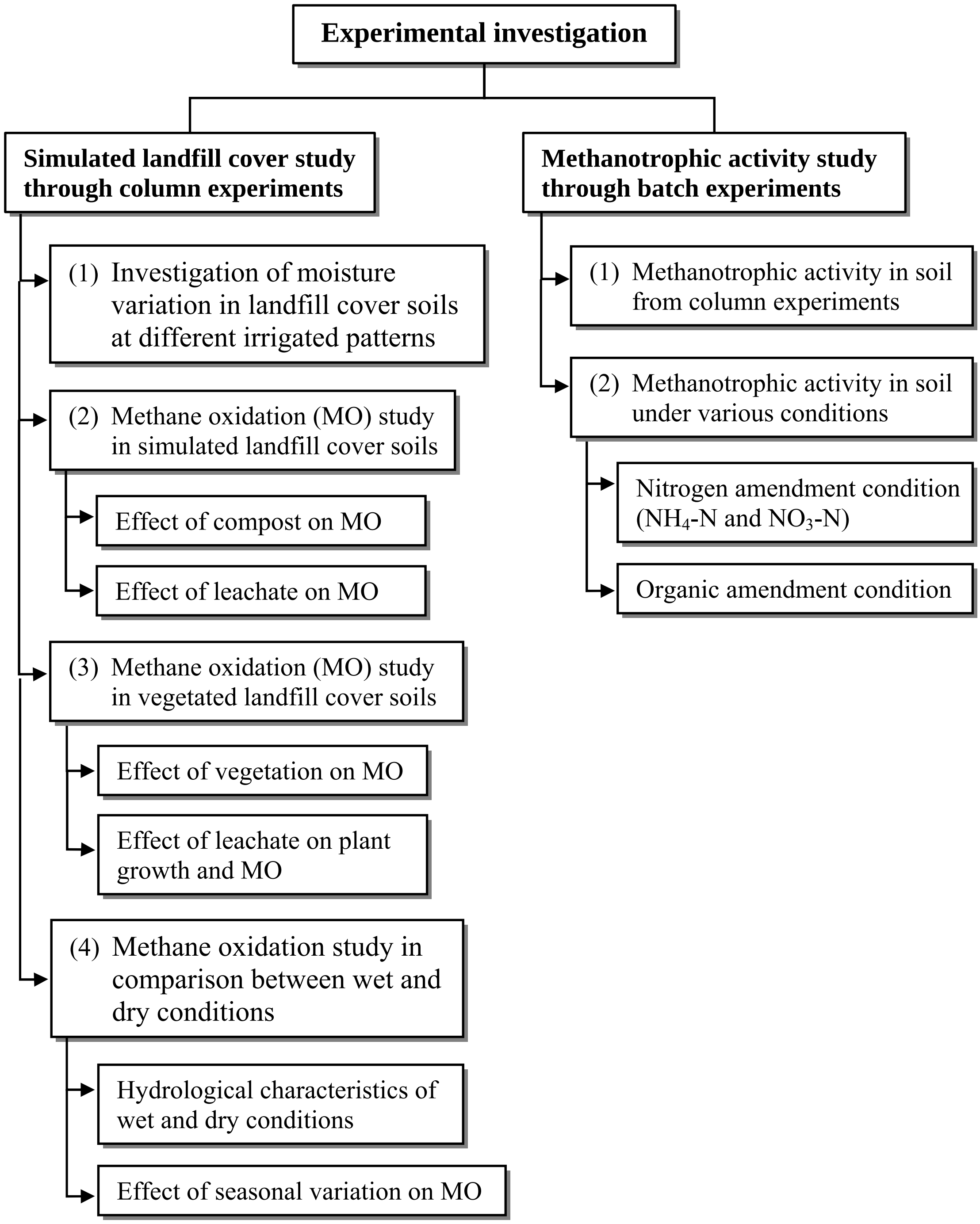



**Figure 22** Overall experimental investigation plan

2.1 Column experimental system

In simulate landfill cover system, all experimental columns were purged at the bottoms with artificial landfill gas ($CH_4$:$CO_2$ = 60:40) at a flow rate of 4 mL/min (equivalent to methane flux of 196 L/$m^2$.d or 14 mol $CH_4$/$m^3$.d). This flow rate was selected as typical of methane production rate (72-274 L/$m^2$.d) derived from a landfill (Emcon, 1980). Air diffusion was supplied naturally from the top of the columns. Each column had 5 rubber septum ports for gas sampling along the depth of column as previously mentioned. The columns were irrigated with either rainwater or leachate at 200 mL every 4 days (equivalent to hydraulic loading of 2.83 L/$m^2$.d) to maintain soil water content and also to represent rainy or wet condition in tropical climate. The dry condition was simulated with no irrigation practice. Additionally, the moisture content of cover materials were also continuously monitored throughout the experimental period by soil moisture sensors (ECHO, model EC-10). These sensors were installed at 5-15, 25-35 and 45-55 cm depth from soil surface and online recorded moisture data via data recorder (ECHO, model Em5). The schematic of experimental system is illustrated in Figure 23.

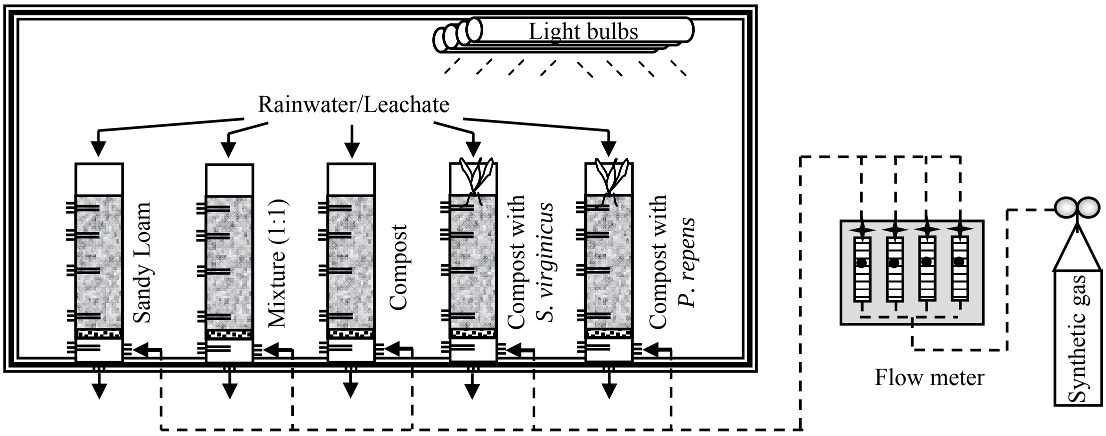



**Figure 23** Schematic of experimental system

2.2 Investigation of moisture variation in landfill cover soils at different irrigated patterns

According to the annual precipitation in Thailand of 1000-1200 mm/year (Tongaram, 1995), the hydraulic loading of 2.83 L/$m^2$.d (about 50 mL/d) was established for simulating rainy season in the column experiment. Different amount of water was applied at corresponding time interval in order to maintain constant overall hydraulic loading, i.e. 50 mL/d, 100 mL/2days and 200 mL/4days, respectively. Moisture content of landfill cover materials were monitored along the experimental period of three irrigated patterns by soil moisture sensors which were installed at the upper, medium and lower positions of landfill cover column. This experiment investigated trend of moisture variation at different patterns of irrigation.

### 2.3 Methane oxidation study in simulated landfill cover column experiment

#### 2.3.1 Effect of compost on methane oxidation

Three types of landfill cover materials (i.e. sandy loam, sandy loam/compost mixture and compost) were employed in the column experiment for investigating the effect of their properties on methane oxidation. The initial moisture of sandy loam was prepared to have optimum moisture content of 10-15% (dry weight basis) for methanotrophic activity while sandy loam/compost mixture and compost used their original moisture content of 20-25% and 45-50%, respectively. The experiment simulated landfill cover system under wet season. Thus, six columns were operated either under rainwater or leachate irrigation (three columns with different cover materials for each operation). Gas samples were collected via gas sampling ports (5 ports throughout column depth) every week for analyzing gas components by gas chromatography (GC) and evaluating methane oxidation rate (MOR). Percolation of rainwater or leachate was also occasionally collected for determining the drainage volume and properties of effluents. Moreover, characteristics of cover materials were analyzed at the beginning and the end of the experimental period.

#### 2.3.2 Effect of leachate on methane oxidation

According to the previous experiment (section 2.3.1), three columns of different landfill cover materials (i.e. sandy loam, sandy loam/compost mixture and compost) which irrigated with leachate were compared for their methane oxidation capacities with other three columns irrigated with rainwater. In this determination, the effect of leachate compared with rainwater on methane oxidation in each of landfill cover material was discussed.

### 2.4 Methane oxidation study in simulated landfill cover column experiment with vegetation

#### 2.4.1 Effect of vegetation on methane oxidation

Vegetation was conducted to evaluate the effect of plant on methane oxidation. Compost was used as landfill cover material in this experimental section. Two tropical grasses (Figure 21), *S. virginicus* and *P. repens*, were cultivated in simulated landfill cover columns. Four vegetated columns were operated with rainwater or leachate irrigation (two columns with different types of grasses for each operation) similar to prior experiment. Two bare columns were also considered as controlled columns for evaluating effect of vegetation. Moreover, simulated sunlight condition was supplied for plant growth during daytime (average light intensity of 35,000 luxes). Gas samples were continually collected via gas sampling ports every week for analyzing gas components by GC and evaluating MOR. Percolation of rainwater or leachate was also occasionally collected for determining the drainage volume and properties of effluents. Observation of plant growth in terms of grass height, number of shoots, leaf width, leaf length and number of leaves was practiced every week.

Moreover, characteristics of cover materials were analyzed at the beginning and the end of the experimental period.

2.4.2 Effect of leachate on plant growth and methane oxidation

As studied above (section 2.4.1), the effect of leachate on plant growth (*S. virginicus* and *P. repens*) was considered in terms of grass height, width and length of leaf, and number of leaves compared to case of rainwater irrigation. Additionally, methane oxidation capacities in the vegetated columns operated with leachate were also investigated in comparison with those of rainwater operation.

2.5 Methane oxidation study in comparison between wet and dry conditions

2.5.1 Experimental simulation of wet and dry conditions

Hydrological characteristics of wet and dry conditions were examined by monitoring the moisture variations of landfill cover materials during the wet and dry condition experiments. In addition, water balance in the landfill cover system was also studied by determining each component in water balance equation in both wet and dry seasons.

2.5.2 Effect of seasonal variation on methane oxidation

In the previous experimental sections, variation of cover material experiment (section 2.3) and vegetation experiment (section 2.4), methane oxidation efficiency was evaluated under intermittent irrigation of rainwater or leachate in wet condition. However, dry condition without irrigation was also operated in this experiment to determine methane oxidation efficiency in each of cover materials (sandy loam and compost) and each of vegetated cover materials (sandy loam with *P. repens* and compost with *P. repens*), and compare their efficiency with that of wet condition operation. Synthetic landfill gas using in this experiment was water saturated gas which flowed past water before upwards to cover materials. Gas samples were continually collected via gas sampling ports every week for analyzing gas components by GC and evaluating MOR compared to wet condition. Moreover, determinations of plant growth and cover material characteristics were practiced every week, and at the beginning and the end of the experimental period, respectively. Furthermore, moisture content of cover materials was also online-monitored throughout the experimental period by soil moisture sensors and data recorder. In bare columns, sensors were installed at the upper and lower parts of column (5-15 and 30-45 cm depth from soil surface), whereas in vegetated columns it was installed at the upper part of column or root zone (5-15 cm depth from soil surface).

## 2.6 Methanotrophic activity study through batch experiment

### 2.6.1 Investigation of methanotrophic activity in landfill cover from column experiment

The activity study was conducted to evaluate methanotrophic activity throughout the depth of landfill cover column experiment, and to examine performance of each cover material. After the experimental period, 10 g of soil samples from experimental columns were transferred to 188 mL serum bottles capped with rubber septum and aluminum ring. Each sample was examined in duplicate. Subsequently, the bottle was added with 10 mL pure methane for 9% methane concentration in headspace and incubated at room temperature (28-30°C). Gas constituents in headspace were investigated by GC at the initial time and everyday for 10 days. However, the actual initial gas concentration was determined 5 min after pure methane was injected to ensure a homogeneous gas distribution inside the bottle. Methane consumption by methanotroph was continually observed throughout the incubated period.

### 2.6.2 Investigation of methanotrophic activity in nitrogen and organic amended landfill cover materials

- Nitrogen amendment

Three types of landfill cover materials (i.e. sandy loam, sandy loam/compost mixture and compost) were studied. Each cover material was incubated at different initial moisture depending on their original moisture content (compost and the mixture material were 45-50% and 20-25%, respectively) except that sandy loam was prepared to have optimum moisture content of 10-15% as mentioned in column experiment.

To study the effect of nitrogen in terms of ammonium nitrogen ($NH_4^+$-N) and nitrate nitrogen ($NO_3^-$-N) on methanotrophic activity, 10 g of each landfill cover material in the bottle was amended with 0.1 mL solution containing 1000, 3000, 5000 and 10000 μg N/mL of $NH_4Cl$ and $KNO_3$, equivalent to $NH_4^+$-N and $NO_3^-$-N concentrations of 10, 30, 50 and 100 μg N/g soil, respectively. The solution was added onto cover material by pipette and mixed by shaking the bottle. For the control bottles, 0.1 mL of distilled water was added instead of nutrient solution. After amendment with nutrient solution, landfill cover materials were incubated following the incubation procedure as previously mentioned (section 2.6.1). Table 12 shows nitrogen contents in landfill cover materials after amendment by nutrient solution.

**Table 12** Nitrogen contents in cover materials after amendment with nutrient solution

| Landfill cover materials | $NH_4^+$-N (µg/g dry soil) | | $NO_3^-$-N (µg/g dry soil) | |
|---|---|---|---|---|
| | Initial contents + addition | Total contents | Initial contents + addition | Total contents |
| Sandy Loam | 46 + 0 | 46 | 116 + 0 | 116 |
| | 46 + 10 | 56 | 116 + 10 | 126 |
| | 46 + 30 | 76 | 116 + 30 | 146 |
| | 46 + 50 | 96 | 116 + 50 | 166 |
| | 46 + 100 | 146 | 116 + 100 | 216 |
| Mixture (1:1) | 45 + 0 | 45 | 126 + 0 | 126 |
| | 45 + 10 | 55 | 126 + 10 | 136 |
| | 45 + 30 | 75 | 126 + 30 | 156 |
| | 45 + 50 | 95 | 126 + 50 | 176 |
| | 45 + 100 | 145 | 126 + 100 | 226 |
| Compost | 46 + 0 | 46 | 122 + 0 | 122 |
| | 46 + 10 | 56 | 122 + 10 | 132 |
| | 46 + 30 | 76 | 122 + 30 | 152 |
| | 46 + 50 | 96 | 122 + 50 | 172 |
| | 46 + 100 | 146 | 122 + 100 | 222 |

- Organic amendment

To study the effect of organic carbon on methane oxidation, sandy loam was amended with compost as natural carbon source at different ratios of 1:0, 3:1, 1:1, 1:3 and 0:1 by wet weight basis. Ten grams of each mixture or non-amendment were also incubated in the bottle following the incubation procedure as previously mentioned. Table 13 shows experiment conditions of organic carbon amendment in sandy loam.

**Table 13** Organic carbon contents in various mixtures of sandy loam and compost

| Ratio of sandy loam and compost | Total organic carbon (%dry weight basis) | Total organic carbon (µg/g dry soil) |
|---|---|---|
| Sandy Loam | 1.24 | 12.4 |
| Mixture (3:1) | 4.55 | 45.5 |
| Mixture (1:1) | 7.03 | 70.3 |
| Mixture (1:3) | 7.91 | 79.1 |
| Compost | 8.48 | 84.8 |

## 2.7 Analytical parameters

### 2.7.1 Methane oxidation rate (MOR) and gas components

Gas samples were collected throughout the depth of soil column via rubber septum ports as previously mentioned. Subsequently, 300 μL gas samples were analyzed for their components ($CH_4$, $CO_2$, $O_2$ and $N_2$) by GC using a model 6890 series (Agilent). The GC analytical condition was set as follows: column model of CTR I; inlet temperature of 105°C; column temperature of 35°C; thermal conductivity detector temperature of 150°C; and carrier gas (helium) flow rate of 65 mL/min. To determine methane conversion efficiency of landfill cover, methane oxidation rate (MOR) was calculated from the reduction of methane concentration in landfill cover as shown in the following equation:

$$\text{MOR } (\text{mol}\,CH_4 / m^3 \cdot d) = \frac{Q \times \left[(CH_4)_{in} - (CH_4)_{out}\right]}{V} \quad (4)$$

with Q as the gas flow rate (mL/day); $(CH_4)_{in}$ and $(CH_4)_{out}$ as the methane concentration (mol/mL) of inflow and outflow, respectively; and V as the volume of landfill cover material ($m^3$). Detail of Eq.(4) solution was described in Appendix A.

### 2.7.2 Fluorescence *in situ* hybridization (FISH) and extracellular polysaccharides (EPS)

After the experimental period, microorganisms in soil samples were evaluated by using FISH technique and EPS determination. Soil samples were recommended to reserve in -20$^{o}$C if instant analysis was not practiced. EPS production was measured in terms of D-glucose by using the “total and labile polysaccharide analysis of soils” method (Lowe, 1993).

For FISH technique, the method used in this study was descried as following steps. Extraction was performed by diluted soil sample with 0.85% NaCl, homogenized and centrifuged at 10,000xg rpm. After that, the fixation was proceeded by transferred the supernatant into 4% paraformaldehyde at pH 7.2, kept under 4$^{o}$C for 2 hrs, then washed with phosphate buffer solution (PBS) and mixture of ethanol and PBS (1:1) was added. The sample was preserved at -20$^{o}$C until hybridizing reaction (Eller *et al.*, 2001). Following step was carried on by immobilization of fixative sample onto the gelatin coated slide and dehydration with various concentrations of ethanol. Oligonucleotide probes Mγ84 + Mγ705 and Mα450 were used to detect type I and type II methanotrophs, respectively (Wagner *et al.*, 1995). The probes were synthesized with purification-desalt method and labeled with Fluorescein. For hybridization step, a buffer and a probe were overlaid on the sample slides and the slides were incubated under specific hybridization temperature of each species for 2 hrs. Then, washing excess probes by dipping the slides in washing buffer and last washing with sterile water. After being dried at room temperature, to observe total microorganisms, the samples were stained with DAPI (4′,6-diamidino-2-phenylindole) and washed with sterile water. To prevent Fluorescein fading out, a Prolong Gold anti-fade reagent was overlaid on the samples. Finally, the samples were examined by fluorescence microscope (Olympus BX51).

2.7.3 Landfill cover materials properties

The physical and chemical properties of landfill cover materials (i.e. pH, EC, CEC, moisture content, organic carbon, TN, $NH_4^+$-N, $NO_3^-$-N, available P and available K) were determined before and after the column experiment according to handbook methods of tropical soil (Anderson and Ingram, 1993).

2.7.4 Plant growth

In the vegetated column experiment, plant growth determination was performed by measuring grass height, number of shoots, leaf width, leaf length and number of leaves every week. Moreover, the unusual appearance of plant was also observed.

2.7.5 Soil permeate characteristics

In the experiment under wet condition, soil permeate of irrigated rainwater or leachate was occasionally collected for determining the drainage volume and properties (i.e. pH, EC, BOD, COD, TKN, $NH_4^+$ - N, $NO_2^-$ - N, $NO_3^-$ - N and TP) following the standard method for the examination of water and wastewater (APHA, 1992).

# RESULTS AND DISCUSSIONS

## 1. Variation of Moisture Content in Landfill Cover Soils at Different Irrigation Patterns

Based on the hydraulic loading of 2.83 L/$m^2$.d (approximately 50 mL/d in case of 176.7 $cm^2$ column area) which was determined from the amount of annual rainwater in Thailand, three irrigation patterns of water (50 mL/d, 100 mL/2days and 200 mL/4days) were performed to investigate the moisture variation throughout the column depth. Moisture content of each landfill cover material (sandy loam, sandy loam/compost mixture and compost) was monitored at three depths of 5-15, 25-35 and 45-55 cm from the soil surface. Moreover, the moisture monitoring was also performed in conditions both with and without synthetic landfill gas upflow.

Figure 24 shows variation of moisture content at different irrigation patterns in the sandy loam column with and without application of synthetic landfill gas upflow. In the case of operation with synthetic landfill gas upflow at the bottom, accumulated water in the soil pores was flushed to the upper layer and consequently evaporated. Thus, the moisture content was found to vary along the depth of cover soil, being highest at the bottom part of the column and lowest at the top part, as a result of evaporative loss (Figure 24(a)). Furthermore, periodical fluctuation of moisture content was also observed, especially at the irrigation pattern of 200 mL/4days. The moisture content was found to be highest just after irrigation and gradually reduced during non-irrigated periods. Longer periods of non-irrigation promoted higher water loss and, therefore, moisture fluctuation. Nevertheless, at 200 mL/4days operation, moisture content of sandy loam over the total column depth was controlled within 13-16% which lied in an appropriate range for methane oxidation reaction.

In another operation without synthetic landfill gas upflow in the sandy loam column, moisture content was observed. Contrary results to that of the applied landfill gas condition are shown in Figure 24(b). Moisture content at the upper layer was higher than the lower, according to high water accumulation at the top which obtained irrigated water directly and had low water loss through only natural evaporation, compared to that of the stimulating situation with landfill gas upflow. However, fluctuation of moisture content at the irrigation pattern of 200 mL/4days was also similar to that of the applied landfill gas condition, but the level was controlled at a high content of 18-20%.

From the experimental results obtained, it was found that intermittent irrigation pattern of 200 mL/4days gave the highest moisture fluctuation which helped to encourage oxygen diffusion into the soil column during the drying period and subsequently improve methane oxidation efficiency. Another benefit of longer drying periods of water irrigation is that more nitrate available due to nitrification in soil (Polprasert, 1988). Therefore, other cover materials of sandy loam/compost mixture and pure compost were investigated for moisture variation at the irrigation pattern of 200 mL/4days only.

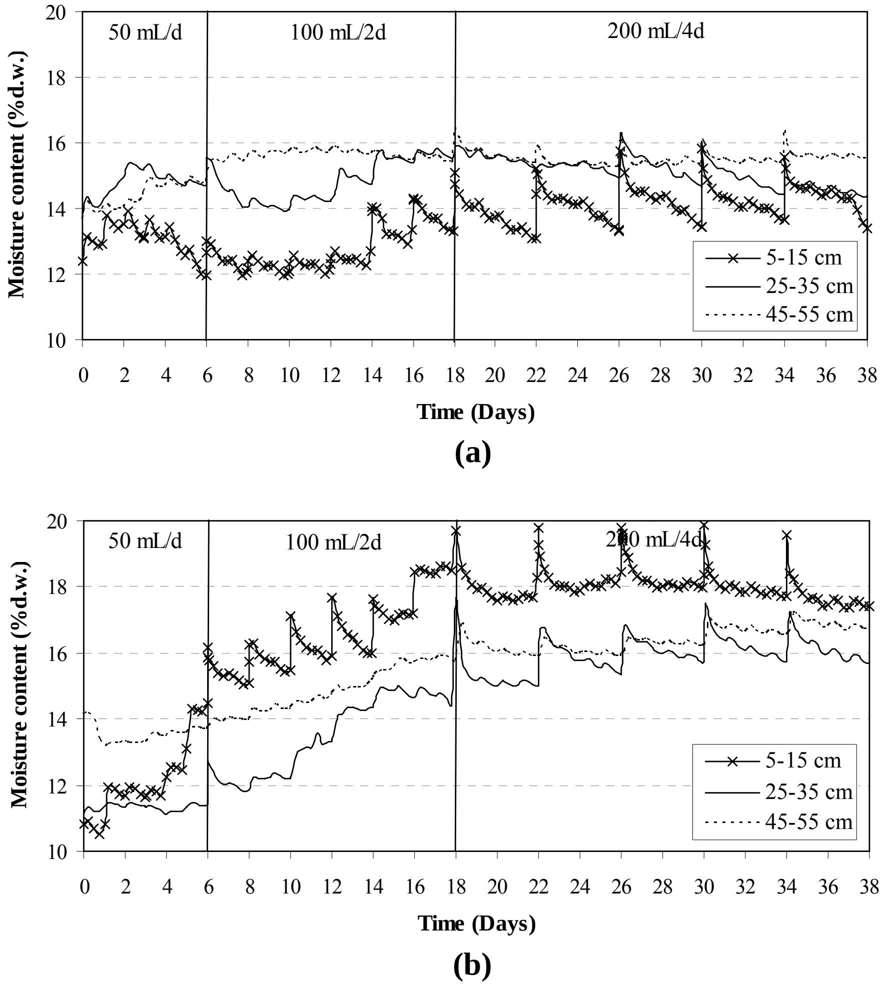



**Figure 24** Variation of moisture content of sandy loam at different irrigation patterns and operations (a) with and (b) without synthetic landfill gas upflow

In sandy loam/compost mixture which was irrigated at 200 mL/4days and operated without gas upflow (Figure 25), the highest moisture content was found at the upper layer until saturated condition took place. Afterwards, moisture content, of the middle and bottom layers respectively, increased to that of the upper layer within a period of 32 days. It was noticed that without the influence of gas upflow all parts of the mixture column presented the same water content of 25%.

After synthetic landfill gas upflow was applied on day 32, moisture content at the upper part gradually declined from 25% to 22% as shown in Figure 25. Landfill gas application significantly affected only the top part of the mixture column which was possibly due to the high water-holding capacity of compost. Introduction of compost in the sandy loam could improve soil physical properties, water-holding capacity, to retain soil water. However, moisture fluctuation during the drying period was found in the upper part of column while small variations, and constant level, were observed in the middle and bottom parts, respectively.

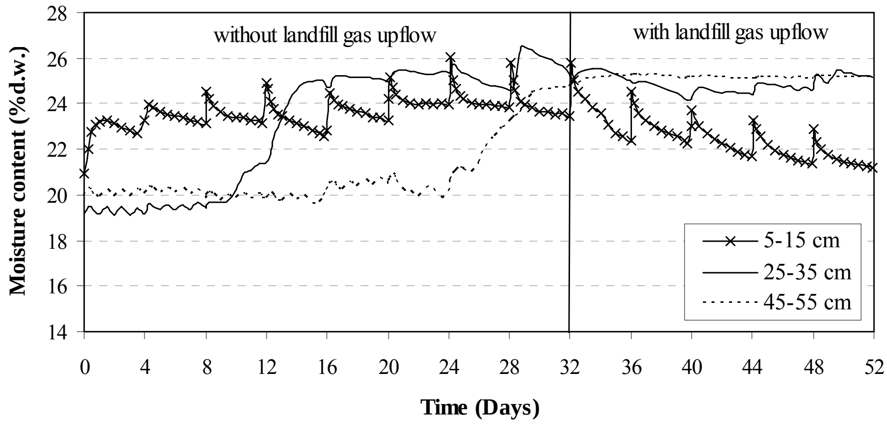



**Figure 25** Variation of moisture content of sandy loam/compost mixture at 200 mL/4days irrigation with and without operation of synthetic landfill gas upflow

The compost material with 200 mL/4days irrigation, also showed the moisture raising steps similar to that of sandy loam/compost mixture but the operating moisture content was much higher at 34-36%. Moreover, it took a longer period to become constant moisture content. Figure 26 shows that moisture content increased from 30% to 36% during days 4-16, 25% to 36% during days 10-20, and 25% to 34% during days 30-45 in the three parts of compost column, respectively. Moisture content in the deeper zone gradually increased as the moisture front moved downwards during the experimental period.

The influence of applied gas upflow slightly affected the moisture variation. As shown in Figure 26, after day 24, the fluctuation of moisture content in the upper layer of the compost column was found to be much less than those in the sandy loam and sandy loam/compost mixture resulting from the water adsorptive capacity of compost material. Furthermore, moisture content at the top part of the compost column was found to be higher than that of sandy loam and sandy loam/compost mixture columns.

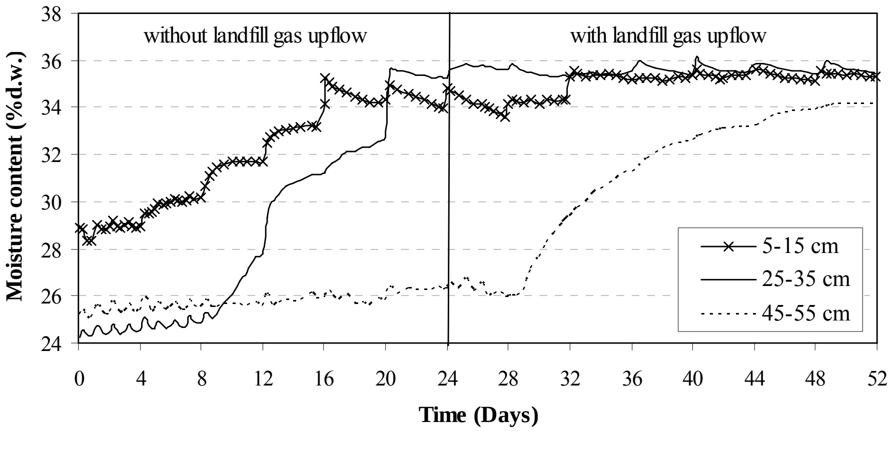



**Figure 26** Variation of moisture content of compost at 200 mL/4days irrigation with and without operation of synthetic landfill gas upflow

## 2. Methane Oxidation Study in Simulated Landfill Cover Soils

In this study, three landfill cover materials (sandy loam, SL; the mixture of sandy loam and compost, SL+C; and compost, C) were compared for their effectiveness in methane oxidation as evaluated by the methane oxidation rate (MOR). According to the simulated landfill condition of the 'wet season' in this section, each landfill cover material was also irrigated, either with leachate or rainwater (as a control), to evaluate the effect of leachate on methane oxidation. The results are described as follows.

### 2.1 Effect of compost on methane oxidation

MOR in the experimental columns with sandy loam, sandy loam/compost mixture and compost are shown in Figure 27. It was found that all materials provided high MOR (8 mol $CH_4/m^3.d$) at the beginning of the experiment. Methanotrophs could rapidly develop their capacity in consuming methane after the start-up. Throughout the experiment, each landfill cover material exhibited different MOR patterns.

In the case of rainwater irrigation (Figure 27(a)), compost application did not significantly affect the efficiency of methane oxidation. Sandy loam and compost materials could continue their capacity of methane oxidation for about 160 and 120 days respectively, whereas the mixture of sandy loam and compost responded for only 60 days. MOR of sandy loam was maintained at a range of 8-10 mol $CH_4/m^3.d$ (60-70% methane removal) and gradually declined to zero on day 160. In compost, MOR increased to a maximum value of 14 mol $CH_4/m^3.d$ before rapidly diminishing on day 120. Different patterns of MOR in sandy loam and compost, which showed lower MOR within longer active periods and higher MOR within shorter periods, could be evaluated by integrating the MOR graph (Figure 27(a)) of each material to obtain the graph area referred to as the total capacity of methane oxidation. The calculated results presented small difference in total methane oxidation capacity of 1,300 and 1,200 mol $CH_4/m^3$ throughout the active period of sandy loam and compost, respectively. Conversely, the mixture of sandy loam and compost gave the shortest period of methane oxidation of about 10-12 mol $CH_4/m^3.d$ (70-85% methane removal) that rapidly dropped down to zero on day 60, which represented the small capacity of total methane oxidation (500 mol $CH_4/m^3$) during the active period. Obviously, water logging took place in that of the mixture column which inhibited downward air flow into the soil media, followed by oxygen depletion throughout the depth profile and therefore no apparent methanotrophic activity. This phenomenon in the mixture material was attributed to the replacement of compost particles in the soil voids which increased water retention capacity and reduced water infiltration (Epstein, 1997), especially at the surface layer. Additionally, the production of extracellular polysaccharides (EPS) by methanotrophs under unsuitable environments might also influence the restriction of downward water movement.

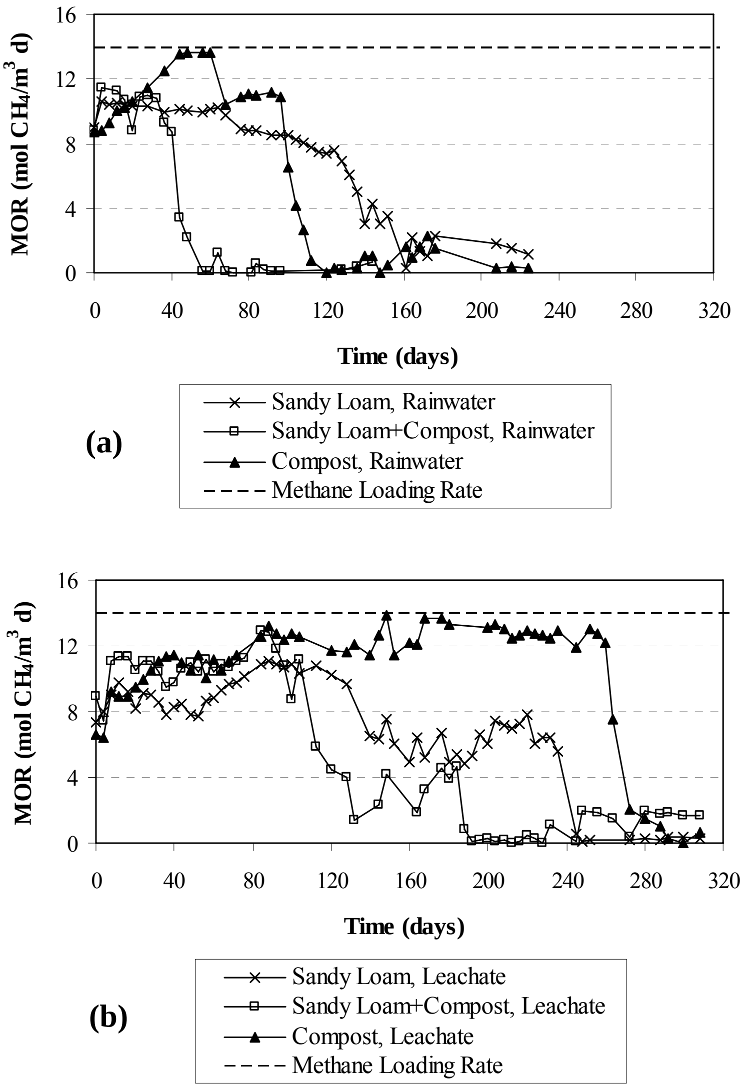



**Figure 27** Variation of total methane oxidation rate (MOR) in landfill cover materials with (a) rainwater and (b) leachate irrigations

Figure 27(b) shows MOR in another operation with leachate irrigation which was monitored for over 300 days. During the first 100 days, high MOR of 8-13 mol $CH_4/m^3$.d (60-90% methane removal) was obtained in all three materials, however, sandy loam/compost mixture and compost gave a slightly higher MOR than that of sandy loam. Afterwards, MOR in the mixture gradually dropped to zero within the next 100 days. Similarly, MOR in sandy loam also gradually decreased to the range of 6-8 mol $CH_4/m^3$.d (50-60% methane removal) in the later period lasting for 240 days. Compost successfully maintained the highest MOR of 12-13 mol $CH_4/m^3$.d (85-90% methane removal) over the longest period of 280 days. According to determination of the total capacity of methane oxidation by integrating the MOR graph (Figure 27(b)), compost clearly demonstrated a higher total capacity of 3,200 mol $CH_4/m^3$ throughout the active period compared with sandy loam and the mixture (1,900 and 1,500 mol $CH_4/m^3$, respectively). From these results, it can be seen that the application of compost material with leachate irrigation practice could actually help in enhancing MOR and prolonging active methane oxidation period.

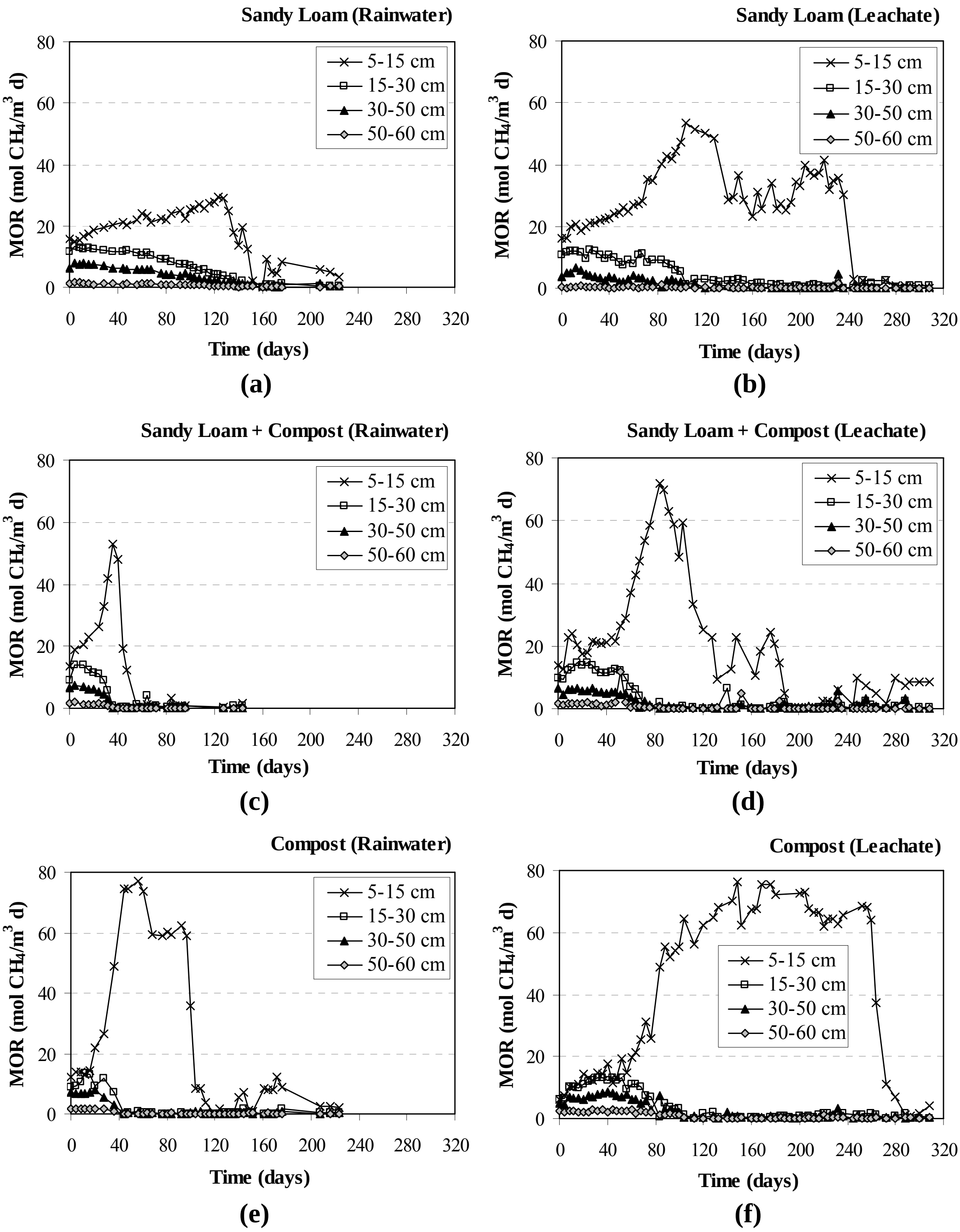



**Figure 28** Methane oxidation rate (MOR) throughout the depth profile of landfill cover materials with rainwater and leachate irrigations

Further consideration into the reaction rate at different depths (Figures 28(b), (d) and (f)) it suggested that compost and the mixture materials had deeper active zones of methanotrophic activity (5-50 cm) compared to sandy loam soil (5-30 cm) during the first 100 days. During the following experimental period, the active zone of all materials was shifted to the upper part (5-15 cm) possibly due to water accumulation in the lower part.

The analysis of gas profiles along the depth of each cover material also confirmed the capability of oxygen diffusion in compost and even in the mixture deeper than in sandy loam. At the beginning of the active period (Figures 29(a), (c) and (e)), after 50 days, methane was effectively reduced throughout the depth of compost while oxygen was consumed to oxidize methane and carbon dioxide was produced. The $CH_4$:$CO_2$ ratio in compost material changed from about 60:40 at the inlet of the column to 20:80 at 5 cm depth from the surface. Similarly in the case of mixture, the active zone was found over almost the entire depth, even if a lower methane oxidation capacity was presented. These results defined a wide horizon and high capacity of methane oxidation in compost and even in the mixture. However, in sandy loam, methane gradually declined between 5 and 30 cm depth and the $CH_4$:$CO_2$ ratio also slightly changed from about 60:40 to 50:50. These profiles were in agreement with the higher methane oxidation capacity in compost and the mixture compared to sandy loam. After 150 days (Figures 29(b), (d) and (f)), the declining period of methane oxidation in sandy loam and the mixture, the active zone shifted to the upper layer (5–15 cm depth) and methane concentration reduced from 60% to 35-40%. In compost, the active zone also shifted to the upper layer but methane concentration was still effectively reduced from 60% to 10%. These results indicated that compost could maintain effective methane oxidation throughout the experimental period, even if the active zone shifted to the upper part in the later stage.

According to the beneficial physical properties of compost (high porosity and water-holding capacity) it could support higher oxygen availability for methane oxidation as compared to sandy loam soil and provide adequate moisture content, both of which have been reported to benefit methane oxidation (Humer and Lechner, 2001a; Streese and Stegmann, 2003; Wilshusen *et al.*, 2004a). Additionally, higher organic content in compost also positively affected methane oxidation. Christophersen *et al.* (2001) reported that MOR increased with increasing organic content in landfill cover. Moreover, Humer and Lechner (2001b) also confirmed that high organic material such as compost gave high effective in oxidizing methane due to high porosity as well as supplemental nutrients for methanotrophs.

From the experimental results, methane oxidation efficiency was proved higher and more sustainable in compost than in sandy loam or even in the mixture. Furthermore, sustention of high MOR in compost was achieved only in the case of leachate irrigation but not in rainwater irrigation. This could imply that leachate also had some positive effects on methanotrophic activity as discussed in the following section.

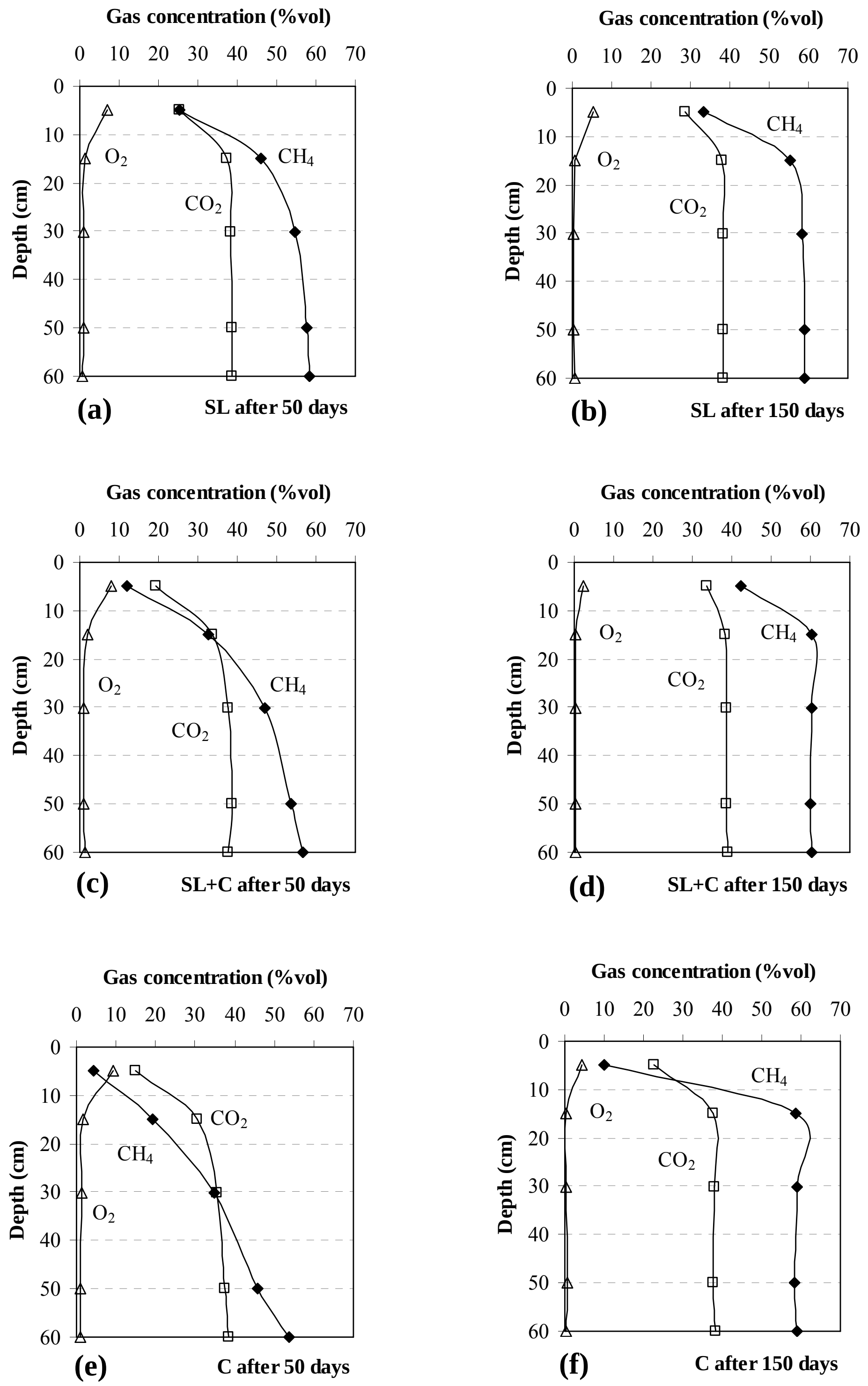
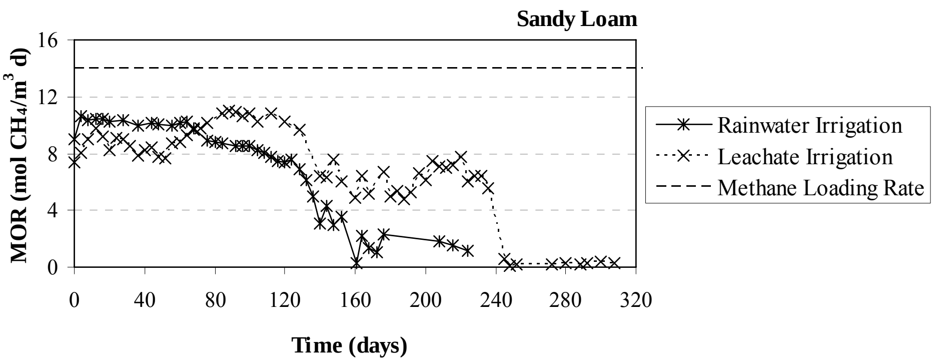



**Figure 29** Gas concentration profiles during leachate application as a function of depth in sandy loam after (a) 50 days and (b) 150 days; mixture of sandy loam and compost after (c) 50 days and (d) 150 days; and compost after (e) 50 days and (f) 150 days of experiment

2.2 Effect of leachate on methane oxidation

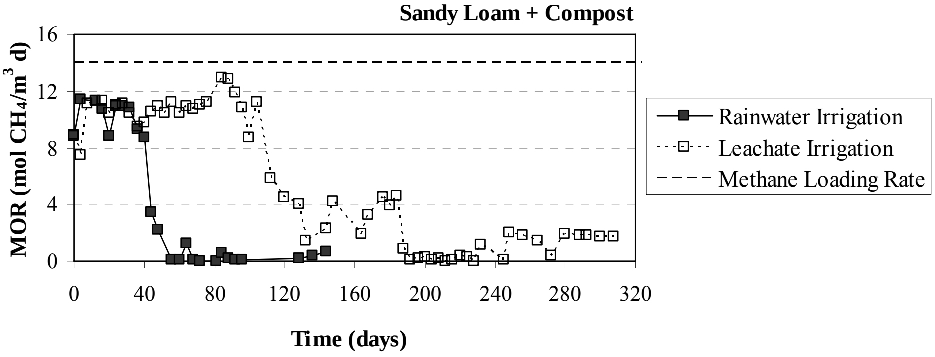
The results of MOR in three landfill cover materials could compare the effect of leachate irrigation in each material with the control rainwater irrigation as shown in Figure 30. Leachate application could extend the steady period of MOR. Significant extension of active methane oxidation period was observed in compost (Figure 30(c)), which increased the steady period from 100 days (rainwater application) to 260 days (leachate application). Otherwise, the active period in sandy loam (Figure 30(a)) was lengthened from 140 days under rainwater irrigation to 240 days under leachate irrigation. In the mixture of sandy loam and compost (Figure 30(b)), the short steady period was also increased from 40 days to 100 days when leachate was applied. Moreover, determination of the total capacity of methane oxidation by evaluating the area of MOR curve evidently confirmed the benefit of leachate on methanotrophic activity. Leachate application, compared with control rainwater, could increase total capacity of methane oxidation in compost from 1,200 to 3,200 mol $CH_4/m^3$, in the mixture from 500 to 1,500 mol $CH_4/m^3$ and in sandy loam from 1,300 to 1,900 mol $CH_4/m^3$ within their active periods.

The comparison results clearly showed the favorable effect of leachate irrigation on methane oxidation, especially in the case of compost material. It was possibly because of the chemical properties of leachate in providing sufficient nutrients which would alter the effect of maintaining moisture content (Maurice, 1998; Maurice *et al.*, 1999). However, long-term irrigation could also deteriorate methane oxidation due to increasing water accumulation which caused clogging in soil pores and restricted oxygen penetration (Watzinger *et al.*, 2005). From the experimental results, it demonstrated that MOR in all columns rapidly declined at the end of the experimental period, caused by the depletion of oxygen concentration below 2-3% by volume. This absence of sufficient oxygen supply was reported to critically affect methane oxidation reactions (Czepiel *et al.*, 1996). Therefore, this negative irrigation effect was possibly one of the reasons for declination of methane oxidation. Nevertheless, methane emission could be effectively controlled over 260 days with leachate irrigation in compost material.

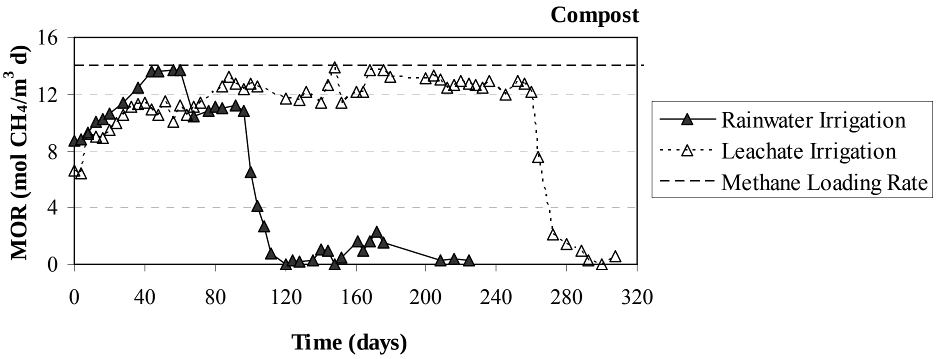



**(a)**

**Figure 30** Comparison of methane oxidation rate (MOR) between rainwater and leachate irrigations in (a) sandy loam, (b) sandy loam/compost mixture, and (c) compost



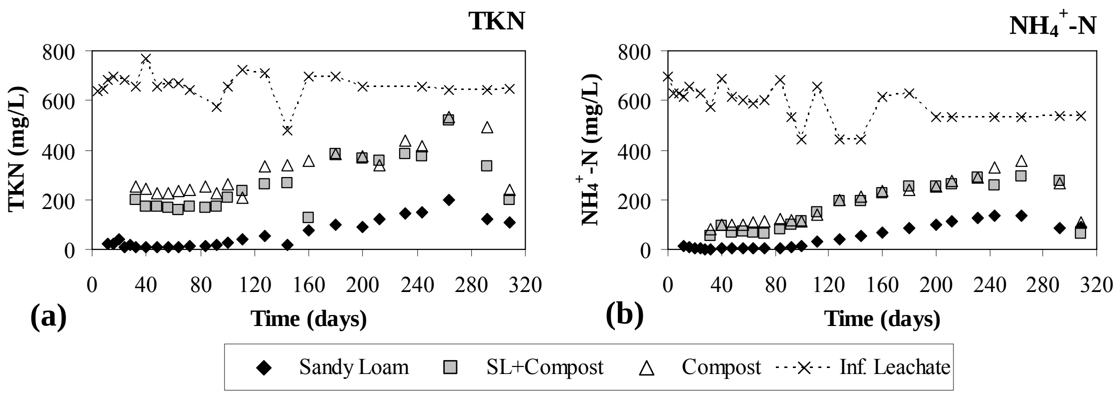

**(b)**




**(c)**

**<u>Figure 30</u>** (Cont'd)

Furthermore, in column experiments with leachate irrigation, the removal of leachate nitrogen through landfill cover materials was also considered. As shown in Figure 31, TKN and $NH_4^+$-N contents of irrigated leachate were significantly removed in all three cover materials. Sandy loam presented higher nitrogen removal capacity of 90% TKN and $NH_4^+$-N, while sandy loam/compost mixture and compost gave similar efficiencies of 50-60% TKN removal and 70% $NH_4^+$-N removal. The purification process of irrigated leachate was probably due to soil adsorption and microbial degradation and assimilation.




**<u>Figure 31</u>** Nitrogen content, (a) TKN and (b) $NH_4^+$-N, of irrigated leachate and effluents from column experiments operated with leachate

2.3 Extracellular polysaccharides (EPS) production

Production of slime or EPS by methanotrophs was also considered at the end of the column experiment. Soil samples from the experimental columns were analyzed for EPS production in terms of glucose carbon concentration. The results showed that EPS formations were found in all columns throughout the depth profile (Figure 32). In sandy loam, EPS content was found to be about 2 mg C/g dry soil throughout the depth profile while in the sandy loam/compost mixture and compost, contents were in the ranges of 4-12 and 10-19 mg C/g dry soil, respectively. Obviously, compost demonstrated higher production of EPS than the two other materials. Additionally, the highest EPS concentration was found in the upper layer (5-15 cm) where the highest methanotrophic activity took place. Many researches proposed that EPS production contributed to the sustenance of methanotrophs from unsuitable conditions such as desiccation, predation, heat tolerance and a carbon-rich environment (Hilger *et al.*, 1999, 2000a; Chiemchaisri *et al.*, 2001a). Thus, compost (referred as organic-rich material) could promote EPS production rather than other materials and the upper part with the abundance of methanotrophs would contribute more EPS formation after long-term operation of the column experiment. The accumulation of EPS correlated with the declination of methane oxidation efficiency due to sealing in soil pores and limiting oxygen penetration (Hilger *et al.*, 1999, 2000a; Chiemchaisri *et al.*, 2001a; Wilshusen *et al.*, 2004a, 2004b). Since the upper part possessed high EPS content, which clogged soil pores, methanotrophic activity at the lower part was also restricted. From this result, EPS accumulation in the soil column was established as another reason for the diminution of methane oxidation besides water accumulation through long-term water irrigation. Additionally, downward soil migration also correlated with increasing soil density and greater resistance to oxygen diffusion which attributed to deterioration of methane oxidation.

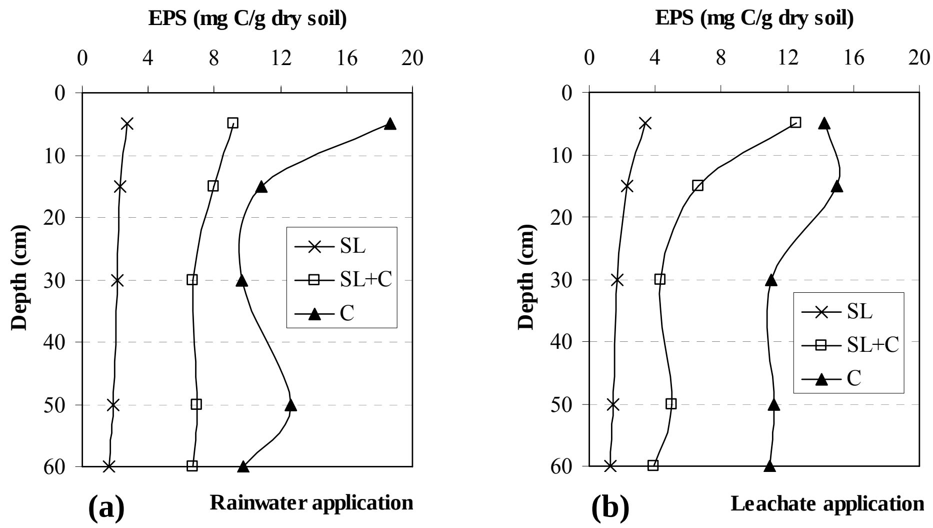



**Figure 32** EPS (expressed as mg C/g dry soil) profiles as a function of depth in landfill cover materials at the end of experiment: (a) rainwater and (b) leachate irrigations

2.4 Methanotrophic activity in batch experiment

The activity of methanotrophs in sandy loam, the mixture and compost was studied in batch incubation. Those three cover materials were sampled from the experimental columns at the end of experiment. Figure 33 illustrates methane consumption activity of the three cover materials at various depths. MOR was evaluated from the slope of those activity curves as summarized in Table 14. In each cover material, the consumption curve was uniform with a significantly higher activity rate in the upper layer than in the lower layer. The degree of oxidation rate in each layer correlated with the activity and population of methanotrophs in the sampled layer (Hilger *et al.*, 2000b).

In sandy loam (Figures 33(a) and (b)), methane concentration gradually declined from 9% to 0% within the period of 100-150 hr, however lower methane consumption rate was observed at 50-60 cm depth in the case of rainwater application. It provided the declination of MOR in the range of 0.1-0.4 µmol $CH_4$/kg.s (Table 14). Nevertheless, sandy loam from the column operated with leachate showed slightly lower oxidation rate than that operated with rainwater.

Contradictory results were obtained in the cases of compost and mixture (Figures 33(c)-(f)). These two materials exhibited similar patterns of methane consumption and methane was completely consumed within a shorter period (20-80 hr) than the sandy loam case. In the active zone of these materials, an MOR of 1.0-1.6 µmol $CH_4$/kg.s was found in the rainwater case, whereas leachate application showed a slightly higher rate of 1.0-2.5 µmol $CH_4$/kg.s (Table 14).

**<u>Table 14</u>** Methane oxidation rate in batch experiment of three cover materials collected from column experiment with rainwater and leachate applications

| Landfill covers | Depth | Methane oxidation rate (µmol $CH_4$/kg dry soil·s) | |
|---|---|---|---|
| | | Rainwater application | Leachate application |
| SL | 0-5 cm | 0.36 | 0.23 |
| | 5-15 cm | 0.40 | 0.20 |
| | 15-30 cm | 0.37 | 0.26 |
| | 30-50 cm | 0.28 | 0.28 |
| | 50-60 cm | 0.11 | 0.19 |
| SL+C | 0-5 cm | 1.35 | 2.21 |
| | 5-15 cm | 1.36 | 1.37 |
| | 15-30 cm | 1.12 | 1.07 |
| | 30-50 cm | 1.18 | 0.84 |
| | 50-60 cm | 0.80 | 0.74 |
| C | 0-5 cm | 1.62 | 2.51 |
| | 5-15 cm | 0.93 | 1.73 |
| | 15-30 cm | 1.06 | 1.18 |
| | 30-50 cm | 0.88 | 1.04 |
| | 50-60 cm | 0.61 | 1.13 |

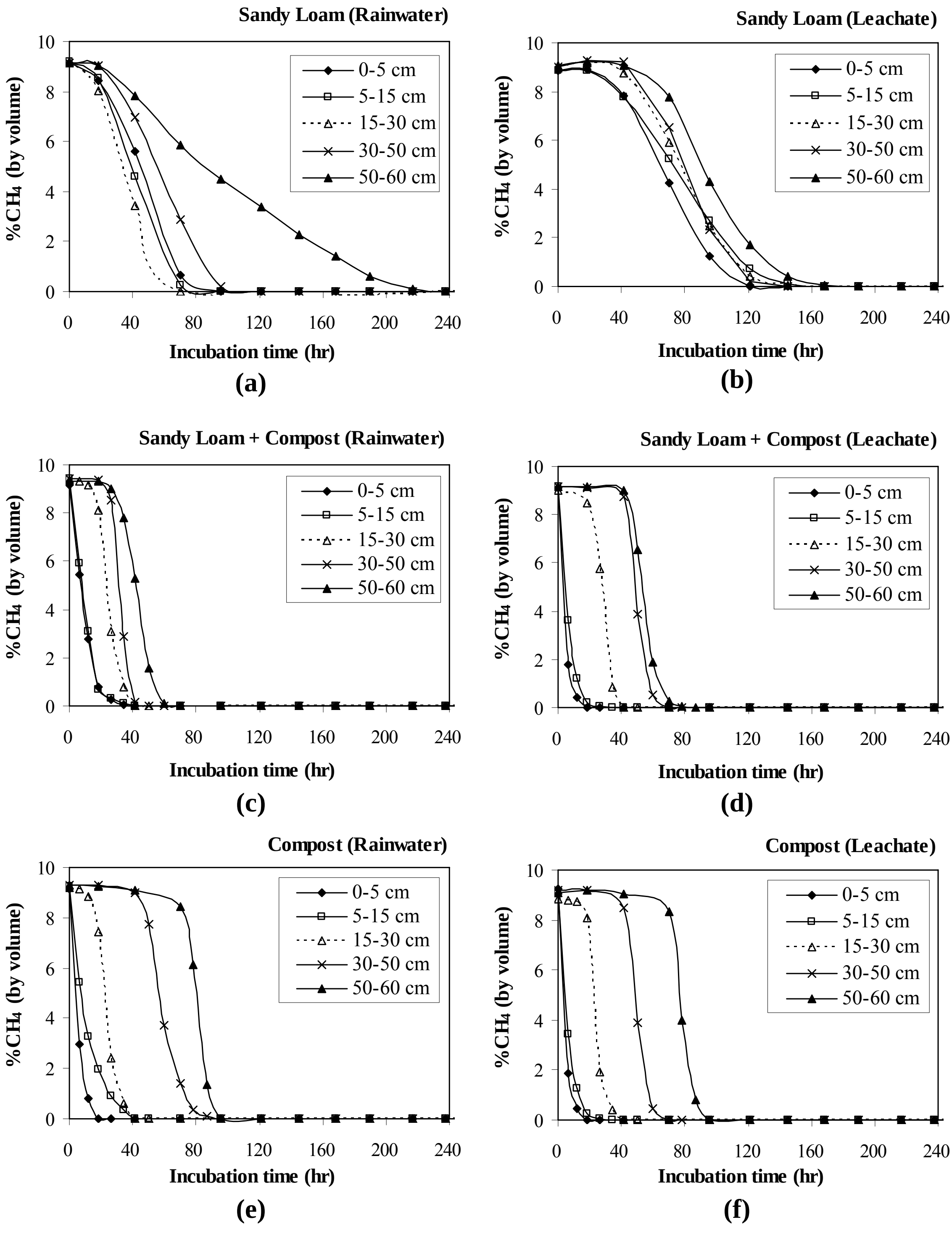



**Figure 33** Methane consumption in batch experiment of three cover materials: (a), (b) sandy loam; (c), (d) sandy loam/compost mixture; and (e), (f) compost with rainwater and leachate applications, respectively

From these results, the activity of methanotrophs in compost and the mixture was higher than in sandy loam, and the active zone was found deeper. This confirms the results of the column experiment that compost and the mixture materials had a higher capacity of methane oxidation in their active periods compared with sandy loam soil.

Furthermore, it should also be noted that the increase of the lag periods before methane consumption (Figure 33), especially in the cases of compost and mixture, was related to the depth of soil sampling. Deeper layers of soil column generally offered more anoxic condition for methanotrophs. However, some methanotrophs could survive under anoxic condition for several months due to cell formation of the resting stages (cysts or exospores), and then the active stage recovered when methane and oxygen once again became available (Roslev and King, 1994, 1995). They also proposed that the duration of lag period increased with increasing starvation (the absence of methane) time. On the contrary, these resting stages were not found in this batch study. It could be validated by staining techniques which found only the gram-negative rod of methane oxidizing bacteria not their cyst or exospore forms. According to the study of Whittenbury *et al.* (1970a), resting cells would be formed due to the absence of methane, desiccation and drying. Therefore, formation of methanotrophic resting cells would not occur in these batch experimental materials (compost, the mixture or sandy loam) which were sampled from the methane available environment. The difference in ratio of oxygen and methane ($O_2$: $CH_4$) was further considered as a significant cause for increase in the lag period. A high $O_2$: $CH_4$ ratio (about 1.8) in this batch experimental condition was close to that of the ratio in the upper layer (15 cm depth from surface) of compost and the mixture columns, thus the methanotrophic activity could rapidly resuscitate when incubation was initiated. A much lower ratio of $O_2$: $CH_4$ in the original surroundings was attributed to an extended period of time in adaptation for methanotrophic activity. This observation could explain the occurrence of lag phases of methanotrophic activity in compost and the mixture.

### 2.5 Soil respiration through batch experiment

Soil respiration was determined through the production of carbon dioxide in batch incubation without spiked methane. The rate of carbon dioxide production was defined by the slope of the linear curve of carbon dioxide content versus incubated time which followed a zero-order kinetic. Table 15 presents the respiration rate of the three cover materials which were sampled from the top layer of the experimental column operated with rainwater and leachate. It clearly demonstrated that compost provided a higher respiration rate than the mixture and sandy loam. A high carbon dioxide production or soil respiration was related to high activity of microorganism (Mor *et al.*, 2006). This probably implied that compost might be still decomposing. However, Humer and Lechner (2001b) reported that compost was almost completely stable when the 7-day respiratory activity value was lower than 10 mg $O_2$/g DM. According to that 7-day respiration rate, compost material using in this study revealed the lower value of 4 mg $O_2$/g DM (equivalent to 0.21 μmol $O_2$/kg dry soil·s) indicating that compost material from the experimental column was stable.

In consideration of respiration rate (Table 15) and MOR (Table 14) of each cover material, it was found that the oxygen consumption in soil respiration was less than 10% of that of methane oxidation. Therefore, the competitive oxygen consumption of methane oxidation by soil respiration was not significant.

**Table 15** Respiration rate of landfill cover materials with rainwater and leachate irrigations

| Landfill covers | Respiration rate [(1)] (μmol $CO_2$/kg dry soil·s) | |
|---|---|---|
| | Rainwater irrigation | Leachate irrigation |
| SL | 0.016 (0.017) | 0.023 (0.022) |
| SL+C | 0.078 (0.071) | 0.112 (0.124) |
| C | 0.201 (0.189) | 0.228 (0.213) |

Note: [(1)] Data in brackets are respiration rates in unit of μmol $O_2$/kg dry soil·s

Furthermore, the respiration rate of each cover material was slightly higher in the cases of leachate irrigation compared with rainwater cases. It implied that the supplemental organic matter from leachate probably encouraged soil respiration, however, was slightly affected by characteristics of stabilized leachate with low BOD/COD ratio (Table 11).

2.6 Effect of nitrogen amendment through batch experiment

From the results of the column experiment (section 2.2), leachate irrigation showed the beneficial effect (nutrient supplement) of extending the active period of methane oxidation and also increasing the total capacity of methane oxidation in all three cover materials. In addition, in each cover material, when considering MOR in the active period between the cases of rainwater and leachate, some different effects of irrigated leachate were found. As shown in Table 16, the former active period (day 0-120) of sandy loam presented similar MOR of about 10 mol $CH_4/m^3$.d (70% removal) in both rainwater and leachate cases. Subsequently, methane oxidation in the rainwater case dropped to zero while that of leachate continued in the later active period (day 120-240) at a lower MOR of 6 mol $CH_4/m^3$.d (45% removal). Different behavior was observed in the case of compost material. MOR in the later active period (day 100-260) of leachate application (13 mol $CH_4/m^3$.d; 90% removal) was higher than that of the former period (day 0-100) in both leachate and rainwater applications (11 mol $CH_4/m^3$.d; 80% removal). In this consideration, leachate irrigation affected methane oxidation in sandy loam and compost in different manners. A negative effect was found in sandy loam whereas a positive effect was shown in compost material. Therefore, the effect of leachate on methane oxidation in each cover material was investigated in terms of nutrient nitrogen ($NH_4^+$ and $NO_3^-$) through batch experiment as follows.

Figure 34 presents the methane consumption curve of batch experiment with $NH_4^+$ and $NO_3^-$ amendment. The methane consumption or MOR was assumed to be a zero-order reaction with constant rate as shown in Tables 17 and 18.

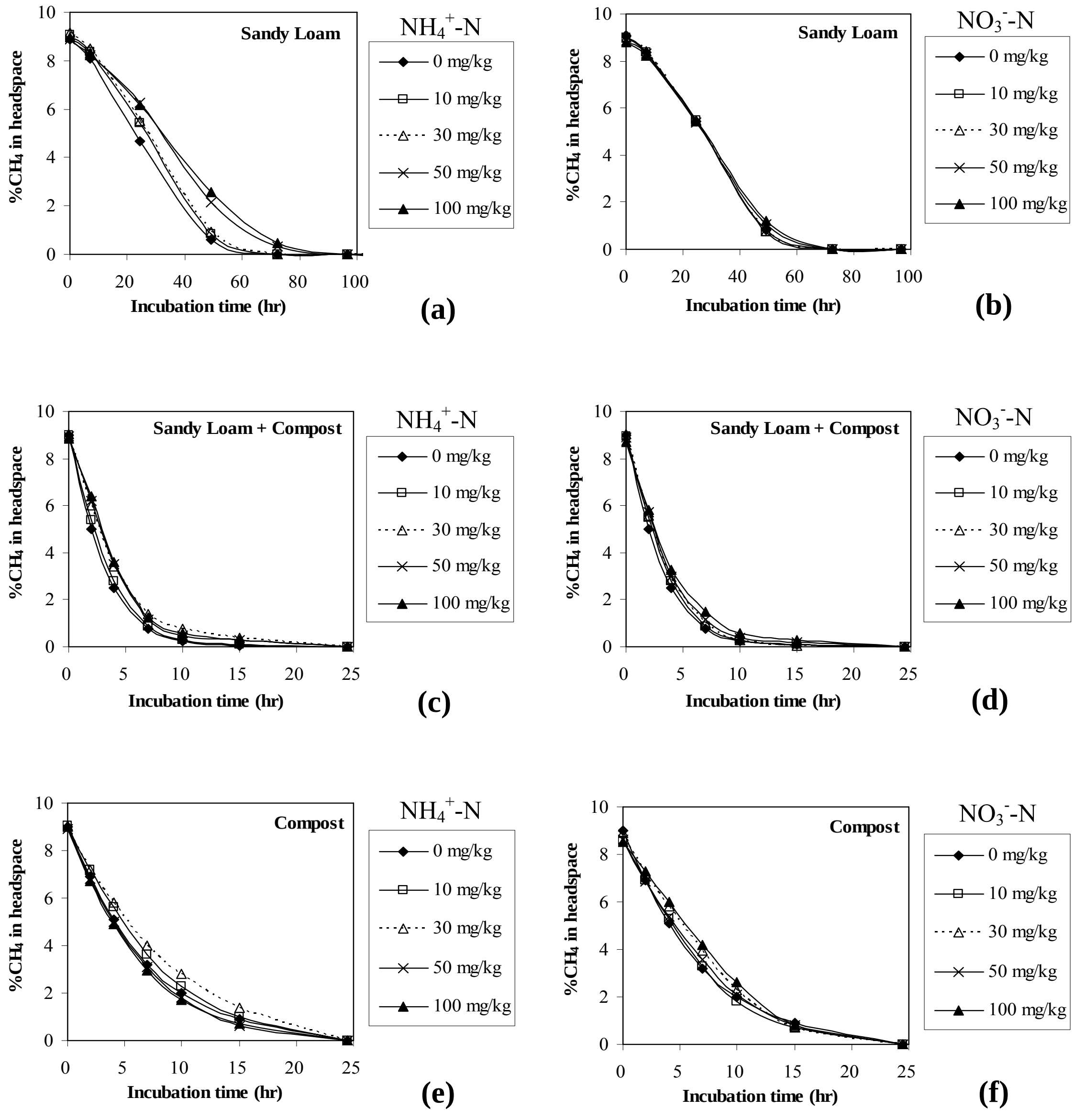



**Figure 34** Methane concentration in headspace over time in batch $NH_4^+$ and $NO_3^-$ amendment of three landfill covers: sandy loam added (a) $NH_4^+$ and (d) $NO_3^-$; sandy loam/compost mixture added (b) $NH_4^+$ and (e) $NO_3^-$; and compost added (c) $NH_4^+$ and (f) $NO_3^-$

**Table 16** Methane oxidation in the active period of column experiment with rainwater and leachate irrigations

| Landfill covers | | Active period (days) | Methane oxidation (1) | |
|---|---|---|---|---|
| | | | mol $CH_4/m^3$.d | % |
| SL | Rainwater | 0-120 | 9.7 ± 0.8 | 69.5 ± 5.5 |
| | Leachate | 0-120 | 9.3 ± 1.1 | 66.7 ± 7.7 |
| | | 120-240 | 6.3 ± 0.9 | 44.8 ± 6.3 |
| SL+C | Rainwater | 0-40 | 10.2 ± 1.1 | 72.9 ± 8.0 |
| | Leachate | 0-40 | 10.3 ± 1.2 | 73.3 ± 8.8 |
| | | 40-100 | 11.1 ± 1.0 | 79.2 ± 7.2 |
| C | Rainwater | 0-100 | 10.9 ± 1.4 | 78.5 ± 9.7 |
| | Leachate | 0-100 | 10.8 ± 1.2 | 77.5 ± 8.3 |
| | | 100-260 | 12.5 ± 0.8 | 89.8 ± 5.7 |

Note: (1) All data are the averages and standard deviations of MOR and removal percentage in the steady active period

2.6.1 Effect of ammonium amendment

The $NH_4^+$ amendment had the slight inhibitory effect on methane oxidation especially in sandy loam, with a high amount of $NH_4^+$ amendment (Table 17). In sandy loam soil, low amended $NH_4^+$ (10 and 30 mg N/kg soil) did not significantly affect the methanotrophic activity, whereas a high amount of $NH_4^+$ amendment (50 and 100 mg N/kg soil) provided the inhibition of about 30%. Same inhibitory effect of $NH_4^+$ amendment (50 and 100 mg N/kg soil) in landfill cover soil was also confirmed by Visscher *et al.* (2001). They proposed that the inhibitory effect of $NH_4^+$ increased with the exposure time of soil to the high $CH_4$ according to the dominant microorganism at that time. Different observations of $NH_4^+$ were reported by Kightley *et al.* (1995), Hutsch (1998), Cai and Yan (1999) and Whalen (2000) showing strong inhibitory effects during incubation studies of landfill cover soil, arable soil, paddy soil and forest soil. They explained that the suppression of methanotrophic activity was due to the competitive metabolism of methane monooxygenase (MMO) in methanotrophs. $NH_4^+$ could be co-oxidized by MMO enzyme according to similar chemical structures and almost equal molecular weights between methane and $NH_4^+$ (Anthony, 1982). Moreover, the intermediate and end products of $NH_4^+$ co-oxidation by methanotrophs were nitrite ($NO_2^-$) and hydroxylamine which could be toxic to methanotrophs (Whittenbury *et al.*, 1970b; Schnell and King, 1995) and further oxidized to $NO_3^-$ by nitrification process.

$NH_4^+$ amendment did not significantly affect methane oxidation in the mixture of sandy loam and compost. Only less than 5% reduction of MOR was observed, even at high $NH_4^+$ amendment (100 mg N/kg soil). However, in compost material, $NH_4^+$ amendment at low content did not significantly affect the methanotrophic activity while high content of $NH_4^+$ (50 and 100 mg N/kg soil) led to slight stimulation of methane oxidation. It could be noticed that the inhibition of $NH_4^+$ amendment was less pronounced when compost was applied in sandy loam. The effect of $NH_4^+$ amendment in cases of mixture and compost could be explained by the mechanisms at the community level and ecosystem level as follows.

Firstly, less or no effect of $NH_4^+$ amendment was probably due to the changes in the bacteria community, i.e. possible shift between $NH_4^+$-tolerant and $NH_4^+$-intolerant methanotrophs or a relative increase of $NH_4^+$ oxidizers consuming methane (Hutsch, 1998; Sitaula *et al.*, 2000). Furthermore, the capacity of soil to adsorb $NH_4^+$ in the soil matrix (referred as cation exchange capacity; CEC) could reduce the competitive inhibition of $NH_4^+$ for methanotrophic activity (Dunfield and Knowles, 1995; Gulledge *et al.*, 1997).

Secondly, the stimulatory effect of $NH_4^+$ amendment was suggested by Cai and Mosier (2000) and Visscher *et al.* (2001). The amount and activity of $NH_4^+$ oxidizers increased at high $NH_4^+$ content and thus methane oxidation also increased. High natural nitrification of soil, especially compost material, also helped to reduce $NH_4^+$ co-oxidation by methanotrophs. Other explanations of the stimulatory effect related to $NH_4^+$-N limitation of methanotrophic growth which was mitigated by $NH_4^+$ amendment and subsequently increased methanotrophic activity (Visscher *et al.*, 1999; Papen *et al.*, 2001; Visscher and Cleemput, 2003b).

**Table 17** Effect of $NH_4^+$ amendment on methane oxidation rate in three landfill covers

| Landfill covers | Added $NH_4^+$ (mg N/kg) | N content before incubation (mg/kg dry soil) | | | N content after incubation (mg/kg dry soil) | | | MOR (µmol $CH_4$/kg dry soil·s) |
|---|---|---|---|---|---|---|---|---|
| | | $NH_4^+$-N | $NO_3^-$-N | $NH_4^+$-N / $NO_3^-$-N | $NH_4^+$-N | $NO_3^-$-N | $NH_4^+$-N / $NO_3^-$-N | |
| SL | 0 | 46 | 116 | 0.40 | 45 | 117 | 0.38 | 0.40 |
| | 10 | 56 | 116 | 0.48 | 54 | 118 | 0.46 | 0.40 |
| | 30 | 76 | 116 | 0.66 | 78 | 120 | 0.65 | 0.39 |
| | 50 | 96 | 116 | 0.83 | 89 | 122 | 0.73 | 0.29 |
| | 100 | 146 | 116 | 1.26 | 126 | 123 | 1.02 | 0.28 |
| SL+C | 0 | 45 | 126 | 0.36 | 36 | 138 | 0.26 | 2.86 |
| | 10 | 55 | 126 | 0.44 | 43 | 140 | 0.31 | 2.83 |
| | 30 | 75 | 126 | 0.60 | 58 | 144 | 0.40 | 2.78 |
| | 50 | 95 | 126 | 0.75 | 63 | 154 | 0.41 | 2.74 |
| | 100 | 145 | 126 | 1.15 | 94 | 168 | 0.56 | 2.70 |
| C | 0 | 46 | 122 | 0.38 | 34 | 136 | 0.25 | 1.89 |
| | 10 | 56 | 122 | 0.46 | 41 | 140 | 0.29 | 1.86 |
| | 30 | 76 | 122 | 0.62 | 57 | 139 | 0.41 | 1.75 |
| | 50 | 96 | 122 | 0.79 | 61 | 152 | 0.40 | 1.94 |
| | 100 | 146 | 122 | 1.20 | 92 | 170 | 0.54 | 1.99 |

Comparison of $NH_4^+$ and $NO_3^-$ contents before and after amendment of $NH_4^+$ (Table 17) presumably defined the nitrification process in each cover material. High $NH_4^+$ utilization and $NO_3^-$ production was found in compost and the mixture. More $NH_4^+$ was consumed and more $NO_3^-$ was produced by increasing the amount of added $NH_4^+$, however, methane oxidation was not reduced. These results confirmed the high activity of $NH_4^+$ oxidizer which responded in $NH_4^+$ utilization trough the nitrification process and probably co-oxidized methane besides methanotrophs.

From these results, it was found that compost application presumably affected the soil microorganism community and their ecosystem as compared to sandy loam. Thus, amendment with $NH_4^+$ increased methane oxidation in compost material, but not in sandy loam. This batch experiment evidently confirmed the observation of inhibitory effects in sandy loam and stimulatory effects in compost column studies as the $NH_4^+$ content in soil during column experiment would be increased with time.

2.6.2 Effect of nitrate amendment

As shown in Table 18, the effect of $NO_3^-$ amendment on methanotrophic activity was not significant in all three materials. In sandy loam soil, the influence of $NO_3^-$ was not observed even at high amount amendment. This result was confirmed with the studies in arable soil and landfill cover soil by Hutsch (1998), Hilger *et al.* (2000b), Visscher *et al.* (2001) and Park *et al.* (2002). Additionally, Hilger *et al.* (2000b) remarked that landfill cover soil collected from the lysimeter operated after long exposure to $CH_4$ had no effect of added $NO_3^-$ on methanotrophic activity.

**Table 18** Effect of $NO_3^-$ amendment on methane oxidation rate in three landfill covers

| Landfill covers | Added $NO_3^-$ (mg N/kg) | N content before incubation (mg/kg dry soil) | | | N content after incubation (mg/kg dry soil) | | | MOR (µmol $CH_4$/kg dry soil·s) |
|---|---|---|---|---|---|---|---|---|
| | | $NH_4^+$-N | $NO_3^-$-N | $NH_4^+$-N / $NO_3^-$-N | $NH_4^+$-N | $NO_3^-$-N | $NH_4^+$-N / $NO_3^-$-N | |
| SL | 0 | 46 | 116 | 0.40 | 45 | 117 | 0.38 | 0.40 |
| | 10 | 46 | 126 | 0.37 | 46 | 125 | 0.37 | 0.39 |
| | 30 | 46 | 146 | 0.32 | 42 | 146 | 0.29 | 0.39 |
| | 50 | 46 | 166 | 0.28 | 45 | 162 | 0.28 | 0.38 |
| | 100 | 46 | 216 | 0.21 | 43 | 219 | 0.20 | 0.38 |
| SL+C | 0 | 45 | 126 | 0.36 | 36 | 138 | 0.26 | 2.86 |
| | 10 | 45 | 136 | 0.33 | 34 | 141 | 0.24 | 2.85 |
| | 30 | 45 | 156 | 0.29 | 35 | 153 | 0.23 | 2.83 |
| | 50 | 45 | 176 | 0.26 | 34 | 182 | 0.19 | 2.74 |
| | 100 | 45 | 226 | 0.20 | 33 | 197 | 0.17 | 2.57 |
| C | 0 | 46 | 122 | 0.38 | 34 | 136 | 0.25 | 1.89 |
| | 10 | 46 | 132 | 0.35 | 31 | 155 | 0.20 | 1.87 |
| | 30 | 46 | 152 | 0.30 | 33 | 161 | 0.20 | 1.79 |
| | 50 | 46 | 172 | 0.27 | 35 | 184 | 0.19 | 1.78 |
| | 100 | 46 | 222 | 0.21 | 37 | 192 | 0.19 | 1.75 |

In compost and the mixture material, a slight inhibitory effect of $NO_3^-$ was obtained only at high concentration. Nevertheless, other studies revealed a stronger inhibitory effect of $NO_3^-$ (Chiemchaisri *et al.*, 2001b; Wang and Ineson, 2003) as caused by nitrite ($NO_2^-$) accumulation. $NO_3^-$ amendment might restrict $NO_2^-$ oxidation through nitrification and thus accumulated $NO_2^-$, causing a decrease in methanotrophic activity (Chiemchaisri *et al.*, 2001b). Meanwhile, Wang and Ineson (2003) proposed that the toxic $NO_2^-$ which inhibited methanotrophic activity was probably produced from $NO_3^-$ reduction through denitrification. Hence, the less inhibitory effect of $NO_3^-$ found in this study was possibly due to low initial content of $NH_4^+$ in compost and the mixture material (Table 18) and no $NO_2^-$ accumulation via nitrification. Furthermore, because an aerobic condition was maintained throughout the batch experiment, $NO_2^-$ production via denitrification was negligible.

The change of $NH_4^+$ and $NO_3^-$ contents before and after $NO_3^-$ amendment was insignificant. Less $NH_4^+$ and $NO_3^-$ were utilized and produced through nitrification process. Thus, the indirect $NO_3^-$ inhibition was not possessed.

From these batch results, it was found that $NH_4^+$ affected the methanotrophic activity, but $NO_3^-$ did not. Therefore, the effect of leachate irrigation in the column study could be attributed to its $NH_4^+$ concentration.

2.7 Effect of organic amendment through batch experiment

From the column results, compost revealed a higher efficiency of methane oxidation than sandy loam and the mixture materials, with both rainwater and leachate applications. Besides the beneficial physical properties of compost (i.e. high porosity and water-holding capacity), some chemical properties, especially organic content, was also responded to the enhancement of methane oxidation. The study of methanotrophic activity in various contents of compost applied to sandy loam was conducted to investigate their performances through batch experiment.

As shown in Figure 35 and Table 19, application of organic compost clearly revealed about 5-7 times higher MOR compared to sandy loam. Nevertheless, a higher ratio of organic compost applied to sandy loam did not change the stimulatory effect on methane oxidation. Several studies supported these results that high effective methanotrophic activity was found in high organic content material such as compost (Christophersen *et al.*, 2001; Humer and Lechner, 2001b), and also demonstrated that the abundance of methanotrophs (especially type II) was significantly higher in the organically fertilized soil which correlated with the enhancement of methane oxidation (Seghers *et al.*, 2005). It could imply that compost application indirectly affected the change of the soil microorganism community by increasing the presence of methanotrophs.

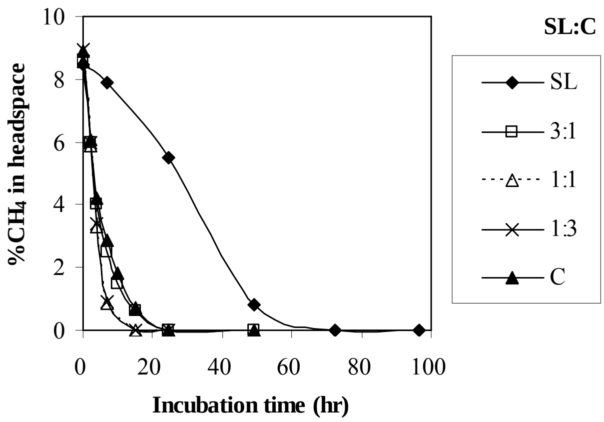



**Figure 35** Methane concentration in headspace over time in batch organic amendment

These batch results support the column results that compost application (both in cases of the presence and absence of sandy loam) enhanced methane oxidation according to increasing methanotrophic activity especially in short periods of column operation. However, in long operation period, other environmental factors would affect the methanotrophic activity.

**Table 19** Effect of different ratios of organic compost amendment on methane oxidation rate

| SL:C ratios | Total organic carbon (%dry weight) | Methane oxidation rate (µmol $CH_4$/kg dry soil·s) |
|---|---|---|
| SL | 1.24 | 0.36 |
| 3:1 | 4.55 | 2.06 |
| 1:1 | 7.03 | 2.75 |
| 1:3 | 7.91 | 2.92 |
| C | 8.48 | 2.34 |

2.8 Summary of results

In this section of the column experiment, compost was utilized to improve the performance of methane oxidation in landfill cover soil. It clearly found that compost provided higher activity and more sustainable methane oxidation than sandy loam in long-term column operation. The study of methanotrophic activity throughout column depth profile confirmed that active zone in compost material was deeper due to favorable physical properties (high porosity and water-holding capacity). Additionally, high organic content of compost was preferred for methanotrophic activity as evidenced by batch incubation. In consideration of soil respiration, compost exhibited stable characteristics with insignificant competitive oxygen consumption for methane oxidation.

Another operation of landfill cover soil with leachate irrigation could successfully extend the active period of methane oxidation in the column study.

Indeed, supplemental nutrients from irrigated leachate caused different effects on methane oxidation in each cover material. Nutrient supply in term of $NH_4^+$ helped stimulating methane oxidation in compost while also inhibiting in sandy loam. Nevertheless, $NO_3^-$ nutrient did not significantly affect the methanotrophic activity.

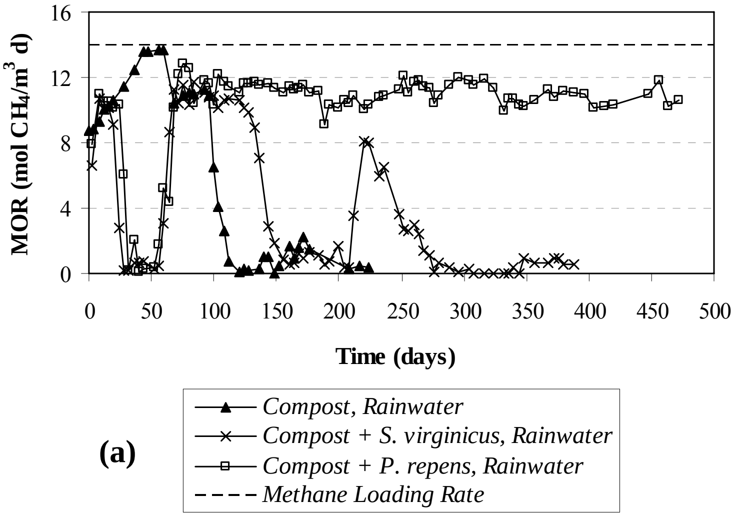
After long-term column operation, the declination of methane oxidation was eventually achieved. It suggested that long-term irrigation caused increasing water accumulation, prohibiting oxygen diffusion and thus deteriorating methane oxidation. Furthermore, EPS accumulation in soil and soil migration after long-term operation also influenced the limit action of oxygen penetration and methanotrophic activity.

## 3. Methane Oxidation Study in Simulated Landfill Cover Soils with Vegetation

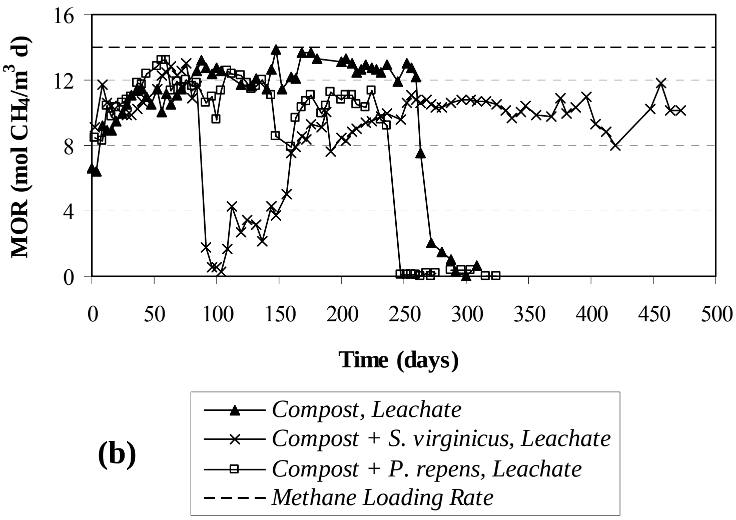
The study of methane oxidation in simulated landfill cover columns with vegetation was investigated for the purpose of improvement of landfill cover system by vegetation. From the previous result compost was an effective landfill cover material for methane oxidation, thus it was used as final cover in this vegetated column experiment. Two species of tropical grasses (*S. virginicus* and *P. repens*) were studied for their performances on stimulating methane oxidation compared to control column without vegetation. Moreover, the simulated landfill condition was performed under the wet season with rainwater and leachate irrigations in which the effect of leachate on plant growth and methane oxidation could be evaluated. The results are discussed as follows.

### 3.1 Effect of vegetation on methane oxidation

The experimental results are shown in Figure 36. In the case of rainwater irrigation (Figure 36(a)), MOR in compost columns with *S. virginicus* and *P. repens* varied with oscillatory fluctuation pattern. During the first 30 days of the experiment, MOR in the vegetated columns rapidly declined to zero as water logging took place in the top soil. However, it could recover after grasses were re-cultivated. Afterwards, the vegetated column with *P. repens* had steady MOR at approximately 12 mol $CH_4/m^3.d$ for over 400 days, whereas *S. virginicus* exhibited a shorter active period (60 days) of MOR (11 mol $CH_4/m^3.d$). In comparison with the non-vegetated compost column, the active zone in the vegetated compost columns was significantly deeper (Figures 37(a), (c) and (e)) while the average MOR in the active period was not significantly different. From these results, it clearly found that the vegetation with *P. repens* could help to sustain methane oxidation in long-term operation. *P. repens* could exist in simulated landfill condition over 340 days after re-cultivation on day 60.




**(a)**




**(b)**

**Figure 36** Variation of total methane oxidation rate (MOR) in vegetated landfill cover compost with (a) rainwater and (b) leachate irrigations

In the case of leachate irrigation (Figure 36(b)), similar trend of MOR was obtained in the vegetated (*P. repens*) and non-vegetated compost columns. These two columns showed high methanotrophic activity with a constant MOR of approximately 12 mol $CH_4/m^3$.d for 250 days, whereas the *S. virginicus* column provided a fluctuating period of MOR before it gradually self-recovered to a constant rate of 11 mol $CH_4/m^3$.d and maintained that of MOR over 300 days. These results suggested that vegetation with *S. virginicus* could prolong the active methane oxidation period, although vegetation with *P. repens* did not significantly extend the active period compared to the non-vegetated control column. However, all columns with leachate application practice revealed the high MOR and the long active period. Vegetation with leachate irrigation seemed to be an effective operation for sustainable methane oxidation.

Vegetation compared with no vegetation did not produce high peak methane oxidation in both irrigated with rainwater and leachate. In the active period, MOR was maintained at the same range of 11-12 mol $CH_4/m^3$.d in the vegetated and non-vegetated compost columns. Similar observation was mentioned by Hilger *et al.* (2000) that methane consumption in the soil at a steady state did not depend on the presence of plant. However, in this study, the vegetation with *P. repens* (in the case of rainwater irrigation) and *S. virginicus* (in the case of leachate irrigation) could prolong the active period over 400 and 300 days, respectively. Moreover, the *P. repens* column in the case of leachate application also provided high MOR in the active period of 250 days similar to the bare compost column.

MOR at various depths in the experimental columns is shown in Figure 37. The vegetated columns had higher MOR at the deeper zones (15-30 and 30-50 cm) compared to non-vegetated one with the support of plant root system (Tudsri, 1997) and the rhizosphere environment for methanotrophs. *P. repens* possessed longer and wider root system compared to *S. virginicus* (Figure 21); hence it could supply more oxygen diffusion into the deeper zone and therefore enhanced MOR. Plant roots played an important role in microbial methane oxidation as described in two manners. First, the vascular systems of plant helped transport action of oxygen from the atmosphere into the rhizosphere (Schütz *et al.*, 1991; Chanton, 2005) and thus supported methane oxidation. In addition, some dead roots due to plant clipping were included in stimulating oxygen diffusion through their vascular systems before it would be naturally decayed (Crider, 1955; Ganskopp, 1988; Ström *et al.*, 2005). On the other hand, transporting oxygen also supported the respiration of plant roots (Glinski and Stepniewski, 1986) which possibly promoted competition for oxygen with methane oxidizing bacteria. Secondly, plant roots could also produce exudates and released them to the rhizosphere which beneficially supported as nutrient supplement and moisture retention for soil microorganisms and stimulated microbial activity (Curl and Truelove, 1986; Hilger *et al.*, 2000b). Therefore, the existence of grasses would encourage methanotrophic activity throughout depth profile until the oxygen deficient condition took place. Furthermore, vegetation on cover soil also helped to reduce soil erosion.

In this study, the *P. repens* columns clearly exhibited the performance on sustaining methane oxidation in long-term operation with rainwater or leachate irrigation. *P. repens* also revealed strong tolerant characteristics to leachate and landfill gas. Moreover, the *S. virginicus* columns could prolong methane oxidation in leachate application but not in rainwater practice. Therefore, leachate possibly gave some beneficial effects for plant growth and methane oxidation which would be discussed in the following section.

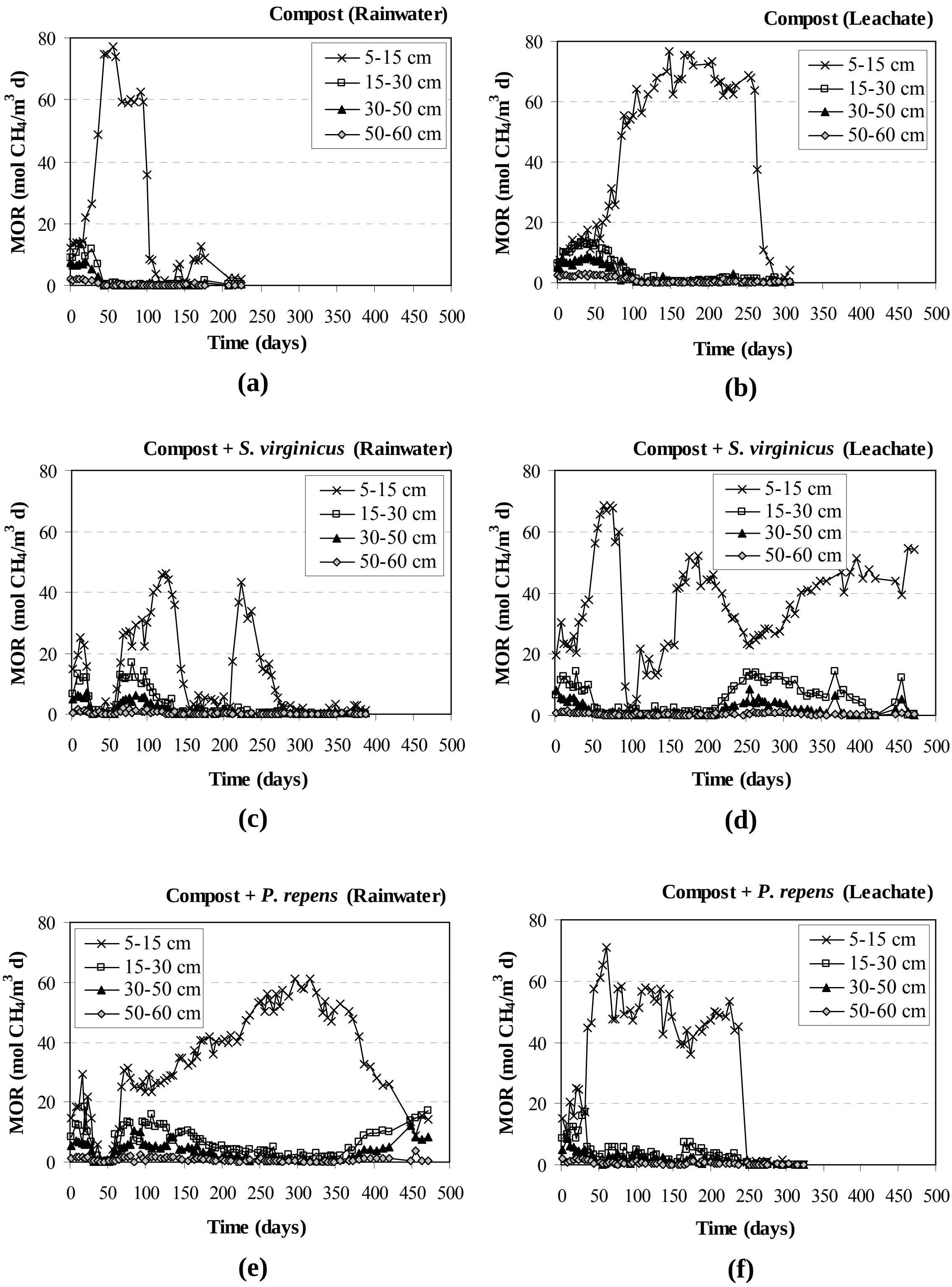


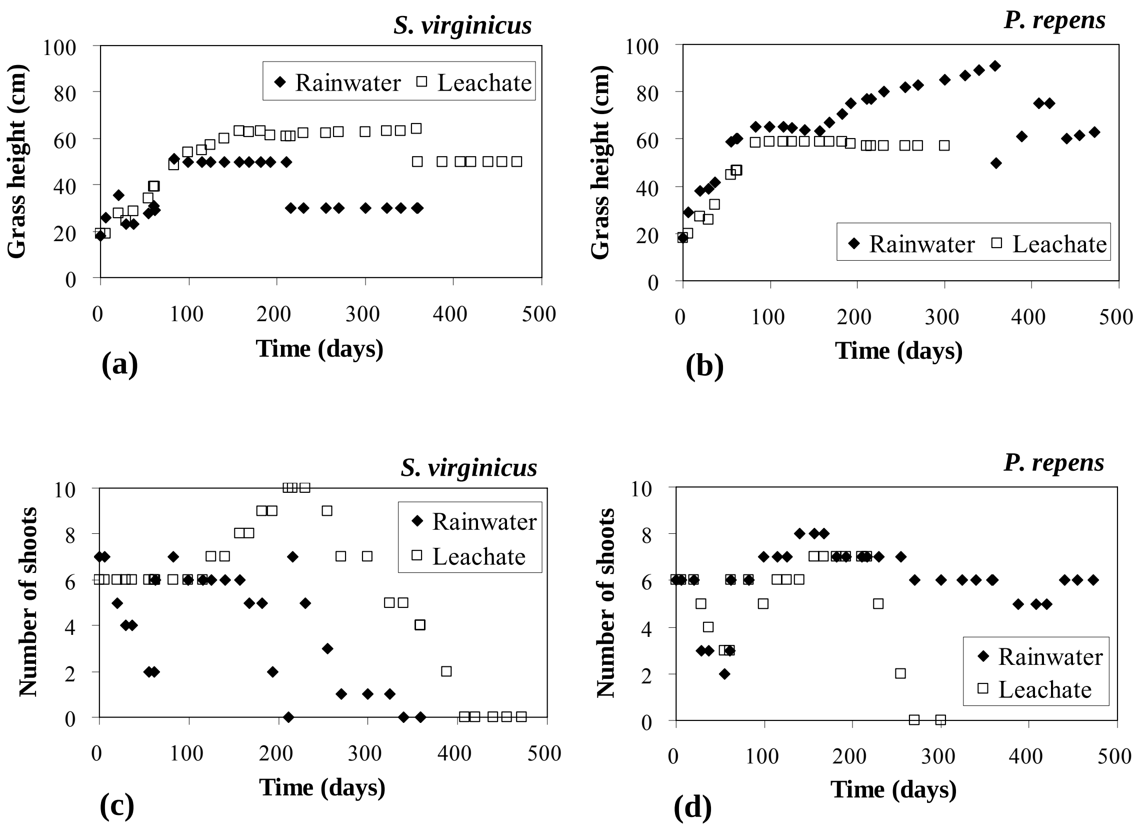

**Figure 37** Methane oxidation rate (MOR) throughout the depth profile of vegetated landfill cover compost with rainwater and leachate irrigations

### 3.2 Effect of leachate on plant growth and methane oxidation

From the previous results, leachate application revealed some positive effects on growth and existence of grasses and further methanotrophic activity. This section would discuss the effect of leachate irrigation in the vegetated compost columns compared to the control with rainwater irrigation.

#### 3.2.1 Effect of leachate on plant growth

The growths of *S. virginicus* and *P. repens* in the vegetated columns had been observed throughout the experimental period (over 300 days). Figure 38 shows the changes in grass height and number of shoots. Figure 39 also presents the changes in width, length and number of leaves.




**<u>Figure 38</u>** Changes in height (a), (b); and number (c), (d) of *S. virginicus* and *P. repens* during a period of vegetated column experiment operated with rainwater and leachate

In the initial 60 days, plant growth (height) was not different between rainwater and leachate applications, but it also exhibited some plant deteriorations (brown leaves and desiccated leaf edges) in the *S. virginicus* and *P. repens* columns operated with rainwater. It was possibly due to the occurrence of water logging in these two columns. However, after re-cultivation of both two grass species, the growth rate of *S. virginicus* (plant size, number of leaves and shoots) was greater under leachate irrigation in comparison with rainwater irrigation due to supplying of additional nutrients from irrigated leachate. *S. virginicus* irrigated with leachate could be existed over 300 days before it was damaged by the increase of soil salinity and eventually died after day 360. These results indicated that *S. virginicus* could grow under landfill condition (exposed with landfill gas) with leachate irrigation practice.

Different growth patterns were found in *P. repens*. After re-cultivation on day 60, growth rate of *P. repens* was greater under rainwater irrigation compared to leachate irrigation. *P. repens* could exist until the end of experiment (over 400 days). Nevertheless, *P. repens* irrigated with leachate also endured over 160 days and then died after day 250 which was possibly due to salt accumulation in soil. Additionally, the occurrence of water logging on day 230 was also involved in deterioration of *P. repens*. From these results, leachate did not significantly affect the growth rate of *P. repens*. This grass species could also grow well under typical landfill condition.

It suggested that the vegetation (with *S. virginicus*) in a final cover of landfill could be stronger possibly due to that the optimal supplementary nutrients from leachate were provided. Although both *P. repens* and *S. virginicus* showed salt-tolerant characteristics, the increase of soil salinity after long-term application of leachate also affected plant deteriorations and death. Salt from irrigated leachate (referred in term of electrical conductivity; EC) was implied as an important factor for grass death (Devitt *et al.*, 1993; Gomez *et al.*, 1996; Hernandez *et al.*, 1999) while organic content which was negligible according to stabilized leachate used in this study provided a slight increase in soil respiration (Table 15) and thus low oxygen competition for root respiration. However, in the landfill condition either operated with rainwater or leachate, *P. repens* existed more sustainable than *S. virginicus*.

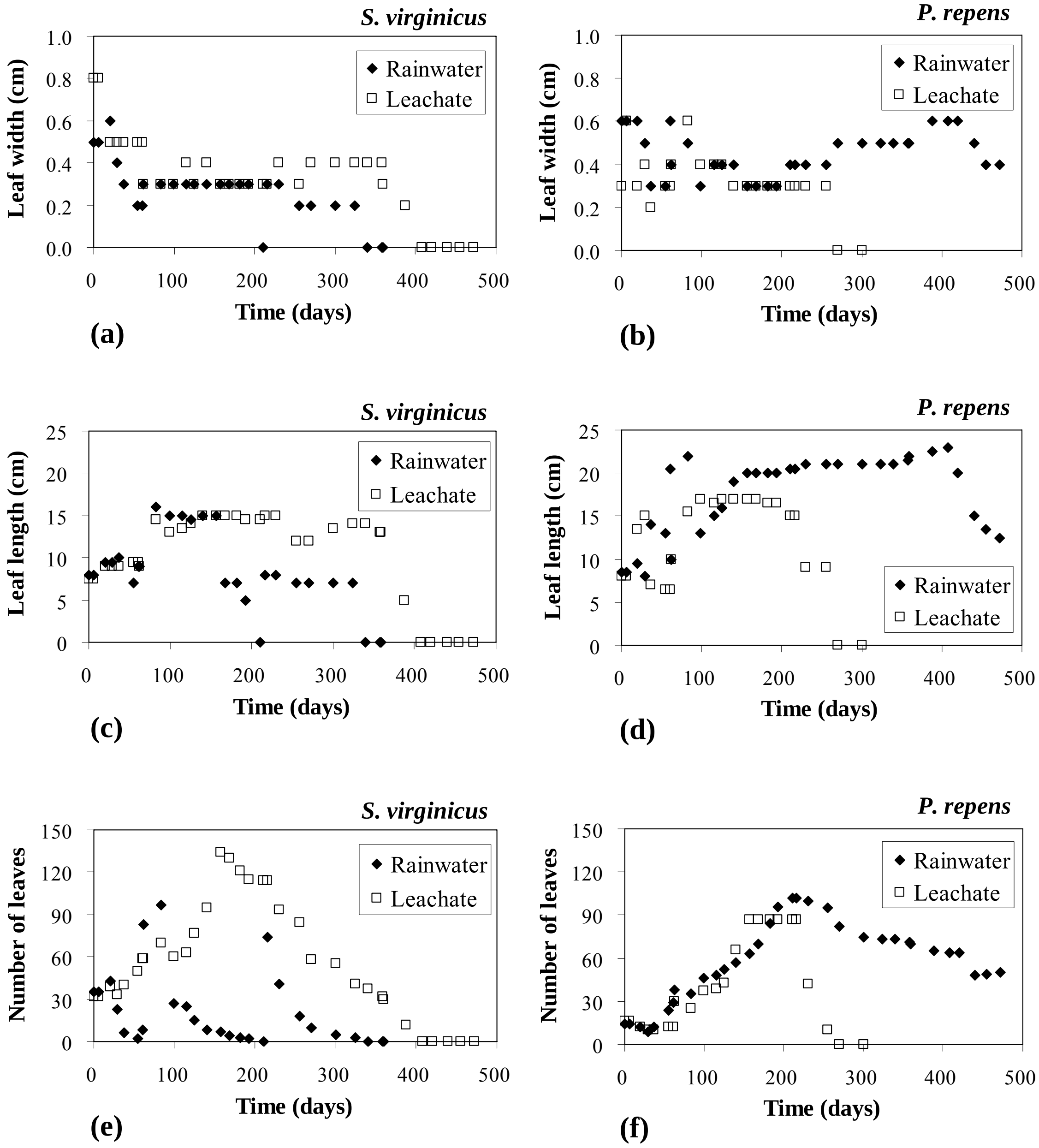
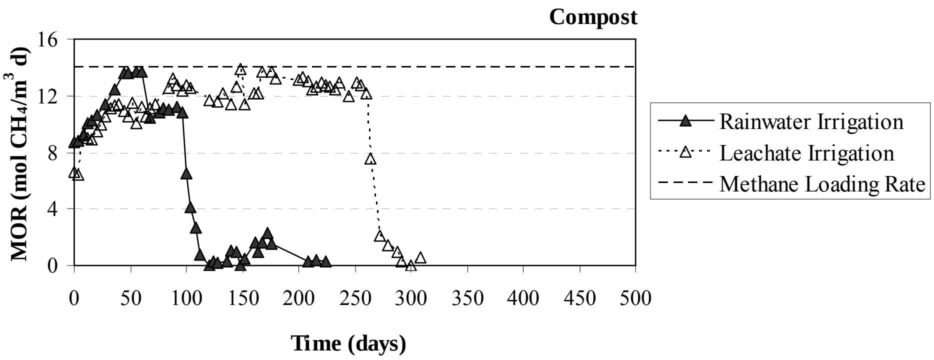


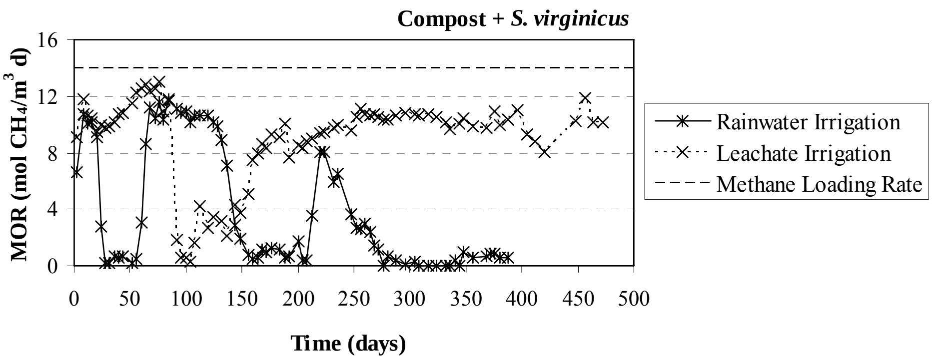

**Figure 39** Changes in leaf width (a), (b); leaf length (c), (d); and number of leaves (e), (f) of *S. virginicus* and *P. repens* during a period of vegetated column experiment operated with rainwater and leachate

3.2.2 Effect of leachate on methane oxidation

In this vegetated column experiment, leachate application did not significantly help improving MOR (Figures 40(b) and (c)). This was in contrast to the result of bare column experiment (Figure 40(a)) indicating that leachate irrigation had positive effects on methane oxidation significantly.




**(a)**

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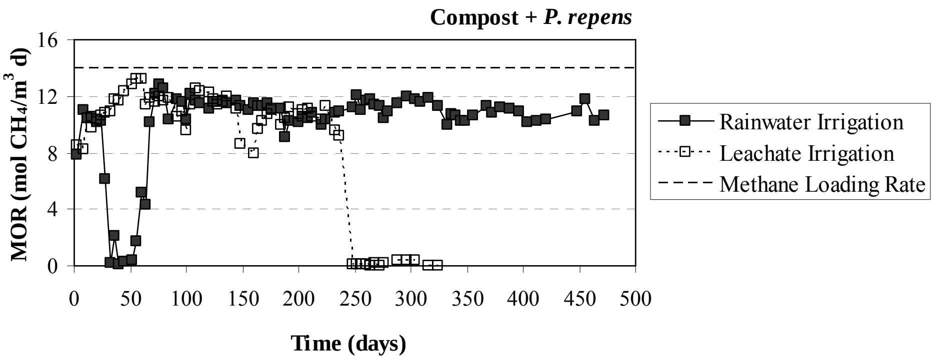



**(c)**

**Figure 40** Comparison of methane oxidation rate (MOR) between rainwater and leachate irrigations in (a) compost, (b) compost with *S. virginicus*, and (c) compost with *P. repens*

As shown in Figure 40(b), the *S. virginicus* columns had the fluctuation pattern of MOR in both rainwater and leachate irrigations. However, leachate application provided longer active period of methane oxidation (300 days) than rainwater application (60 days). In the *P. repens* columns (Figure 40(c)), stable capacity of methane oxidation was observed in both rainwater and leachate applications, but the active period in the leachate case (240 days) was shorter than the rainwater case (400 days).

According to these results, leachate gave some positive effects on increasing the active period of methane oxidation only in the vegetated compost column with *S. virginicus*. It implied that leachate provided supplemental nutrients for methanotrophs and grasses which supported favorable environment for methanotrophs. Similar to the results reported by Maurice *et al.* (1999) that the abundance of plant irrigated with leachate might contribute to an increased amount of plant roots which provided favorable surroundings for methane oxidizing bacteria and further enhanced MOR. Unlike in the vegetated column with *P. repens*, leachate did not significantly improve the active period of methane oxidation, however, it could also maintain the active period over 240 days. Anyway, after long-term irrigation either water or salt accumulation was occurred and then resulting in deterioration of methane oxidation due to restricted oxygen diffusion (Watzinger *et al.*, 2005) and plant damage (Devitt *et al.*, 1993; Gomez *et al.*, 1996; Hernandez *et al.*, 1999).

This could be concluded that methanotrophic activity and plant growth were not negatively affected by leachate over a period of 240 days. It could provide high MOR and growth rate within this period. Afterwards, general accumulations of water and salt from long-term leachate irrigation contributed to decrease in methane oxidation and plant growth. Leachate application at appropriate approach was also considered as beneficial landfill operation in order to sustain methane oxidation and prevent vegetation damage.

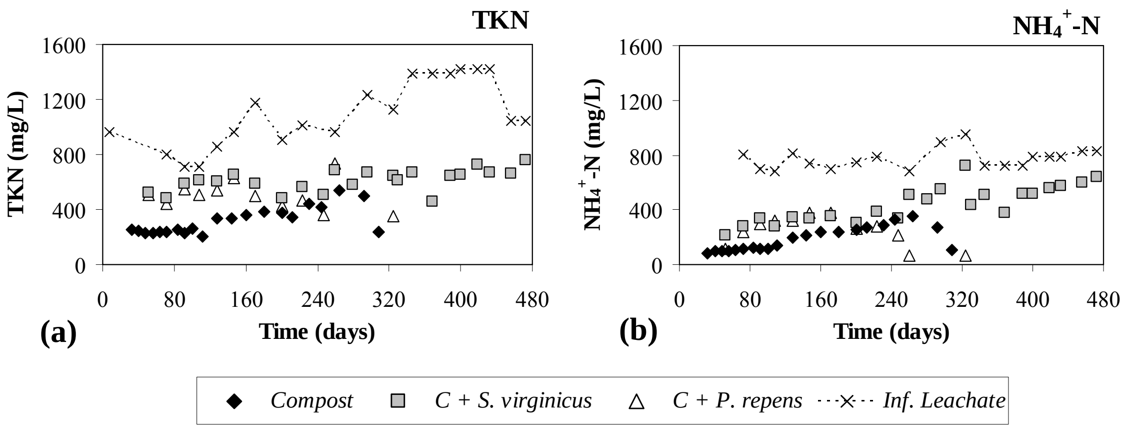



**Figure 41** Nitrogen content, (a) TKN and (b) $NH_4^+$-N, of irrigated leachate and effluents from vegetated column experiment operated with leachate

Additionally, application of leachate in landfill cover soil would be regarded as treatment of leachate. As shown in Figure 41, the vegetated columns with *S. virginicus* and *P. repens* presented the capacity in removing nitrogen contents (TKN and $NH_4^+$-N) of irrigated leachate. Average TKN and $NH_4^+$-N removal efficiencies in the compost column with *P. repens* were found to be 60 and 70%, respectively, similar to those of bare compost column. Lower efficiencies were found in the compost column with *S. virginicus* at 55% TKN removal and 50% $NH_4^+$-N removal. The providing nutrient from leachate was presumably adsorbed by soil and assimilated by soil microorganisms and also plant roots.

3.3 Extracellular polysaccharides (EPS) production

At the end of the vegetated column experiment, EPS content throughout the column depth was examined. Figure 42 shows that high production of EPS was found at the top layer (5-15 cm) of the vegetated columns (with *S. virginicus* and *P. repens*) and the control bare column while lower content was found at the lower layer. Similar trend of EPS profiles were observed in all experimental columns especially in case of leachate application. Nevertheless, the *P. repens* column gave the highest EPS contents (15-19 mg C/g dry soil) in comparison with the *S. virginicus* column and bare column, respectively. High EPS production was resulted from unfavorable condition for methanotrophs as described in section 2.3. In this experiment, it was also related to high $O_2$:$CH_4$ ratio at the upper layer which stimulated EPS formation (Chiemchaisri *et al.*, 2001a) and further the abundance of methanotrophs in the vicinity of roots promoted high EPS production. Subsequently, high EPS clogging soil pores and coating root system were observed as reddish-brown band especially in the root zones similar to the study of Wilshusen *et al.* (2004a). This caused low oxygen diffusion and then restricted methanotrophic activity. From these results, EPS production was confirmed as an important reason for declining of methane oxidation.

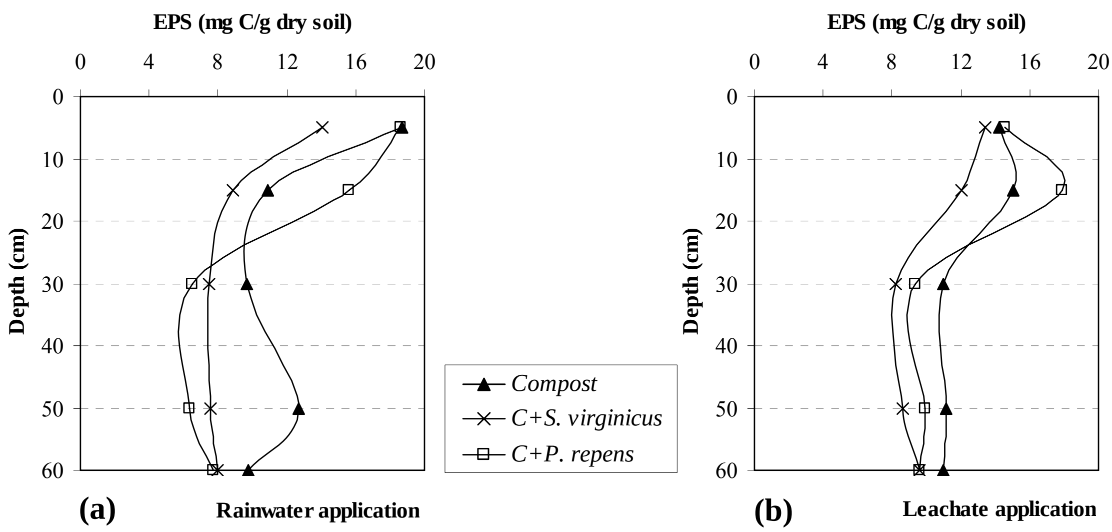



**Figure 42** EPS (expressed as mg C/g dry soil) profiles as a function of depth in vegetated landfill cover compost at the end of experiment: (a) rainwater and (b) leachate irrigations

### 3.4 Methanotrophic activity in batch experiment

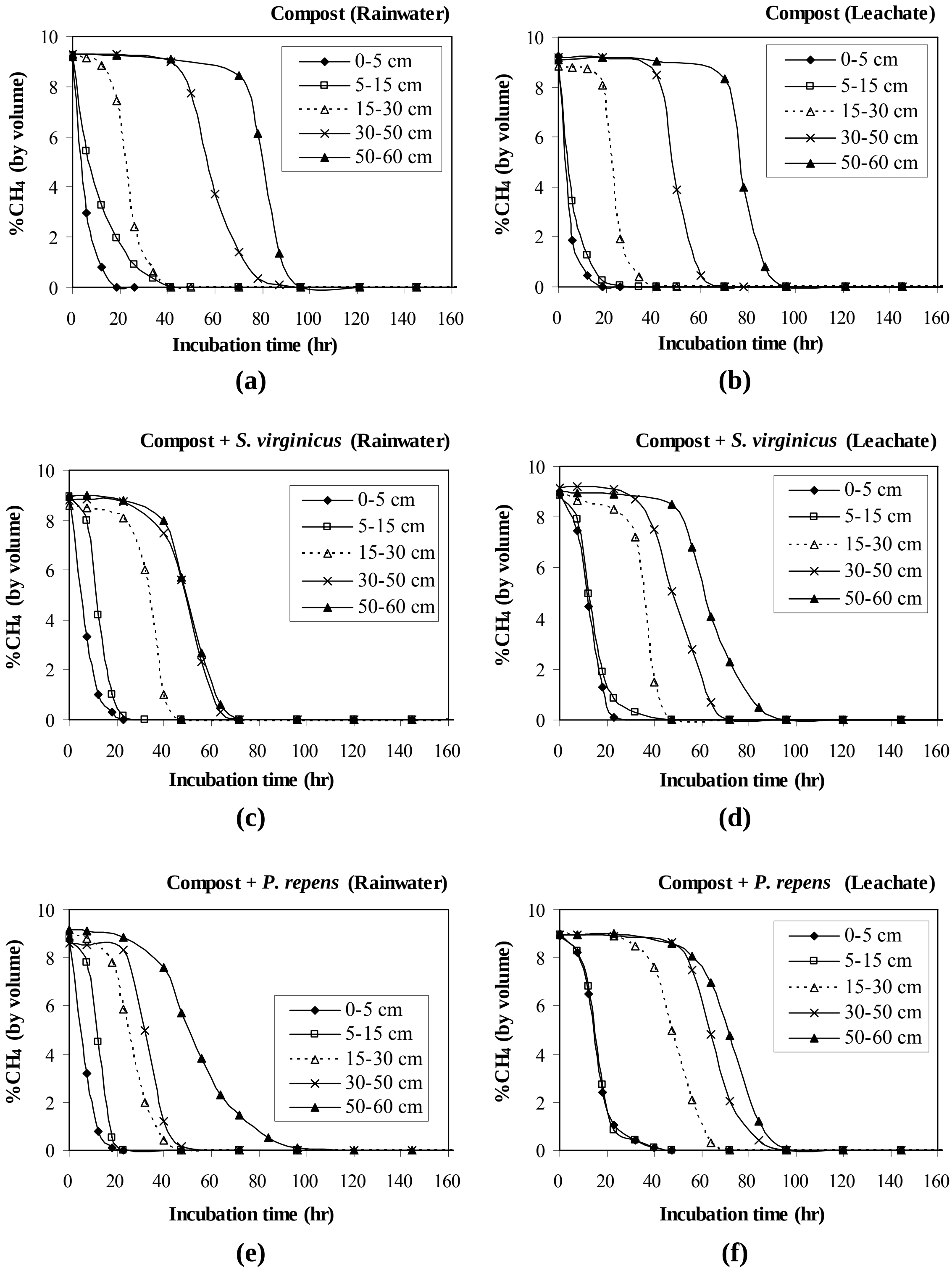
Batch incubation was conducted to investigate methanotrophic activity in landfill cover composts which was sampled from vegetated columns. Methane consumption curves of vegetated cover compost at different depths are shown in Figure 43. All curves illustrated similar trends in consuming methane according to similar experiment using compost as landfill cover materials. Higher MOR was found in the upper layer while lower value was observed in the lower part as presented in Table 20.

In the upper layer (0-30 cm) of the vegetated compost columns, methane was completely consumed within 40 hr (Figures 43(c)-(f)) and high MOR of 1.1-1.6 μmol $CH_4$/kg.s was obtained. Meanwhile, compost in the lower part took more than 80 hr to complete methane consumption and revealed lower MOR of 0.7-1.0 μmol $CH_4$/kg.s. From these results, there were no significant differences between methanotrophic activities in *S. virginicus* and *P. repens* columns. These vegetated columns showed similar capacity of methane oxidation in their active zones. Furthermore, leachate application did not significantly improve MOR in these vegetated columns. In comparison of MOR with the control compost column, it showed lower MOR at depths of 0-5 and 5-15 cm but higher at depth of 15-30 cm. It could imply that plant roots helped extending the active zone into deeper layer.

These batch results were consistent with the vegetated column experiment. Neither vegetation nor leachate application insignificantly stimulated capacity of methane oxidation. Vegetation merely prolonged the active period of methane oxidation in column experiment.

**Table 20** Methane oxidation rate in batch experiment of vegetated cover compost collected from column experiment with rainwater and leachate applications

| Landfill covers | Depth | Methane oxidation rate (μmol $CH_4$/kg dry soil·s) | |
|---|---|---|---|
| | | Rainwater application | Leachate application |
| C | 0-5 cm | 1.62 | 2.51 |
| | 5-15 cm | 0.93 | 1.73 |
| | 15-30 cm | 1.06 | 1.18 |
| | 30-50 cm | 0.88 | 1.04 |
| | 50-60 cm | 0.61 | 1.13 |
| C + *S. virginicus* | 0-5 cm | 1.43 | 1.40 |
| | 5-15 cm | 1.47 | 1.39 |
| | 15-30 cm | 1.30 | 1.45 |
| | 30-50 cm | 0.75 | 0.79 |
| | 50-60 cm | 0.74 | 0.87 |
| C + *P. repens* | 0-5 cm | 1.58 | 1.34 |
| | 5-15 cm | 1.41 | 1.33 |
| | 15-30 cm | 1.25 | 1.07 |
| | 30-50 cm | 0.97 | 0.82 |
| | 50-60 cm | 0.65 | 0.76 |




**<u>Figure 43</u>** Methane consumption in batch experiment of vegetated cover compost: (a), (b) compost; (c), (d) compost with *S. virginicus*; and (e), (f) compost with *P. repens* irrigated with rainwater and leachate, respectively

Consideration of the lag periods before methane consumption took place (Figure 43), the increase of the lag periods were also related to the depth of soil sampling according to anoxic condition in the deeper zone. However, the lag periods of composts sampled from vegetated columns (Figures 43(c)-(f)) were shorter than that of sampled from bare column (Figures 43(a) and (b)). As described in section 2.4, the different ratios of $O_2$:$CH_4$ between the batch and column studies were involved in causing lag phase of methanotrophic activity. High $O_2$:$CH_4$ ratio of about 1.8 in this batch study was near to that of ratio in the root zone (about 0-30 cm) of vegetated columns. Thus, methanotrophic activity in compost sampled from the root zone could instantly recovery at the beginning of batch incubation. Otherwise, a much lower $O_2$:$CH_4$ ratio in the sampled environment was attributed to more time requirement for methanotroph adaptation. Furthermore, the variation of $O_2$:$CH_4$ ratio also caused the different population and distribution of methanotrophic bacteria in the experimental columns which would be discussed as follows.

### 3.5 Methanotroph population study by fluorescence *in situ* hybridization (FISH) technique

Detection of methanotrophic bacteria in vegetated column experiment was performed by using FISH technique. Cover composts were sampled at different depths of the experimental columns after the end of experiment to analyze the population and distribution of methanotrophs. Table 21 identifies the types and numbers of methanotrophs at the top (5-15 cm), middle (15-30 cm), bottom (30-50 cm) layers and also rhizosphere (5-15 cm) of the vegetated columns. The numbers of type I and type II methanotrophs were defined as the percentage of total cell numbers determined by DAPI counting. Figure 44 also shows the photomicrographs of *in situ* hybridization with Mγ84 + Mγ705 probes for detecting type I methanotrophs (Figure 44(a)), Mα450 probe for detecting type II methanotrophs (Figure 44(c)) and corresponding DAPI stained cells (Figures 44(b) and (d)).

All vegetated columns with *S. virginicus* and *P. repens* contained high amount of methanotrophs (10-30% of the DAPI counts) at almost entire column depth especially at the rhizosphere, whereas the control column without vegetation revealed the abundance of methanotrophs only at the top soil (5-15 cm). Distributions of type I and type II methanotrophs were significantly different between the cases of rainwater and leachate applications. In columns operated with rainwater, type II methanotrophs was dominant species at the depth of 5-15 cm and the rhizosphere while the other compartments contained the same proportion between type I and type II methanotrophs. Otherwise, leachate application presented the dominance of type I methanotrophs in all compartments.

Amaral *et al.* (1995) and Amaral and Knowles (1995) proposed the hypothesis that the concentrations of methane, oxygen and nutrient nitrogen were primary factors influencing the presence of methanotroph species in the environment. Their studies indicated that type I methanotrophs preferred to exist at low-methane and high-oxygen conditions on the surface layer, whereas the growth of type II methanotrophs was flavored under high-methane and low-oxygen conditions. This hypothesis had been supported by Graham *et al.* (1993) that type I methanotrophs outcompeted type II methanotrophs in surviving under methane-limiting condition and type II methanotrophs preferably grew under nitrogen-limiting condition.

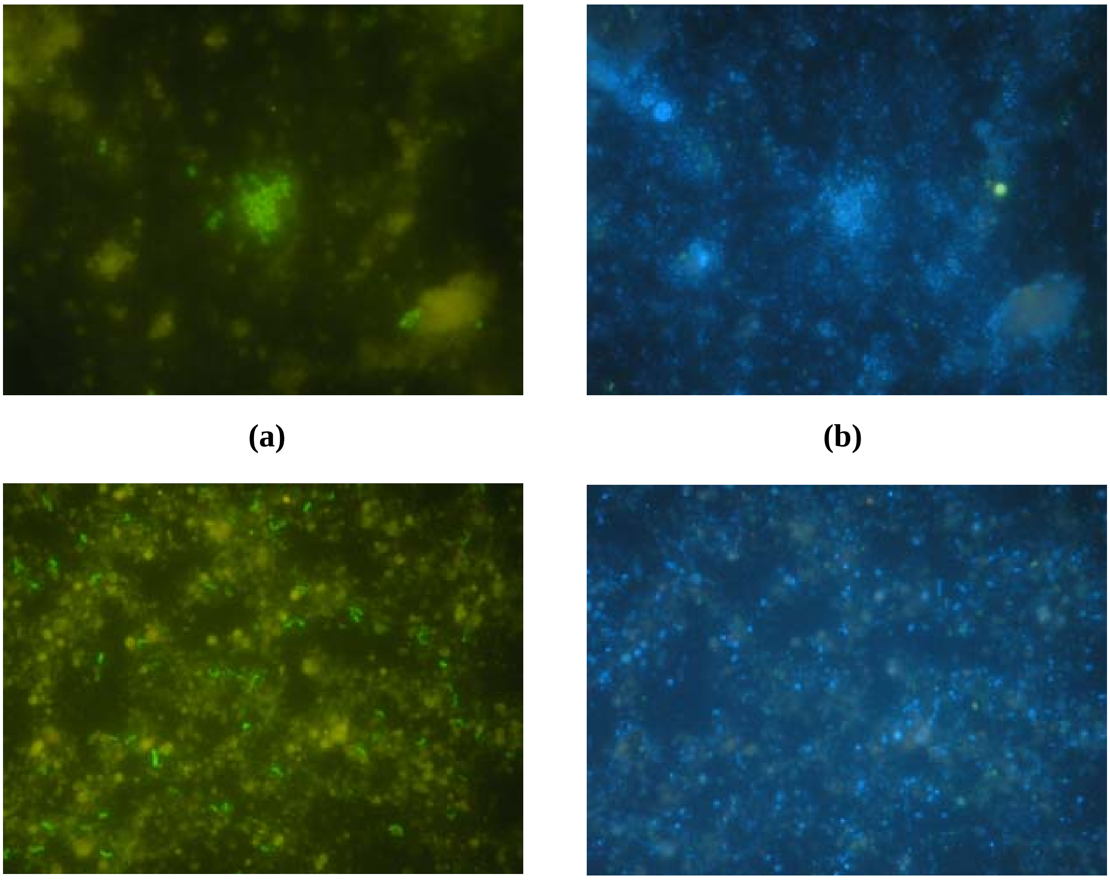
From that of hypothesis, it corresponded to the results of methanotroph distribution in the vegetated column experiment that type I methanotrophs was abundant in the top layer and rhizosphere where high oxygen and nitrogen were available especially in the case of leachate application. However, it contrasted to the case of rainwater application that most methanotrophic species in the upper part was type II. This could imply that after long irrigation with rainwater, the available nutrients for methanotrophs was deficient and thus type II methanotrophs was predominated over type I methanotrophs under this nitrogen-limiting condition. Furthermore, root systems were significantly responded to the abundance of methanotrophs in the lower part in comparison with the non-vegetated columns. The oxygen supplied in deeper zone by root systems seemed to be an important factor regulating methanotrophic growth, followed by the availability of nitrogen sources (Eller and Frenzel, 2001).

**Table 21** Numbers of methanotrophs detected by FISH technique in relation to the total DAPI counts in vegetated column experiment with rainwater and leachate applications

| Landfill covers | Depth | Numbers of methanotrophs (% of the DAPI counts) | | | |
|---|---|---|---|---|---|
| | | Rainwater application | | Leachate application | |
| | | Type I | Type II | Type I | Type II |
| C | 5-15 cm | 13.12 | 46.83 | 14.74 | 2.71 |
| | 15-30 cm | 5.90 | 6.07 | 10.02 | 0.70 |
| | 30-50 cm | 1.29 | 1.39 | 2.98 | 0.90 |
| C + *S. virginicus* | 5-15 cm | 15.52 | 30.51 | 27.65 | 12.44 |
| | Rhizosphere [(1)] | 13.30 | 24.21 | 26.05 | 1.84 |
| | 15-30 cm | 9.16 | 9.54 | 7.78 | 0.80 |
| | 30-50 cm | 2.89 | 3.87 | 1.82 | 0.75 |
| C + *P. repens* | 5-15 cm | 2.78 | 13.15 | 9.77 | 8.88 |
| | Rhizosphere [(1)] | 0.75 | 16.68 | 20.32 | 15.71 |
| | 15-30 cm | 30.41 | 31.82 | 11.11 | 11.08 |
| | 30-50 cm | 10.58 | 7.29 | 7.26 | 10.76 |

Note: [(1)] Soil sampled from the rhizosphere at depth of 5-15 cm

This study of methanotroph population and distribution confirmed the methanotrophic active zone (especially root zone) of vegetated column experiment with the abundance of methanotrophs at high percentage of 10-30%. In addition, type II methanotrophs was responsible for methanotrophic activity in the case of rainwater application while type I methanotrophs was responsible for that of leachate case.



(a) (b) (c) (d)

**Figure 44** Photomicrographs of *in situ* hybridization with (a) Mγ84 + Mγ705 and (c) Mα450 probes for detecting type I and type II methanotrophs, respectively; and (b), (d) corresponding DAPI stained cells

3.6 Summary of results

In the vegetated column experiment, the *P. repens* columns successfully performed sustainable methane oxidation either with rainwater or leachate operation over 240-400 days besides protecting soil erosion. In addition, the *S. virginicus* columns also extended the active methanotrophic period over 300 days in leachate application but not in rainwater practice. Both tropical grasses showed salt-tolerant characteristics and some stimulation of plant growth was observed in *S. virginicus* due to supplementary nutrients from supplied leachate. Nevertheless, *P. repens* would rather exist in the landfill conditions either operated with rainwater or leachate than *S. virginicus*. Leachate application did not significantly improve methane oxidation in vegetated column experiment as confirmed in batch study. However, appropriate leachate irrigation was also recognized as favorable landfill operation in order to sustain methane oxidation and remove contaminants and volume of leachate.

Furthermore, investigation of methanotroph population by FISH technique also demonstrated the abundance of methanotrophs (10-30% of the DAPI counts) in the methanotrophic active zone (5-30 cm) especially the rhizosphere. Consideration of distribution between type I and type II methanotrophs, type II methanotrophs was mainly responsible for the methanotrophic activity in column operated with rainwater while type I methanotrophs was dominantly responsible for that of leachate practice.

Declining of methane oxidation capacity was achieved after long-term operation. It was possibly caused by many incidences. High water and EPS accumulations limited oxygen penetration through soil pores and therefore suppressed methanotrophic activity. Moreover, the excess exudates from plant roots were also partial reason of oxygen deficiency for methanotrophic activity.

## 4. Methane Oxidation Study in Seasonal Variation (Wet and Dry Conditions)

### 4.1 Experimental simulation of wet and dry conditions

In simulated landfill cover system, wet and dry conditions were conducted to simulate seasonal variation in tropical regions. Wet condition was performed by intermittent irrigation of rainwater or leachate (sections 2 and 3) while dry condition was proceeded without irrigation (this section). The effect of wet and dry conditions to the moisture variations in landfill cover materials during the experimental periods was investigated. Furthermore, water balance in the landfill cover systems under wet and dry seasons was also studied by determining each component in water balance equation.

#### 4.1.1 Variations of moisture content in simulated landfill cover soils under wet and dry conditions

Figure 45 demonstrates moisture content along the depth of landfill cover materials (sandy loam and compost) operated with and without irrigation (referred as wet and dry conditions). In case of wet condition (Figures 45(a) and (b)), sandy loam exhibited periodical fluctuation in moisture content but maintained in an appropriate range for methanotrophic activity (13-16% dry weight basis). The fluctuation was found higher at the top layer due to the evaporative loss. Otherwise, much higher moisture content (33-36%) and less fluctuation were found in the compost case according to its higher water adsorptive capacity. Wet condition provided a constant range of moisture variation in this short-term observation (20 days).

In case of dry condition (Figures 45(c)-(f)), moisture content was observed throughout the depth of sandy loam and compost, whereas in the vegetated cover systems (with *P. repens*), moisture content was monitored only at the upper layer representing as the root zone. Sandy loam could maintain proper moisture content in a range of 11-14% only in the middle and bottom layers (25-35 and 45-55 cm) and subsequently increased to about 16% after 200 days due to the supply of water saturated landfill gas upflow. Meanwhile, moisture content in the upper layer

(5-15 cm) of the bare and vegetated sandy loam columns gradually declined to a low content of about 7% within 100 and 40 days, respectively. Vegetation caused more rapidly water loss through evapotranspiration which included direct evaporation from soil surface and transpiration by plant. Similarly in the compost column, a steady moisture content of 50% in the lower part (30-40 cm) was also maintained, and a decrease in low moisture content (below 5%) was found only in the upper part (5-15 cm). Vegetation in compost also accelerated water loss. Afterwards, low water content in the root zone of the vegetated sandy loam and compost columns initiated plant deteriorations (brown leaves and desiccated leaf edges) and then died after 130 and 80 days possibly due to soil water deficiency.

As remarked in Figures 45(d)-(f), sandy loam with *P. repens* and compost with and without *P. repens* were operated under dry condition for 160 days before re-irrigated with rainwater (wet condition) for 40 days. Re-irrigation was conducted to investigate the recovery of plant growth and methanotrophic activity which was discussed in the following section. After re-irrigation at 200 mL/4 days, moisture content in the vegetated sandy loam column rapidly increased to a range of 10-13% with the periodical fluctuation pattern while that of compost and vegetated compost gradually increased to the constant contents of 40 and 30%, respectively. Although soil moisture increased to be similar to that of the beginning of the experiment, *P. repens* did not recover their growth. It was possibly due to that soil water content under dry condition was below the permanent wilting point, which plants did not obtain the available water from soil and then permanently wilted (Or and Wraith, 2000).

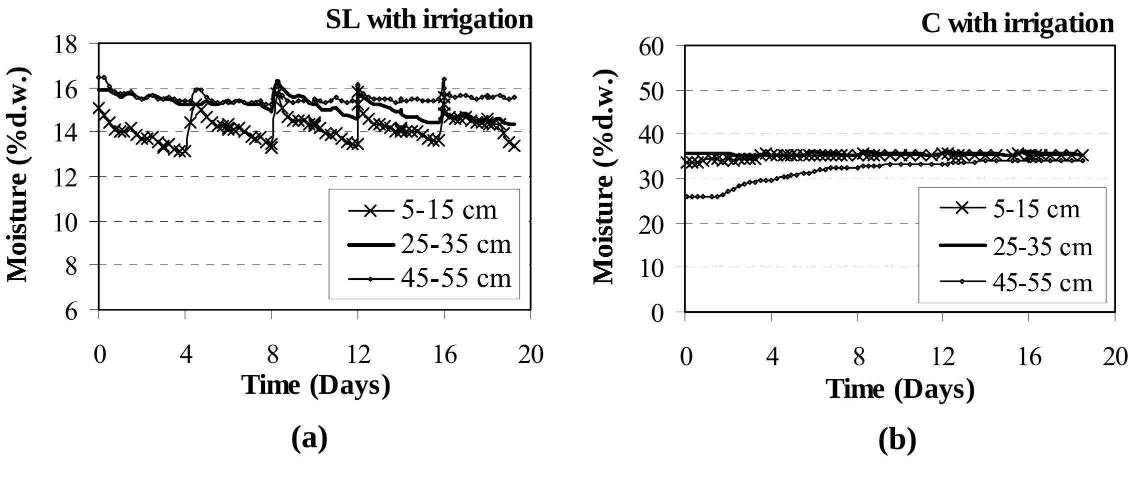
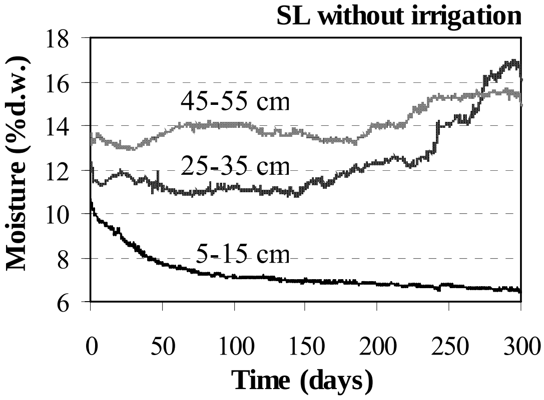
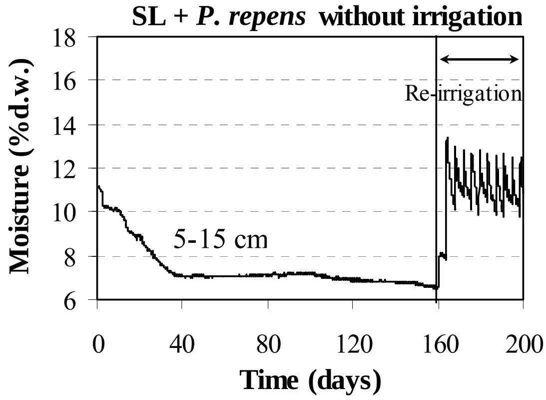


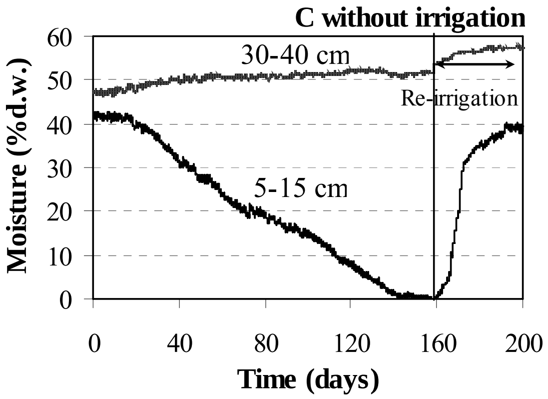

**Figure 45** Variation of moisture contents on vegetated and non-vegetated sandy loam and compost under wet and dry conditions



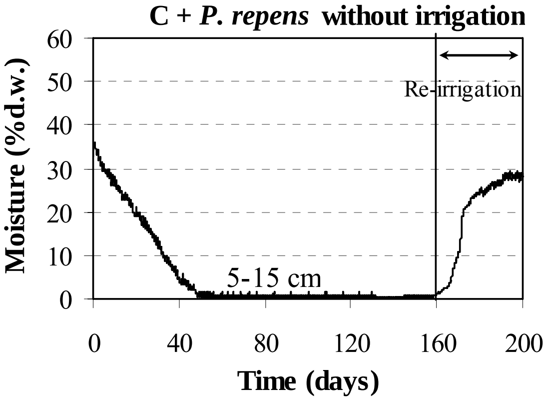

(c)




(d)




(e)




(f)

**Figure 45** (Cont'd)

#### 4.1.2 Water balance in simulated landfill cover soils under wet and dry conditions

To investigate the water balance in landfill cover systems, three main components of water balance including water input, water output and change in soil water storage were examined. In this simulated landfill cover experiment, water input consisted of water irrigation (I) and water production (WP) from microbial methane oxidation while water output were exhibited in terms of percolation (P) and evaporation (E) or evapotranspiration (ET) in case of vegetated landfill cover system. The change in soil water storage (ΔS) could be expressed by the water balance equation as follows.

$$(I+WP) - (P+ET) = \Delta S \qquad (5)$$

Figure 46 shows the relationship of water balance components in vegetated and non-vegetated landfill cover systems under wet and dry conditions. Irrigation and percolation was involved in the water balance only in case of wet condition. However, in dry condition, water vapor (V) supplied from the water saturated landfill gas upflow was considered as water input in the water balance, thus percolation was not observed in this experimental condition. In non-vegetated landfill cover system, soil water directly evaporated into the atmosphere at the soil surface, whereas in the vegetated landfill cover system, water loss through atmosphere included both soil evaporation and plant transpiration which represented in combination term of evapotranspiration.

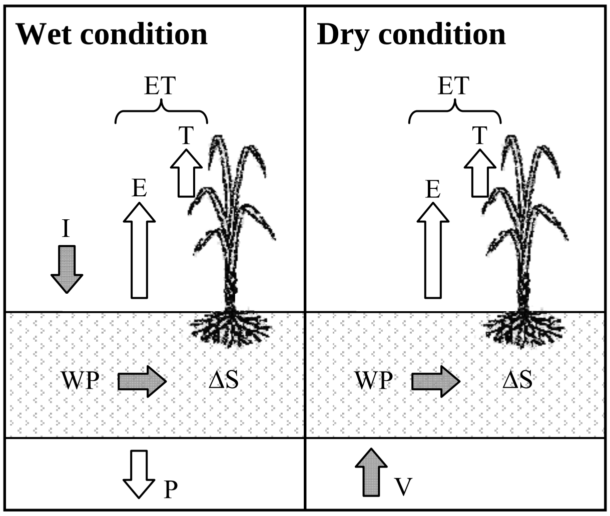



**Figure 46** Components of water balance in vegetated and non-vegetated landfill cover systems under wet and dry conditions (I = irrigation, V = vapor upflow, WP = water production, E = evaporation, T = transpiration, ET = evapotranspiration, P = percolation, and ΔS = change in soil water storage)

Irrigation was continually applied every 4 days during the experimental period. Percolation and soil water content were measured directly from the experimental columns. The change in soil water storage was calculated from water content at the beginning and the end of experiment. Based on landfill cover system, water was another by-product of methane oxidation reaction. Thus, water production rate (WPR) could be calculated from MOR as presented in the following equation.

$$\mathrm{WPR\ (cm^3H_2O/cm^2d)} = \mathrm{MOR}\left(\frac{\mathrm{mol\,CH_4}}{\mathrm{m^2 \cdot d}}\right) \times \frac{\mathrm{2\ mol\,H_2O}}{\mathrm{1\ mol\,CH_4}} \times \frac{\mathrm{1\ m^2}}{\mathrm{10^4\ cm^2}} \times \frac{\mathrm{18\ cm^3\ H_2O}}{\mathrm{1\ mol\,H_2O}} \tag{6}$$

From Eq.(5), evapotranspiration under wet condition could be computed by subtracting percolation and the change in soil water storage from irrigation and water production.

$$\mathrm{ET} = (\mathrm{I+WP}) - \mathrm{P} - \Delta\mathrm{S} \tag{7}$$

In dry condition, vapor from the water saturated gas upflow was expressed as water input instead of irrigation term and percolation was neglected from this case of water balance as shown in Eq.(8). Vapor could be determined from the decrease of water level in a unit of water saturated landfill gas preparation.

$$ET = (V+WP) - \Delta S \quad (8)$$

The water balance components are listed in Table 22. In landfill cover systems under wet condition (rainwater and leachate irrigations), major water input was irrigation while water production from methane oxidation involved small fraction of water input. Total water input applied to each cover system was about 1100 mm/yr which were percolated and evapotranspirated from the experimental column. And the remaining of water input was accumulated in the experimental column (expressed as water storage). In sandy loam, it showed the lowest water storage of 160 mm/yr with high percolation and evaporation of 500-600 and 300-400 mm/yr, respectively. Otherwise, compost demonstrated higher water storage of 500-600 mm/yr compared with sandy loam according to its water-holding capacity, which correlated to low percolation and evaporation of 400-500 and about 100 mm/yr, respectively. Moreover, application of vegetation in compost could promote water loss through evapotranspiration at 300-400 mm/yr and decreased water storage at 200-300 mm/yr. From the results, it indicated that in sandy loam most of water input was percolated from the experimental column while in compost most of water input was stored in the column and percolated from the column, respectively. Vegetation in compost cover system helped to stimulate water evapotranspiration. Therefore, water input was proportionally distributed by percolation, evapotranspiration and water storage.

Under dry condition of landfill cover systems, water input (about 100 mm/yr) was supplied by water vapor saturated gas upflow and water production in soil medium. Water loss in these cover systems was mainly caused by evaporation or evapotranspiration (60-100 mm/yr). Sandy loam revealed higher evaporation than compost according to lower water-holding capacity as previously mentioned. Vegetation with *P. repens* stimulated water evapotranspiration in both vegetated sandy loam and compost. Furthermore, vegetation also forced water to remove from soil water storage and then caused lower water content than that of the beginning of experiment (expressed as negative value of $\Delta S$).

After continuing dry condition, irrigation was further applied to be wet condition and observed the recovery of plant growth and methanotrophic activity. Hence, water input was approximately 1100 mm/yr which included irrigation, water production and water vapor upflow. Re-irrigation in landfill cover systems could slightly enhance water production from methane oxidation due to proving appropriate water content for methanotrophic activity. Most of water input was evapotranspirated (1000 mm/yr) in vegetated sandy loam, but in compost both with and without vegetation demonstrated almost similar degree of evapotranspiration (600 mm/yr) and water storage (500 mm/yr). However, all these cover systems with irrigation did not provide water percolation possibly due to lower water content than that of field capacity.

**Table 22** Quantities of water balance components for landfill cover systems under wet and dry conditions

| Landfill cover systems | Water balance components [1] (mm/yr) | | | | | |
|---|---|---|---|---|---|---|
| | I | V | WP | P | ΔS | ET [2] |
| Wet season | | | | | | |
| Rainwater irrigation | | | | | | |
| SL | 1033 | - | 46 | 499 | 160 | 421 |
| C | 1033 | - | 42 | 388 | 624 | 63 |
| C + *S. virginicus* | 1033 | - | 27 | 462 | 327 | 271 |
| C + *P. repens* | 1033 | - | 74 | 463 | 274 | 370 |
| Leachate irrigation | | | | | | |
| SL | 1033 | - | 46 | 611 | 160 | 307 |
| C | 1033 | - | 75 | 504 | 471 | 133 |
| C + *S. virginicus* | 1033 | - | 65 | 550 | 228 | 320 |
| C + *P. repens* | 1033 | - | 58 | 345 | 319 | 426 |
| Dry season | | | | | | |
| No irrigation | | | | | | |
| SL | - | 50 | 58 | - | 36 | 71 |
| SL + *P. repens* | - | 26 | 56 | - | -16 | 97 |
| C | - | 26 | 59 | - | 27 | 58 |
| C + *P. repens* | - | 25 | 55 | - | -3 | 83 |
| Re-irrigation | | | | | | |
| SL | n.a. | n.a. | n.a. | n.a. | n.a. | n.a. |
| SL + *P. repens* | 1033 | 21 | 75 | - | 121 | 1008 |
| C | 1033 | 20 | 81 | - | 651 | 482 |
| C + *P. repens* | 1033 | 18 | 82 | - | 628 | 505 |

Note: [1] All components are presented in unit of millimeter of water per year (mm/yr) according to different experimental periods in each landfill cover system
[2] ET should be evaporation in case of no vegetation
n.a. = not analyzed

### 4.2 Effect of seasonal variation on methane oxidation

Based on soil water content is an important factor of methane oxidation in landfill cover soils, wet and dry conditions were simulated to investigate the efficiency of methane oxidation under different seasons. In the previous experiments (sections 2 and 3), methane oxidation was studied under application of rainwater or leachate. However, under dry condition without irrigation, this experiment was conducted to investigate the efficiency of methane oxidation in sandy loam and compost both with and without vegetation (*P. repens*). After that, the efficiencies of methane oxidation from wet and dry experimental conditions were compared and the results are discussed below.

4.2.1 Methane oxidation efficiency in dry condition

As shown in Figure 47, low MOR about 8 mol $CH_4/m^3$.d was found in all experimental columns. There was no significant difference between the cases of sandy loam and compost or the cases of vegetated and non-vegetated columns. Sandy loam provided the steady low MOR along the experimental period of 290 days. Similar to that of other three columns, the steady MOR was also maintained throughout the active period. Nevertheless, after 160 days, the operated condition was changed to be wet condition by irrigating with rainwater for the purposes of recovery of methane oxidation capacity and plant growth. During the irrigated period of 40 days, MOR gradually increased to a constant rate of 10 mol $CH_4/m^3$.d which was close to that of rates in cases of wet condition experiments (sections 2 and 3). It indicated that the capacity of methane oxidation could be recovered by re-irrigation due to the supply of a suitable water content for methanotrophic bacteria.

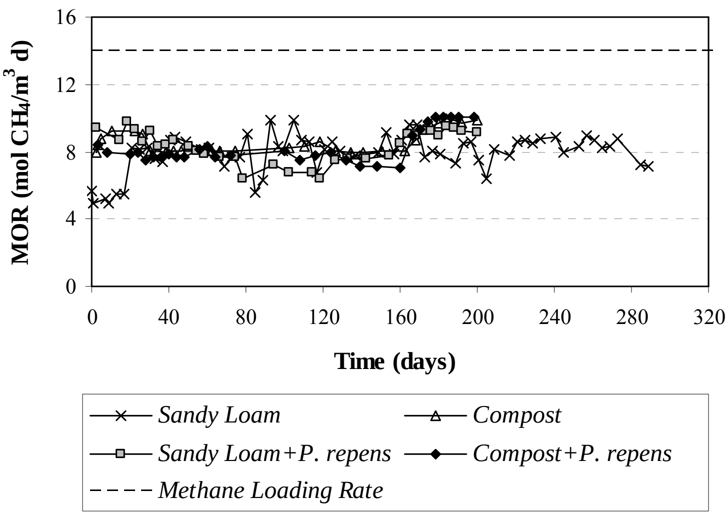



**Figure 47** Variation of total methane oxidation rate (MOR) in vegetated and non-vegetated landfill cover materials without irrigation

Figure 48 shows MOR at different depths of the experimental columns. Both vegetated and non-vegetated sandy loam exhibited the same range of MOR with a slight fluctuation throughout the active zone of 5-50 cm. Otherwise, compost both with and without vegetation provided higher MOR in the upper part (5-15 and 15-30 cm) and lower MOR in the bottom part (30-50 cm). From this result, it could be seen that sandy loam and compost had similar active zone of 5-50 cm but different MOR on each layer. It could suggest that dry condition without irrigation caused the shift of active zone in sandy loam to the lower part as compared with the results in wet condition experiment, whereas that of active zone in compost was insignificantly different. Furthermore, after re-irrigation, the active zone (Figures 48(b)-(d)) was shifted to the upper part (5-15 and 15-30 cm) with higher MOR which corresponded to the recovery of methane oxidation capacity as previously mentioned.

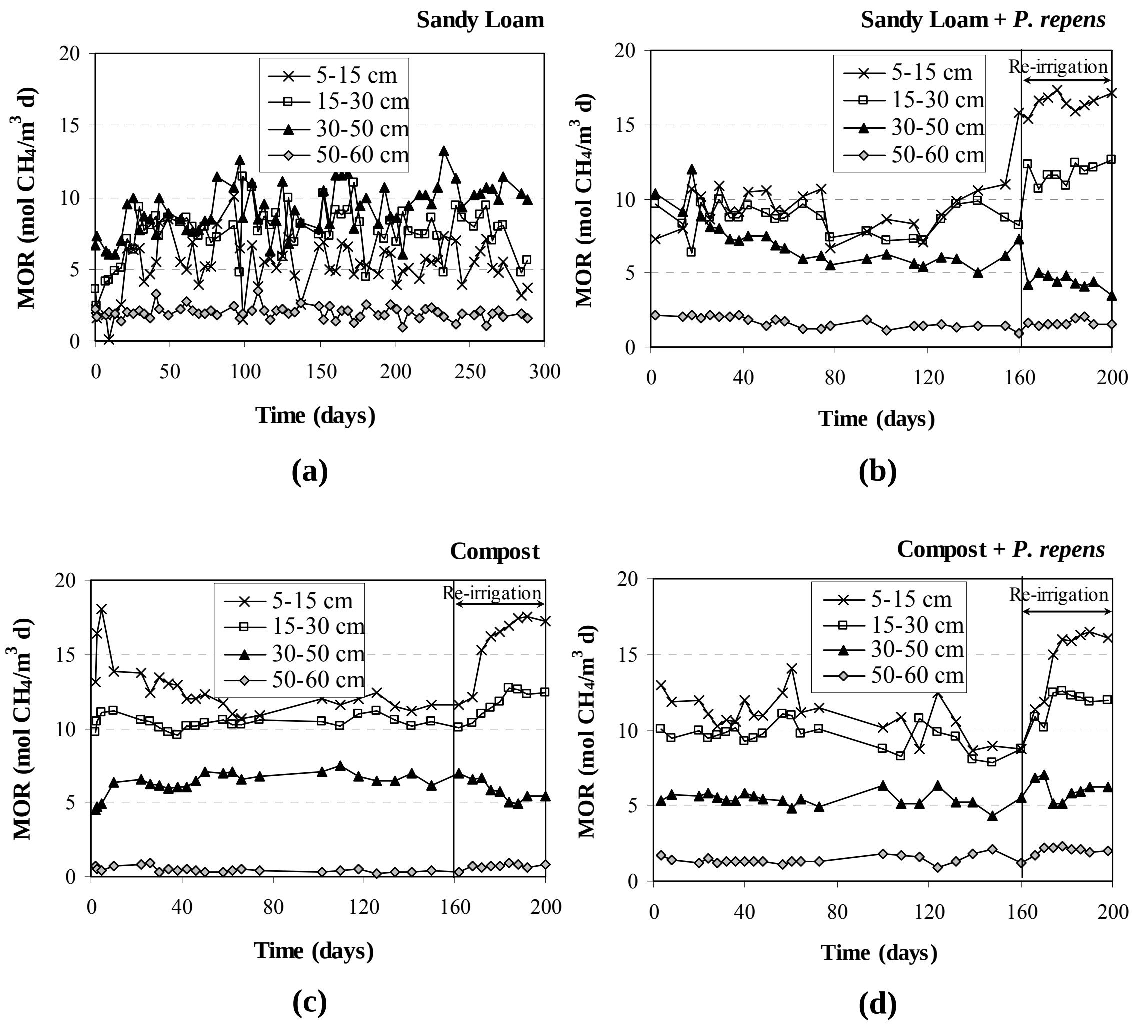



**Figure 48** Methane oxidation rate (MOR) throughout the depth profile of vegetated and non-vegetated landfill cover materials without irrigation

Consideration of gas profiles along the depth of each cover material (Figure 49), the high content of oxygen (5-16%) throughout the active zone (5-50 cm) of all experimental columns was also confirmed. Moreover, the change of $CH_4$:$CO_2$ ratio also confirmed the horizon of methane oxidation. During dry condition (Figures 49(a), (b)), $CH_4$:$CO_2$ ratio significantly declined from 60:40 at the bottom inlet to 40:60 and 50:50 at 5-50 cm depth of sandy loam and vegetated sandy loam, respectively. In compost both with and without vegetation (Figures 49(d), (f)), this ratio also declined from 60:40 to 50:50 at 5-30 cm depth. However, after re-irrigation, the oxygen content at the lower part (30-60 cm) slightly decreased according to the increasing of water storage in soil pores. Further, the $CH_4$:$CO_2$ ratio, especially in compost and vegetated compost columns, was more decreased to 40:60 at the top layer. These results also confirmed that re-irrigation could recover the capacity of methane oxidation especially at the upper zone (5-15 cm).

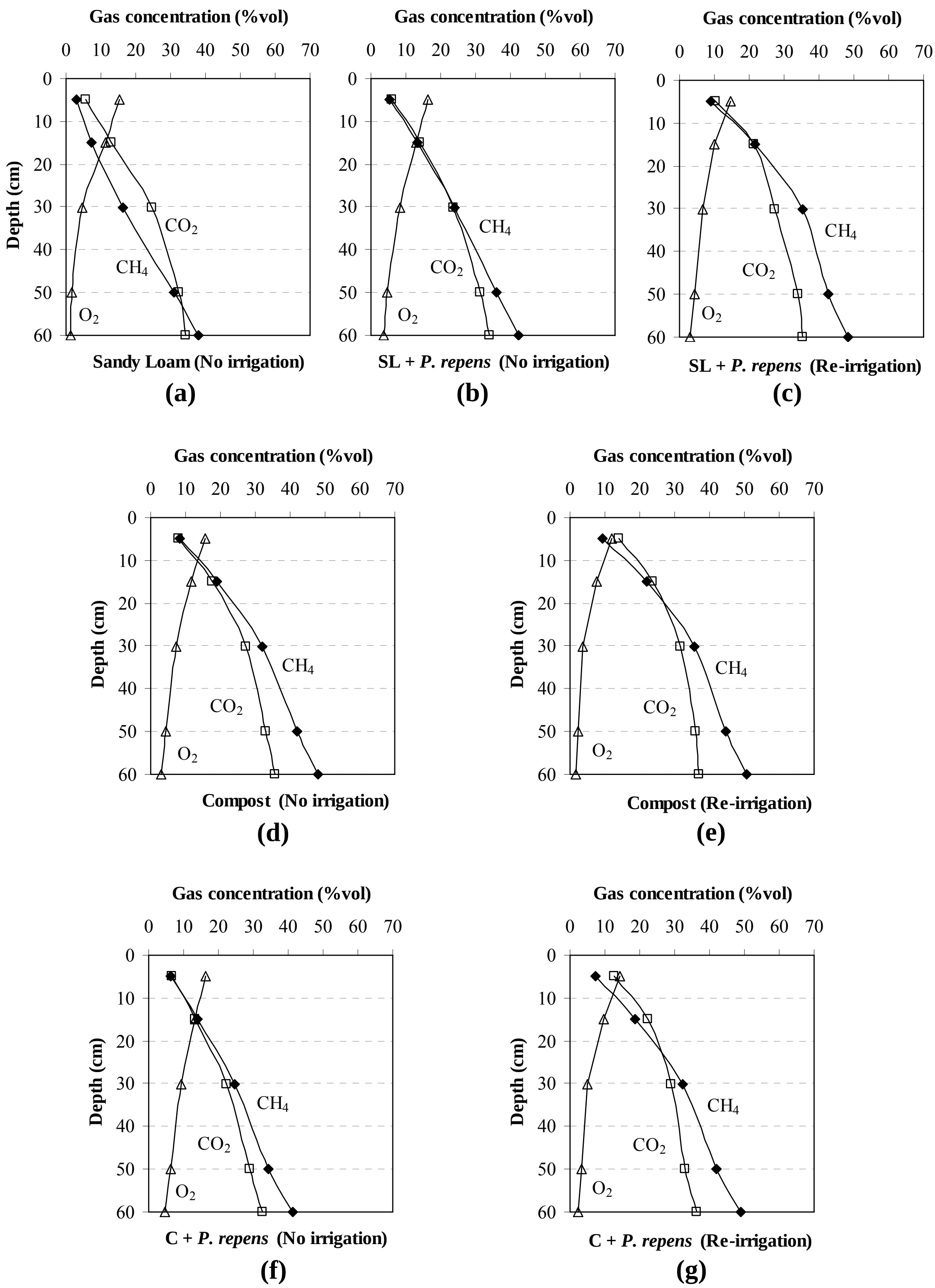
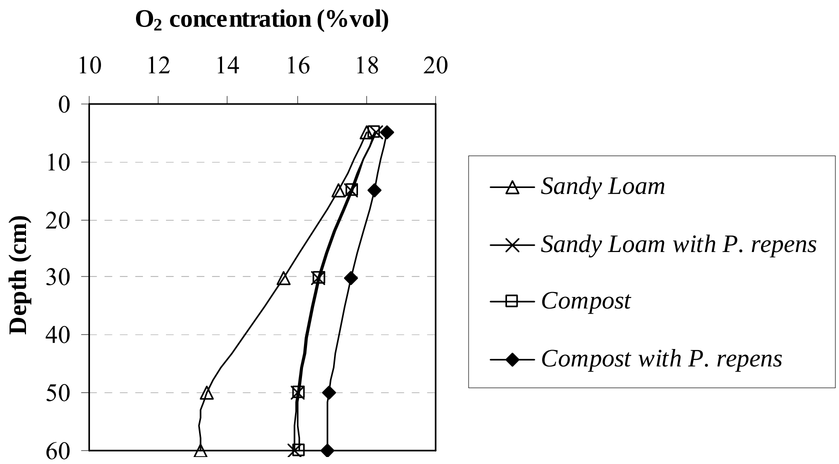



**Figure 49** Gas concentration profiles during dry condition (day 0-160) and re-irrigation (after day 160) as a functions of depth in (a) sandy loam; (b), (c) sandy loam with *P. repens*; (d), (e) compost; and (f), (g) compost with *P. repens*, respectively

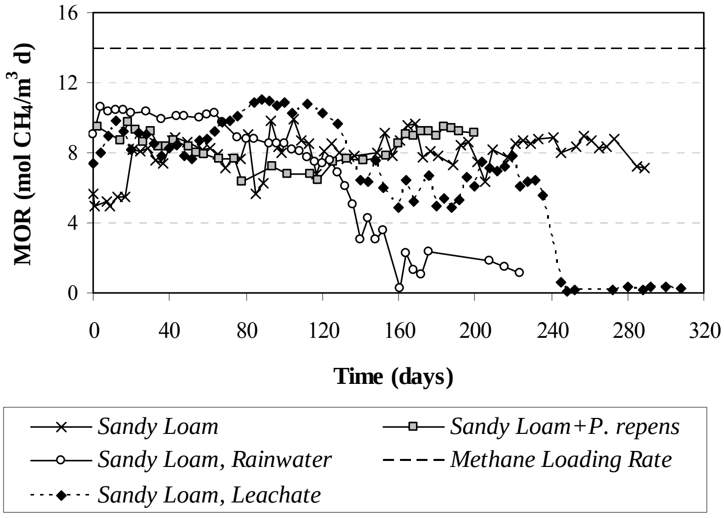
Additionally, oxygen penetrations without the influence of landfill gas upflow were also observed (Figure 50). It was clearly seen that compost provided higher natural penetration of oxygen than sandy loam due to its high porosity characteristics (Humer and Lechner, 2001a; Streese and Stegmann, 2003). Vegetation could also increase the oxygen content throughout the column depths according to the oxygen supply through plant root system (Schütz *et al.*, 1991; Chanton, 2005). In comparison with the case of applied landfill gas, all cover systems had higher oxygen contents (14-18%) than the contents (5-16%) in the case with landfill gas. Landfill gas upflow caused the decrease of oxygen diffusion from the atmosphere. In general, oxygen was used to oxidize methane (landfill gas) by methanotrophic bacteria via methane oxidation reaction. Moreover, counter current between landfill gas upflow and diffused air downflow also affected the oxygen penetration into the soil.



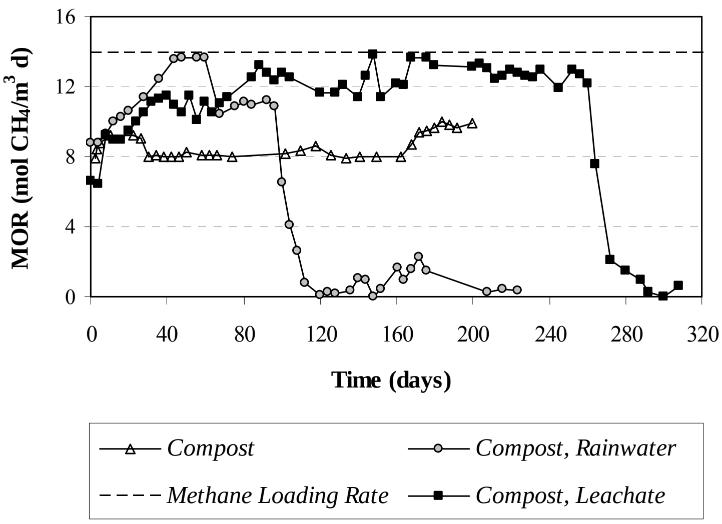

**<u>Figure 50</u>** Oxygen penetrations in vegetated and non-vegetated cover materials without synthetic landfill gas upflow

4.2.2 Comparison of methane oxidation efficiency between wet and dry conditions

The comparison of methane oxidation efficiency between wet and dry conditions is shown in Figure 51 and Table 23. In sandy loam (Figure 51(a)), MOR about 8 mol $CH_4/m^3$.d (60% removal) was maintained throughout the active period (over 200 days) of both wet and dry conditions, even though the sandy loam irrigated with rainwater provided higher MOR of about 10 mol $CH_4/m^3$.d (70% removal) within a shorter active period of 120 days. Moreover, after long-term operation under dry condition, application of rainwater in the vegetated sandy loam column could enhance the capacity of methane oxidation to the higher MOR of 9 mol $CH_4/m^3$.d (65% removal).

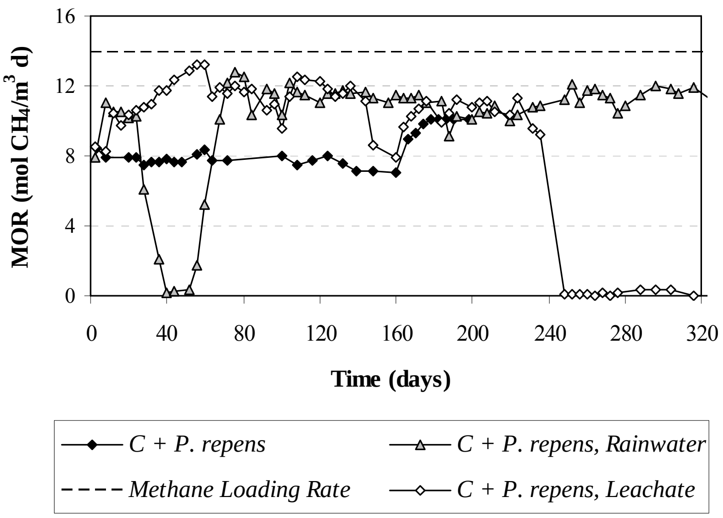



**(a)**




**(b)**

**<u>Figure 51</u>** Variation of total methane oxidation rate (MOR) in vegetated and non-vegetated landfill cover materials without irrigation compared to rainwater and leachate irrigations: (a) sandy loam and sandy loam with *P. repens*; (b) compost; and (c) compost with *P. repens*




**(c)**

**Figure 51** (Cont'd)

As shown in Figure 51(b), compost exhibited different capacities of methane oxidation between wet and dry conditions. Wet condition maintained higher MOR of 11-12 mol $CH_4/m^3$.d (80-85% removal) along the active period. Meanwhile, dry condition had a lower MOR of 8 mol $CH_4/m^3$.d (60% removal). Re-irrigation could recover MOR to about 10 mol $CH_4/m^3$.d (70% removal) even if it was lower than that of the wet condition. Similar to the case of vegetated compost (Figure 51(c)), MOR in wet condition was also higher than that of dry condition and the recovery of MOR was achieved by re-irrigation with rainwater.

Furthermore, MOR on each layer of landfill cover materials was also significantly different between the cases of wet and dry seasons as listed in Table 23. Under wet season, MOR was extremely high at the upper layer (5-15 cm) according to water accumulation in the lower layer after long irrigation. Contrary to dry season, the moderate MOR was found along the active zone of 5-15, 15-30 and 30-50 cm. Moreover, MOR at the lower part (30-50 cm) was rather higher than the rate in that of wet condition. However, after re-irrigation, an increase of MOR was found at the upper parts (5-15 and 15-30 cm) while some decline of MOR was observed in the lower part (30-50 cm). This change of MOR after re-irrigation performed similar trend of MOR to that of wet condition experiment.

Comparing the experimental results under wet and dry conditions indicated that moisture maintenance in cover soil was an important factor governing methane oxidation. The water content should be maintained at the optimum level for methanotrophic bacteria and gas transport in soil. An increase in water content could increase water fill in the soil pores and then inhibited oxygen diffusion into the soil (Boeckx and Cleemput, 1996). Low water content, on the other hand, resulted in microbial desiccation and activity reduction (Whalen *et al.*, 1990). Intermittent irrigation of rainwater and leachate in wet conditions maintained appropriate water content for methanotrophic activity and supported plant growth in landfill cover systems. Nevertheless, leachate application also helped to stimulate MOR and methanotrophic active period due to the provision of supplemental nutrients. However, the absence of moisture control in dry condition gave moderate methanotrophic activity in both vegetated and non-vegetated columns. Their methane oxidation capacities would be reduced eventually due to water loss to below the critical point for microorganism survival. These results suggested that methane oxidation in landfill was successfully maintained over the year duration by application of leachate if rainfall was not available. Moreover, the operation without any irrigation in dry condition also provided a moderate methane oxidation rate for a while (over 160 days).

**Table 23** Methane oxidation rate (MOR) in different cover materials (sandy loam, SL and compost, C) and vegetated cover layer (*S. virginicus* and *P. repens*) during wet and dry seasons

| Cover systems | Depth [(1)] (cm) | | | | | Active period (days) |
|---|---|---|---|---|---|---|
| | 5-15 | 15-30 | 30-50 | 50-60 | Total | |
| Wet season | | | | | | |
| Rainwater irrigation | | | | | | |
| SL | 22.9 | 9.4 | 4.9 | 0.9 | 9.7 | 120 |
| C | 37.8 | 8.4 | 4.4 | 1.0 | 10.9 | 100 |
| C + *S. virginicus* | 31.7 | 10.2 | 4.3 | 0.9 | 11.0 | 60 |
| C + *P. repens* | 31.4 | 11.9 | 6.3 | 1.5 | 11.9 | 400 |
| Leachate irrigation | | | | | | |
| SL | 33.4 | 3.6 | 1.4 | 0.3 | 8.0 | 240 |
| C | 58.7 | 2.4 | 1.3 | 0.5 | 11.7 | 260 |
| C + *S. virginicus* | 51.2 | 3.6 | 1.5 | 0.7 | 11.4 | 300 |
| C + *P. repens* | 54.1 | 4.7 | 2.2 | 0.8 | 12.0 | 240 |
| Dry season | | | | | | |
| No irrigation | | | | | | |
| SL | 5.2 | 7.4 | 9.0 | 2.1 | 7.9 | 290 |
| SL + *P. repens* | 9.3 | 8.6 | 7.1 | 1.7 | 8.0 | 160 |
| C | 12.6 | 10.4 | 6.4 | 0.5 | 8.3 | 160 |
| C + *P. repens* | 11.0 | 9.6 | 5.4 | 1.4 | 7.8 | 160 |
| Re-irrigation | | | | | | |
| SL | n.a. | n.a. | n.a. | n.a. | n.a. | n.a. |
| SL + *P. repens* | 16.4 | 11.8 | 4.4 | 1.7 | 9.2 | 40 |
| C | 16.7 | 12.0 | 5.4 | 0.7 | 9.7 | 40 |
| C + *P. repens* | 15.9 | 12.2 | 5.7 | 2.1 | 9.9 | 40 |

Note: [(1)] All data are the average MOR (mol $CH_4/m^3.d$) in the steady active periods
n.a. = not analyzed

4.3 Extracellular polysaccharides (EPS) production

After long-term operation under dry condition (over 160 days), EPS content was determined along the column depth. As shown in Figure 52, low EPS production was found in sandy loam both with and without vegetation. The content was about 2 mg C/g dry soil throughout the column depth except at the lower part (30-50 cm) of the bare sandy loam column in which the highest methanotrophic activity took place. In addition, high EPS formation in range of 7-10 mg C/g dry soil was observed in both vegetated and non-vegetated compost and the highest content existed at the upper active zone (5-15 cm). It could imply that EPS formation in this experimental condition was mainly caused by an unfavorable condition of soil desiccation for methanotrophic bacteria (Hilger *et al.*, 1999) and a high ratio of $O_2$:$CH_4$ almost throughout the depth which also stimulated EPS formation (Chiemchaisri *et al.*, 2001a). Rather dissimilar to the wet condition experiments, EPS formation did not significantly clog soil pores as evidenced by the oxygen concentration profile (Figure 49). Oxygen also penetrated almost the entire depth of experimental columns. However, this EPS production consequently limited methanotrophic activity by embedding methanotrophic bacteria in the EPS biofilm and then restricting oxygen diffusion to that of embedded bacteria (Hilger *et al.*, 2000a). These results did not clearly indicate that EPS production caused the decrease in methane oxidation. They only exhibited the limitation of methane oxidation by EPS to a lower rate as compared to the experimental results of wet condition.

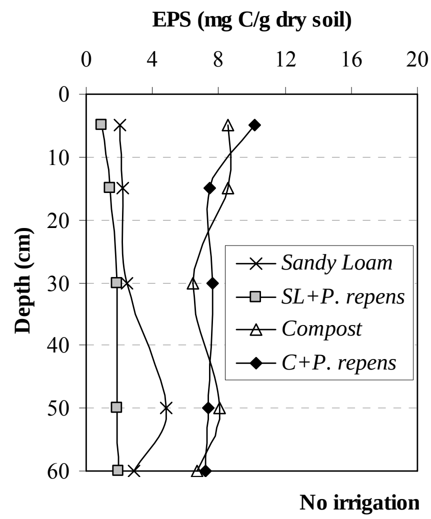



**Figure 52** EPS (expressed as mg C/g dry soil) profiles as a function of depth in vegetated and non-vegetated landfill cover materials at the end of experiment without irrigation

4.4 Methanotrophic activity in batch experiment

Soil samples from the experimental columns under dry condition were investigated methanotrophic activity through batch incubation. Figure 53 shows methane consumption in sandy loam and compost both with and without vegetation along the incubation periods. Most curves demonstrated long incubation period in consuming methane and thus MOR was evaluated from slopes as listed in Table 24.

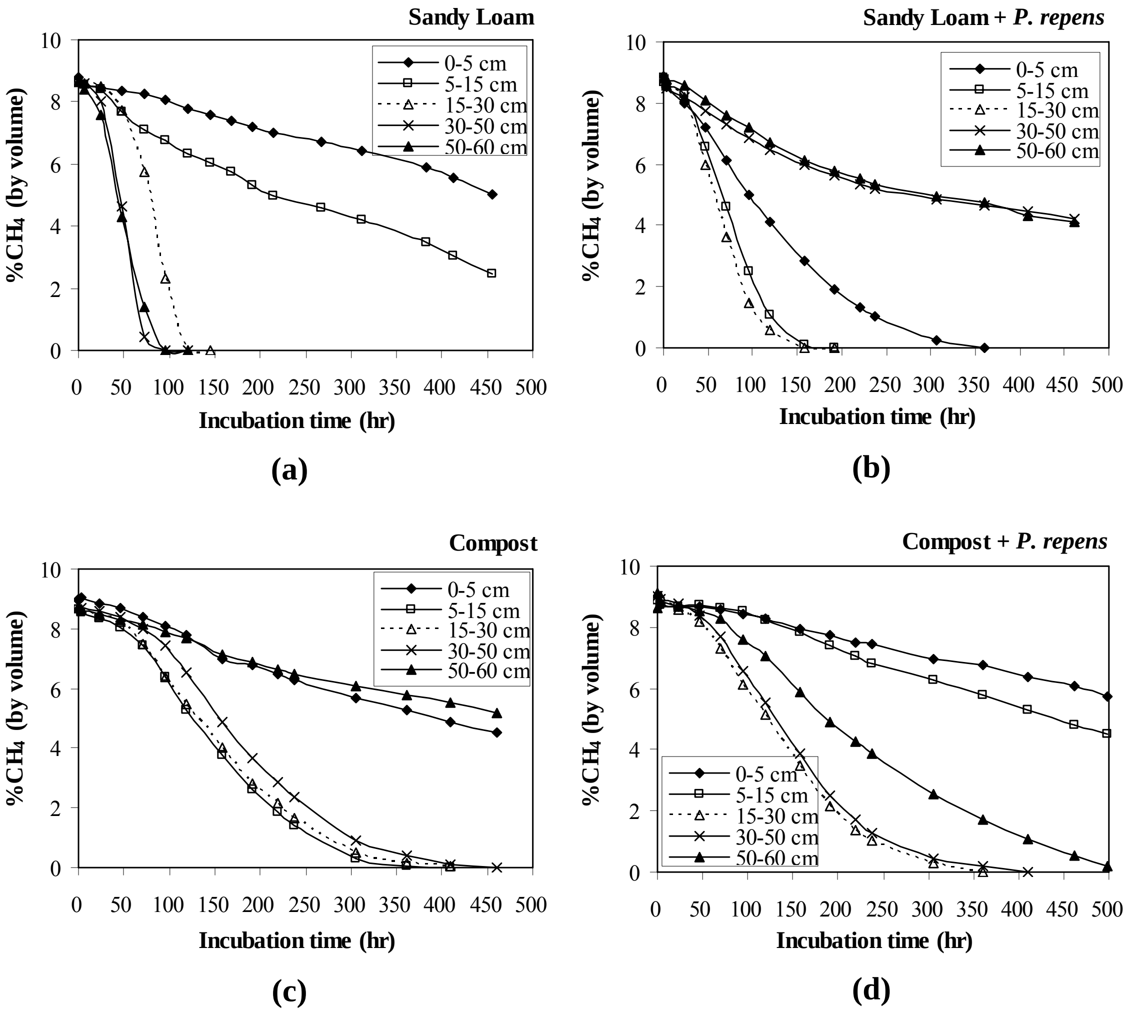



**Figure 53** Methane consumption in batch experiment of vegetated and non-vegetated cover materials (no irrigation): sandy loam (b) with and (a) without *P. repens*; and compost (d) with and (c) without *P. repens*

Based on the experimental condition without irrigation, the active zone of sandy loam (Figure 53(a)) was shifted to deeper layer (15-60 cm) with a MOR about 0.2 μmol $CH_4$/kg.s. Besides, the vegetated sandy loam (Figure 53(b)) provided the methanotroph activity about 0.1-0.2 μmol $CH_4$/kg.s in the top and middle layers (0-30 cm). This could indicate that both vegetated and non-vegetated sandy loam had similar capacity of methane oxidation but the active zone of sandy loam was rather deeper than that of vegetated one. Furthermore, compost with and without vegetation (Figures 53(c), (d)) also manifested the trend of methane consumption similar to those of sandy loam cases. Both compost cases provided approximately 0.1 μmol $CH_4$/kg.s in their active zones (5-50 cm). Similar methanotrophic activity from these batch results were correlated to the results of column experiment.

In comparison with the wet condition experiment, methanotrophic activity in dry condition was much lower and its active horizon was shifted to the middle and bottom parts. These results also evidenced the low capacity of methane oxidation in the operation without irrigation (dry condition) and also suggested that maintenance of moisture content by irrigation (wet condition) mainly influenced methanotrophic activity.

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**Table 24** Methane oxidation rate in batch experiment of vegetated and non-vegetated cover materials collected from column experiment without irrigation

| Landfill covers | Depth | Methane oxidation rate (μmol $CH_4$/kg dry soil·s) |
|---|---|---|
| SL | 0-5 cm | 0.02 |
| | 5-15 cm | 0.03 |
| | 15-30 cm | 0.21 |
| | 30-50 cm | 0.25 |
| | 50-60 cm | 0.23 |
| SL + *P. repens* | 0-5 cm | 0.07 |
| | 5-15 cm | 0.14 |
| | 15-30 cm | 0.17 |
| | 30-50 cm | 0.02 |
| | 50-60 cm | 0.02 |
| C | 0-5 cm | 0.03 |
| | 5-15 cm | 0.09 |
| | 15-30 cm | 0.09 |
| | 30-50 cm | 0.09 |
| | 50-60 cm | 0.02 |
| C + *P. repens* | 0-5 cm | 0.01 |
| | 5-15 cm | 0.02 |
| | 15-30 cm | 0.10 |
| | 30-50 cm | 0.11 |
| | 50-60 cm | 0.06 |

Furthermore, the lag phase of methanotrophic activity was absent in these methane consumption curves (Figure 53). It was possibly due to high oxygen diffusion throughout the depth profile of column experiment (Figure 49) and consequently contributed to high ratio of $O_2$:$CH_4$ which was close to that of ratio (about 1.8) in batch incubation.

## 4.5 Methanotroph population study by fluorescence *in situ* hybridization (FISH) technique

The population and distribution of methanotrophs in the experimental columns, operated under dry condition, was studied by FISH technique. At the end of experimental period, each cover material (sandy loam and compost) was sampled at the top (5-15 cm), middle (15-30 cm), bottom (30-50 cm) layers and further rhizosphere if vegetation was applied. FISH detection allowed the identification of types and quantification of methanotroph numbers as listed in Table 25. Methanotrophs were classified in two types, type I and type II, and their numbers were reported in term of the percentage of total microorganisms obtained by DAPI staining.

In two sandy loam columns, with and without *P. repens*, they possessed small amount of methanotrophs below 7% of the total microorganisms. Most methanotrophs were existed at the active zone, 30-50 cm of the sandy loam column and 5-30 cm including root zone of the vegetated sandy loam column. In addition, distributions of type I and type II methanotrophs were similar in proportions throughout the sandy loam column, whereas the predominance of type I methanotrophs was found in the upper part (5-15 cm) including rhizosphere of the column with vegetation.

**Table 25** Numbers of methanotrophs detected by FISH technique in relation to the total DAPI counts in vegetated and non-vegetated column experiment without irrigation

| Landfill covers | Depth | Numbers of methanotrophs (% of the DAPI counts) | |
|---|---|---|---|
| | | Type I | Type II |
| SL | 5-15 cm | 1.01 | 0.48 |
| | 15-30 cm | 0.81 | 2.68 |
| | 30-50 cm | 4.27 | 5.45 |
| SL + *P. repens* | 5-15 cm | 7.11 | 1.50 |
| | Rhizosphere [(1)] | 6.87 | 3.05 |
| | 15-30 cm | 3.07 | 5.52 |
| | 30-50 cm | 0.43 | 0.94 |
| C | 5-15 cm | 28.56 | 23.73 |
| | 15-30 cm | 4.20 | 0.38 |
| | 30-50 cm | 5.45 | 0.51 |
| C + *P. repens* | 5-15 cm | 14.33 | 0.65 |
| | Rhizosphere [(1)] | 9.15 | 1.04 |
| | 15-30 cm | 2.29 | 0.69 |
| | 30-50 cm | 2.33 | 0.14 |

Note: [(1)] Soil sampled from the rhizosphere at depth of 5-15 cm

Other two columns, vegetated and non-vegetated compost, contained higher methanotroph populations (10-30% of the total microorganisms) at the upper active zone and also rhizosphere. The most abundance of methanotrophs detected were members of type I similar to that of vegetated sandy loam column. High oxygen diffusion in the experiment operated with dry condition was considered as a favorable condition for type I methanotrophs which preferred to survive under the conditions of low-methane and high-oxygen at the top cover (Amaral *et al.*, 1995; Amaral and Knowles, 1995). This simulated dry season offered an oxic condition for type I methanotrophs rather than an anoxic condition for type II methanotrophs.

The results indicated an abundance of methanotrophs in the top layer and also rhizosphere of all experimental columns as the methanotrophic active zone, although some abundant methanotrophs occupied at the bottom part of the sandy loam column. Type I methanotrophs predominantly responded to methanotrophic activity, even if the capacity was rather lower in comparison with that of methanotrophic activity in the wet condition experiment.

## 4.6 Summary of results

Simulated wet and dry conditions in landfill cover operation significantly influenced the capacity of methane oxidation. Intermittent irrigation of rainwater or leachate in wet conditions could maintain an appropriate water content for methanotrophic activity and also supported the plant growth which consequently provided a high efficiency of methane oxidation about 10-12 mol $CH_4/m^3$.d over 240 days especially the compost columns both with and without vegetation. Nevertheless, no water supply in dry condition also maintained the moderate methane oxidation of about 8 mol $CH_4/m^3$.d over 160 days.

Dry condition caused a wide horizon of the active zone (5-50 cm) according to high oxygen penetration into the deeper layer. However, that of active zone especially the top soil gave a lower capacity of methane oxidation due to declination of soil water content to below 7% resulting in microbial desiccation, production of EPS and reduction of methanotrophic activity eventually. However, methanotrophic activity at the lower active zone (30-50 cm) was also higher than that of activity in the columns of wet condition. In addition, detection of methanotroph populations by FISH technique confirmed an abundance of type I methanotrophs (10-30% of the total microorganisms) in the upper active zone, although their methanotrophic activity was rather low.

These results could summarize that the continuation of methane oxidation was successfully performed over the year duration by application of leachate if rainfall was not available. Moreover, it could operate without any irrigation for a moderate methane oxidation capacity, otherwise it would recover that of capacity to the higher value by re-irrigation.

# CONCLUSIONS AND RECOMMENDATIONS

## 1. Conclusions

From the experimental investigation of methane oxidation in compost based landfill cover with vegetation, the following conclusions can be drawn:

2.9 Compost was found to be an effective landfill cover material for methane oxidation. It successfully maintained the highest MOR at about 12-13 mol $CH_4/m^3$.d (85-90% methane removal) over 260 days under leachate irrigation as compared to sandy loam and sandy loam/compost mixture. The utilization of compost responded to the high methanotrophic activity in the deeper active zone due to its beneficial properties, i.e. high porosity, water-holding capacity and organic content supporting more oxygen diffusion and methanotrophic activity. Additionally, this compost also exhibited stable characteristics with low competitive oxygen consumption for methane oxidation.

2.10 Vegetation in compost based landfill cover systems did not significantly increase methane oxidation capacity in comparison with non-vegetated compost cover system, however it could also maintain MOR at about 12 mol $CH_4/m^3$.d (85% methane removal) over 400 days under rainwater irrigation and 240 days under leachate irrigation, especially in vegetation with *P. repens*. Moreover, vegetation with *S. virginicus* also continued methane oxidation over 300 days under leachate application. Plant root systems influenced more diffusion of oxygen into the deeper soil layers, especially the longer and wider root system of *P. repens*. Additionally, this root system also demonstrated the favorable environment for methanotrophs with high amount of 10-30% of the total microorganisms.

2.11 Leachate irrigation significantly extended the active period of methane oxidation in comparison with rainwater irrigation. Indeed, supplemental nutrients from irrigated leachate in term of $NH_4^+$ helped stimulating methane oxidation in compost while slightly inhibiting in sandy loam. Nevertheless, $NO_3^-$ nutrient did not significantly affect the methanotrophic activity. However, leachate application also demonstrated positive effects in sustaining methane oxidation in landfill cover systems.

2.12 Leachate irrigation insignificantly affected plant growth. Both tropical grasses, *S. virginicus* and *P. repens*, showed salt-tolerant characteristics resulting from the application of leachate. However, *P. repens* could survive better in the landfill conditions either when being irrigated with rainwater or leachate as compared to *S. virginicus*.

2.13 The operation of landfill cover systems under dry condition had a moderate methane oxidation of about 8 mol $CH_4/m^3$.d (60% methane removal) over a period of 160 days. However, this capacity could be recovered to the higher value of 10 mol $CH_4/m^3$.d (70% methane removal) when the cover material was re-irrigated with rainwater.

2.14 Determination of water balance suggested that majority of irrigated rainwater or leachate in compost based cover system was accumulated in the soil matrix, while practice with vegetation resulted in an increase of water loss through evapotranspiration. Contrary to dry condition, most of water input was evaporated in non-vegetated cover systems and entire water input was evapotranspirated in vegetated cover systems.

2.15 The continuation of methane oxidation was successfully operated over a year duration in tropical climate by application of leachate (11.32 L/$m^2$ every 4 days) into compost cover material if rainfall was not available. This operation not only encouraged methane oxidation, but also substantially reduced the volume of leachate (by about 60% through evaporation and accumulation) which needed to be treated and discharged to the environment. Moreover, vegetation with tropical grass (*P. repens*) also helped sustaining methane oxidation capacity and protected cover soil erosion. In addition, these landfill cover systems could also operate without any irrigation of dry condition for a moderate methane oxidation capacity to prevent high water accumulation after long-term operation under wet condition. However, re-irrigation with rainwater or leachate could recover its capacity to almost full capacity of that achieved under wet condition.

## 2. Recommendations for Future Work

Based on the results of the present study, the following recommendations are proposed for future work:

2.1 Interrelations between methanotrophs with other heterotrophs or nitrifying bacteria should be further studied. Also, population and distribution of other heterotrophs or nitrifying bacteria should be determined by FISH technique.

2.2 In vegetation system, the effect of plant harvesting or replanting should be considered in regulatory procedures.

2.3 The operating strategies of landfill cover system proposed in this simulated column study should be further practiced in the actual landfill cover condition with the fluctuation of methane input.

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# APPENDICES

# Appendix A

## Calculations

## 1. Calculation of Hydraulic Loading for Column Experiment

The average amount of annual rainwater in Thailand (Tongaram, 1995) was 1000-1200 mm/year (1.0-1.2 m/year). Surface area of experimental column was 0.0177 $m^2$. Thus, the hydraulic loading was calculated as following:

$$
\begin{aligned}
\text{Hydraulic loading} &= (0.0177\ m^2) \times (1.1\ m/year) \times (1\ year/365\ d) \\
&= 5.3 \times 10^{-5}\ m^3/d \\
&= 50\ mL/d \\
&= (50\ mL/d) \times (1\ L/1000\ mL) \times (1/0.0177\ m^2) \\
&= 2.83\ L/m^2.d
\end{aligned}
$$

## 2. Standardization of Gas Chromatography

Normalization method was used for GC standardization. The determined gases were $CH_4$, $CO_2$, $O_2$ and $N_2$. For accurate and precise standardization, each standard gas was analyzed eight times to obtain average peak area and exhibit relative standard deviation (RSD) below 5%. Gas concentration and average peak area were showed in Appendix Table A1. Furthermore, correction factor was calculated from gas concentration (%vol.) and peak area as shown below.

$$\text{Correction Factor} = \frac{\left(\dfrac{\text{Area}_{\text{std}}}{\%\text{vol}_{\text{std}}}\right)}{\left(\dfrac{\text{Area}_{\text{i}}}{\%\text{vol}_{\text{i}}}\right)} \qquad \text{(A1)}$$

**Appendix Table A1** Gas concentrations (%vol.), average peak areas and correction factors of standard gases

| Gas | %vol. | Peak Area | | Area/%vol. | Correction Factor | Note |
|---|---|---|---|---|---|---|
| | | Average | RSD | | | |
| *$CH_4$ | 99.99 | 15147.7 | 3.42% | 151.5 | 1.00 | *Std. |
| $CO_2$ | 1 | 217.6 | 1.73% | 217.6 | 0.70 | |
| $O_2$ | 1 | 335.3 | 2.45% | 335.3 | 0.45 | |
| $N_2$ | 95 | 27177.0 | 1.98% | 286.1 | 0.53 | |

Correction factor was used to adjust peak area of gas sample to be corrected value (Eq.(A2)). Then, corrected gas concentration (%vol.) was evaluated from that of corrected peak area as shown in Eq.(A3).

$$\text{Corrected Area} = \text{Area} \times \text{Corrected Factor} \qquad \text{(A2)}$$

$$\text{Corrected Concentration } (\%\text{vol}_{\text{i}}) = \frac{\text{Corrected Area}_{\text{i}}}{\text{Total Corrected Area}} \times 100\% \qquad \text{(A3)}$$

**3. <u>Calculation of Methane Concentration and Methane Oxidation Rate (MOR) in Column Experiment</u>**

Eq.(A4) demonstrates a conversion of gas concentration between units of mass per volume ($\mu g/m^3$) and $ppm_v$ (Mihelcic *et al.*, 1999) which can be reformed to Eq.(A5) and Eq.(A6).

$$\frac{\mu g}{m^3} = ppm_v \times MW \times \frac{10^3 P}{RT} \qquad (A4)$$

Where $ppm_v$ = percentage x $10^4$

MW = molecular weight

$10^3$ = conversion factor ($10^3$ L = $m^3$)

P = pressure (use 1 atm)

R = 0.08205 L.atm/mol.K

T = temperature in degree K (use 303 K)

$$\frac{g}{L} = \text{percentage} \times MW \times \frac{10^{-2}}{RT} \qquad (A5)$$

$$\frac{mol}{L} = \text{percentage} \times \frac{10^{-2}}{RT} \qquad (A6)$$

Landfill gas ($CH_4$:$CO_2$ = 60:40) was performed at a flow rate of 3.91 mL/min (5.6304 L/d). Then, gas concentration in terms of g/L and mol/L were transformed to be expressed as Eq.(A7) and Eq.(A8) in terms of g $CH_4$/d and mol $CH_4$/d respectively.

$$\frac{g\,CH_4}{d} = \left[\text{percentage} \times MW \times \frac{10^{-2}}{RT}\right]\frac{g}{L} \times 5.6304\,\frac{L}{d}$$
$$= \text{percentage} \times 0.0362 \qquad (A7)$$

$$\frac{mol\,CH_4}{d} = \left[\text{percentage} \times \frac{10^{-2}}{RT}\right]\frac{mol}{L} \times 5.6304\,\frac{L}{d}$$
$$= \text{percentage} \times 0.00226 \qquad (A8)$$

Methane oxidation rate (MOR) can be expressed in terms of g $CH_4/m^3$.d and mol $CH_4/m^3$.d by substituting methane concentrations (Eq. A7 and Eq. A8) to the following equations (Eq. A9 and Eq. A10), respectively.

$$MOR\ \frac{g\,CH_4}{m^3 \cdot d} = \left[(CH_4)_{in} - (CH_4)_{out}\right]\frac{g}{d} \times \frac{1}{(\text{soil volume})\ m^3} \qquad (A9)$$

$$\text{MOR}\ \frac{\text{mol CH}_4}{\text{m}^3\cdot\text{d}} = \left[(\text{CH}_4)_{in} - (\text{CH}_4)_{out}\right]\frac{\text{mol}}{\text{d}} \times \frac{1}{(\text{soil volume})\ \text{m}^3} \quad \text{(A10)}$$

However, MOR in Eq.(A10) can be rewritten in the universal form as:

$$\text{MOR}\ \frac{\text{mol CH}_4}{\text{m}^3\cdot\text{d}} = \frac{Q\left[(\text{CH}_4)_{in} - (\text{CH}_4)_{out}\right]}{V} \quad \text{(A11)}$$

Where Q = gas flow rate (mL/day)

$(CH_4)_{in}$ = inflow methane concentration (mol/mL)
$(CH_4)_{out}$ = outflow methane concentration (mol/mL)
V = volume of soil ($m^3$)

**4. <u>Calculation of Methane Concentration and Methane Oxidation Rate (MOR) in Batch Experiment</u>**

Batch experiment was performed under following conditions:

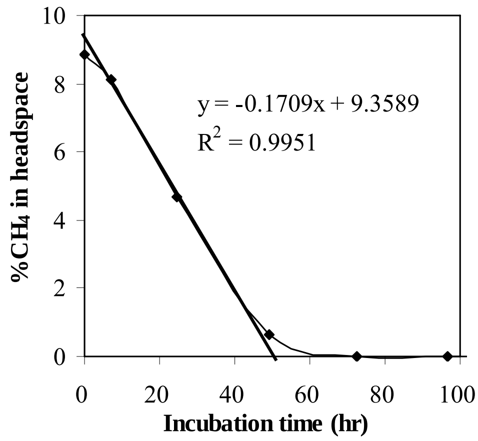
| | |
|---|---|
| Volume of the incubation bottle | = 188 mL |
| Wet weight of incubated soil | = 10 g |
| Soil moisture (%) | = depend on soil type |
| Dry weight of soil (g) | = soil wet wt.- water wt. |
| | $= 10\,\text{g} - \left(10 \times \frac{\text{MC\%w.w}}{100}\right)\text{g}$ |
| Bulk density of soil (kg/$m^3$ or g/mL) | = depend on soil type |
| Volume of soil (mL) | $= \frac{\text{soil wet wt. (g)}}{\text{bulk density (g/mL)}}$ |
| | $= \frac{10\ \text{g}}{\text{bulk density (g/mL)}}$ |
| Volume of headspace in bottle (mL) | = volume of bottle – volume of soil |
| | = 188 mL – volume of soil |

According to Eq.(A4) and Eq.(A5), methane concentration in the incubation bottle could obtain as following:

$$\frac{\text{g CH}_4}{\text{L}} = \text{percentage} \times 6.4357 \times 10^{-3} \quad \text{(A12)}$$

$$\text{g CH}_4 = \text{percentage} \times 6.4357 \times 10^{-3} \times V_{headspace}\ (\text{L}) \quad \text{(A13)}$$

Additionally, methane consumption curve (Appendix Figure A1) of batch experiment was presumed to be zero order reaction. Therefore, the activity rate could obtain from a slope of curve (0.1709 $\%CH_4$/hr in this example curve).




**Appendix Figure A1** Methane consumption curve

The methane oxidation rate of incubation experiment could calculate from the activity rate (%/hr) or slope of curve.

$$\frac{\text{g CH}_4}{\text{hr}} = \text{slope}\left(\frac{\%}{\text{hr}}\right) \times 6.4357 \times 10^{-3} \times V_{\text{headspace}}\ (\text{L}) \tag{A14}$$

$$\frac{\mu\text{g CH}_4}{\text{g} \cdot \text{hr}} = \text{slope}\left(\frac{\%}{\text{hr}}\right) \times 6.4357 \times V_{\text{headspace}}\ (\text{L}) \times \frac{1}{\text{dry wt. soil (g)}} \tag{A15}$$

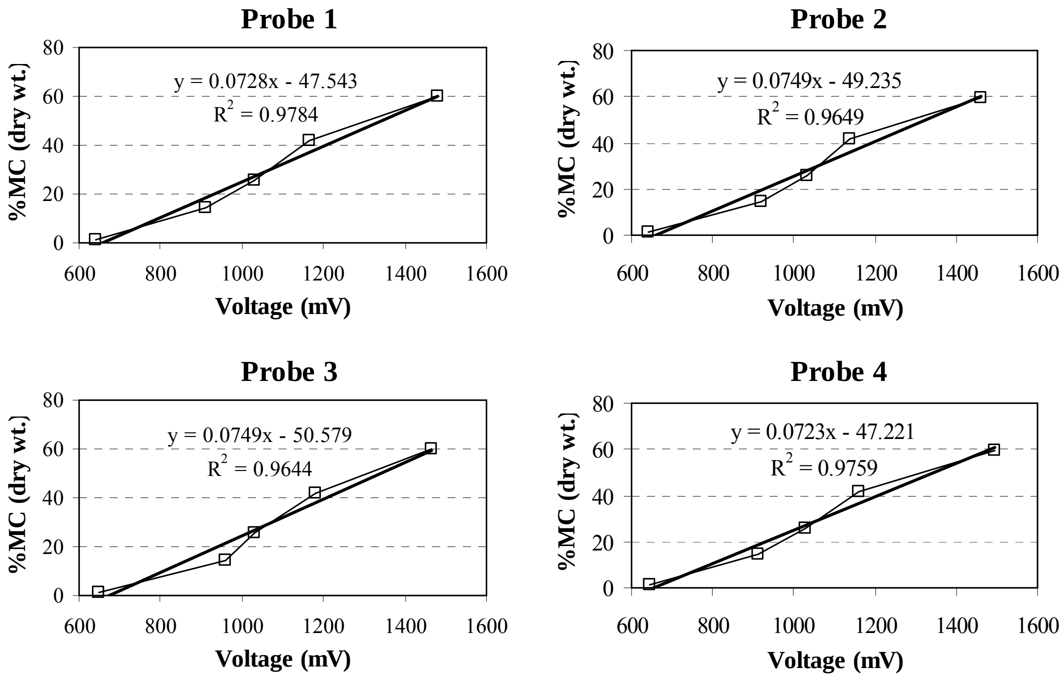
Moreover, methane oxidation rate could also calculate in another unit as following.

$$\frac{\text{mol CH}_4}{\text{hr}} = \text{slope}\left(\frac{\%}{\text{hr}}\right) \times 4.0223 \times 10^{-4} \times V_{\text{headspace}}\ (\text{L}) \tag{A16}$$

$$\frac{\mu\text{mol CH}_4}{\text{kg} \cdot \text{s}} = \text{slope}\left(\frac{\%}{\text{hr}}\right) \times 0.1117 \times V_{\text{headspace}}\ (\text{L}) \times \frac{1}{\text{dry wt. soil (kg)}} \tag{A17}$$

**5. Calibration of Soil Moisture Sensors (ECHO, model EC-10)**

Soil moisture sensors calibration generally followed the standard procedure for calibrating capacitance probes outlined by Starr and Paltineanu (2002). Soil moisture sensors were calibrated by measuring voltage (mV) of soil samples at different moisture content. Soil samples were then determined their moisture by gravimetric method or oven drying method (Anderson and Ingram, 1993). Calibration curves (Appendix Figure A2) of moisture sensors can be expressed in terms of voltage (mV) and soil moisture content (%dry weight basis).




**Appendix Figure A2** Calibration curves of soil moisture sensors

From these calibration curves, soil moisture content (MC, %dry wt.) was calculated by using the equations below:

Probe 1: MC (%dry wt.) = 0.0728 (voltage, mV) – 47.543 (A18)

Probe 2: MC (%dry wt.) = 0.0749 (voltage, mV) – 49.235 (A19)

Probe 3: MC (%dry wt.) = 0.0749 (voltage, mV) – 50.579 (A20)

Probe 4: MC (%dry wt.) = 0.0723 (voltage, mV) – 47.221 (A21)

# Appendix B

## Data of Gas Concentrations in Column Experiment

**Appendix Table B1** Gas concentrations in non-vegetated sandy loam column with rainwater irrigation

| Day | Depth (cm) | Gas concentrations | | | | Day | Depth (cm) | Gas concentrations | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | $\%CH_4$ | $\%CO_2$ | $\%O_2$ | $\%N_2$ | | | $\%CH_4$ | $\%CO_2$ | $\%O_2$ | $\%N_2$ |
| 0 | 5 | 14.3 | 12.5 | 14.0 | 59.2 | 76 | 5 | 19.9 | 24.5 | 5.9 | 49.7 |
| | 15 | 26.4 | 21.6 | 10.0 | 42.0 | | 15 | 37.5 | 35.6 | 0.8 | 26.1 |
| | 30 | 39.8 | 30.1 | 5.8 | 24.3 | | 30 | 48.4 | 37.7 | 0.4 | 13.5 |
| | 50 | 49.3 | 34.5 | 3.5 | 12.7 | | 50 | 55.6 | 38.4 | 0.3 | 5.7 |
| | inf. | 53.1 | 36.1 | 2.5 | 8.4 | | inf. | 58.2 | 38.2 | 0.4 | 3.2 |
| 4 | 5 | 9.9 | 13.2 | 12.2 | 64.7 | 84 | 5 | 21.6 | 24.8 | 5.7 | 48.0 |
| | 15 | 21.6 | 26.2 | 5.2 | 47.0 | | 15 | 40.4 | 35.1 | 0.8 | 23.7 |
| | 30 | 37.1 | 35.9 | 0.8 | 26.2 | | 30 | 50.3 | 36.6 | 0.6 | 12.5 |
| | 50 | 49.6 | 37.7 | 0.7 | 12.0 | | 50 | 56.5 | 37.5 | 0.4 | 5.6 |
| | inf. | 55.5 | 38.4 | 0.6 | 5.5 | | inf. | 59.2 | 37.6 | 0.4 | 2.8 |
| 8 | 5 | 10.5 | 14.4 | 11.5 | 63.6 | 92 | 5 | 23.2 | 25.4 | 5.5 | 45.9 |
| | 15 | 22.5 | 27.2 | 4.8 | 45.5 | | 15 | 42.6 | 35.8 | 0.6 | 21.0 |
| | 30 | 37.6 | 35.5 | 1.2 | 25.8 | | 30 | 51.4 | 36.6 | 0.6 | 11.4 |
| | 50 | 49.5 | 37.3 | 1.0 | 12.1 | | 50 | 57.6 | 37.7 | 0.3 | 4.4 |
| | inf. | 55.2 | 38.0 | 0.9 | 5.9 | | inf. | 60.0 | 37.8 | 0.3 | 1.9 |
| 16 | 5 | 10.3 | 17.4 | 9.1 | 63.2 | 100 | 5 | 22.9 | 25.2 | 5.4 | 46.5 |
| | 15 | 23.8 | 29.5 | 2.5 | 44.2 | | 15 | 42.8 | 35.6 | 0.6 | 21.0 |
| | 30 | 39.1 | 34.7 | 1.2 | 25.0 | | 30 | 50.9 | 36.5 | 0.5 | 12.1 |
| | 50 | 50.4 | 36.8 | 1.1 | 11.6 | | 50 | 56.9 | 37.4 | 0.4 | 5.4 |
| | inf. | 55.2 | 37.3 | 1.0 | 6.5 | | inf. | 59.5 | 37.8 | 0.3 | 2.5 |
| 28 | 5 | 12.5 | 18.0 | 8.7 | 60.7 | 108 | 5 | 24.2 | 25.2 | 5.5 | 45.1 |
| | 15 | 27.6 | 31.8 | 1.6 | 39.0 | | 15 | 45.3 | 35.7 | 0.8 | 18.2 |
| | 30 | 41.6 | 35.7 | 0.8 | 22.0 | | 30 | 51.7 | 36.2 | 0.7 | 11.3 |
| | 50 | 52.9 | 38.2 | 0.4 | 8.5 | | 50 | 56.6 | 36.8 | 0.7 | 5.9 |
| | inf. | 56.9 | 38.4 | 0.5 | 4.2 | | inf. | 58.8 | 37.0 | 0.6 | 3.5 |
| 36 | 5 | 14.2 | 18.8 | 8.6 | 58.3 | 116 | 5 | 27.8 | 25.5 | 5.2 | 41.5 |
| | 15 | 30.2 | 32.6 | 1.7 | 35.6 | | 15 | 49.0 | 35.4 | 0.6 | 14.9 |
| | 30 | 43.6 | 36.7 | 0.7 | 19.0 | | 30 | 54.5 | 36.2 | 0.5 | 8.9 |
| | 50 | 53.3 | 38.1 | 0.6 | 8.0 | | 50 | 58.2 | 37.0 | 0.4 | 4.4 |
| | inf. | 57.0 | 38.3 | 0.6 | 4.2 | | inf. | 59.8 | 37.6 | 0.3 | 2.3 |
| 44 | 5 | 14.2 | 18.8 | 8.6 | 58.4 | 124 | 5 | 26.1 | 25.6 | 5.9 | 42.3 |
| | 15 | 30.8 | 32.5 | 1.5 | 35.1 | | 15 | 49.1 | 36.0 | 0.9 | 14.0 |
| | 30 | 44.6 | 36.7 | 0.5 | 18.3 | | 30 | 53.8 | 37.3 | 0.6 | 8.3 |
| | 50 | 54.3 | 38.0 | 0.4 | 7.3 | | 50 | 57.1 | 37.8 | 0.5 | 4.6 |
| | inf. | 57.7 | 38.2 | 0.4 | 3.6 | | inf. | 58.7 | 37.8 | 0.5 | 3.0 |
| 56 | 5 | 14.6 | 18.5 | 8.9 | 57.9 | 132 | 5 | 32.0 | 28.0 | 4.2 | 35.7 |
| | 15 | 31.8 | 32.7 | 1.6 | 33.9 | | 15 | 51.6 | 36.4 | 0.8 | 11.2 |
| | 30 | 45.1 | 36.3 | 0.6 | 18.0 | | 30 | 54.5 | 36.8 | 0.8 | 7.8 |
| | 50 | 54.1 | 38.0 | 0.5 | 7.4 | | 50 | 57.2 | 37.5 | 0.6 | 4.7 |
| | inf. | 57.6 | 38.3 | 0.4 | 3.7 | | inf. | 58.2 | 37.1 | 0.9 | 3.8 |
| 64 | 5 | 14.0 | 19.0 | 8.6 | 58.4 | 140 | 5 | 37.5 | 28.6 | 4.6 | 29.4 |
| | 15 | 32.0 | 33.8 | 1.2 | 33.0 | | 15 | 46.8 | 31.2 | 3.8 | 18.1 |
| | 30 | 44.9 | 36.7 | 0.6 | 17.8 | | 30 | 46.1 | 30.2 | 4.5 | 19.3 |
| | 50 | 53.9 | 37.9 | 0.5 | 7.8 | | 50 | 49.0 | 31.8 | 3.8 | 15.4 |
| | inf. | 57.9 | 38.5 | 0.3 | 3.2 | | inf. | 48.6 | 31.1 | 4.2 | 16.1 |

**Appendix Table B1** Cont'd

| Day | Depth (cm) | Gas concentrations | | | | Day | Depth (cm) | Gas concentrations | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | $\%CH_4$ | $\%CO_2$ | $\%O_2$ | $\%N_2$ | | | $\%CH_4$ | $\%CO_2$ | $\%O_2$ | $\%N_2$ |
| 148 | 5 | 44.8 | 33.5 | 1.7 | 20.1 | 176 | 5 | 49.0 | 34.9 | 0.7 | 15.4 |
| | 15 | 54.5 | 36.5 | 1.0 | 8.0 | | 15 | 55.4 | 37.0 | 0.5 | 7.1 |
| | 30 | 55.1 | 36.1 | 1.2 | 7.5 | | 30 | 56.8 | 37.7 | 0.4 | 5.1 |
| | 50 | 56.6 | 36.7 | 1.0 | 5.7 | | 50 | 58.2 | 38.2 | 0.4 | 3.2 |
| | inf. | 57.7 | 36.8 | 1.0 | 4.5 | | inf. | 59.0 | 38.1 | 0.4 | 2.5 |
| 152 | 5 | 42.8 | 32.9 | 1.6 | 22.7 | 208 | 5 | 50.7 | 34.9 | 0.9 | 13.4 |
| | 15 | 44.3 | 30.1 | 4.0 | 21.5 | | 15 | 55.4 | 36.7 | 0.7 | 7.2 |
| | 30 | 54.1 | 35.9 | 1.3 | 8.7 | | 30 | 55.9 | 36.7 | 0.8 | 6.5 |
| | 50 | 57.0 | 37.1 | 0.9 | 5.0 | | 50 | 57.8 | 37.6 | 0.6 | 4.0 |
| | inf. | 58.0 | 37.2 | 0.8 | 4.0 | | inf. | 58.4 | 37.3 | 0.7 | 3.6 |
| 164 | 5 | 49.3 | 33.2 | 1.7 | 15.8 | 216 | 5 | 52.3 | 35.1 | 0.9 | 11.7 |
| | 15 | 56.5 | 36.6 | 0.8 | 6.1 | | 15 | 56.3 | 36.8 | 0.6 | 6.3 |
| | 30 | 57.5 | 37.2 | 0.6 | 4.8 | | 30 | 56.9 | 37.2 | 0.7 | 5.2 |
| | 50 | 58.0 | 37.2 | 0.7 | 4.1 | | 50 | 57.6 | 37.5 | 0.7 | 4.2 |
| | inf. | 58.9 | 37.5 | 0.7 | 2.9 | | inf. | 58.8 | 37.5 | 0.5 | 3.2 |
| 172 | 5 | 53.9 | 35.6 | 0.7 | 9.9 | 224 | 5 | 54.3 | 35.6 | 1.0 | 9.1 |
| | 15 | 57.3 | 37.1 | 0.6 | 4.9 | | 15 | 56.7 | 37.0 | 0.5 | 5.8 |
| | 30 | 57.9 | 37.4 | 0.6 | 4.2 | | 30 | 57.3 | 37.4 | 0.6 | 4.7 |
| | 50 | 57.6 | 36.9 | 0.9 | 4.6 | | 50 | 58.0 | 37.8 | 0.5 | 3.7 |
| | inf. | 58.5 | 37.3 | 0.8 | 3.5 | | inf. | 59.2 | 37.8 | 0.4 | 2.7 |

**Appendix Table B2** Gas concentrations in non-vegetated sandy loam/compost mixture column with rainwater irrigation

| Day | Depth (cm) | Gas concentrations | | | | Day | Depth (cm) | Gas concentrations | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | $\%CH_4$ | $\%CO_2$ | $\%O_2$ | $\%N_2$ | | | $\%CH_4$ | $\%CO_2$ | $\%O_2$ | $\%N_2$ |
| 0 | 5 | 9.5 | 10.3 | 14.0 | 66.2 | 28 | 5 | 9.8 | 21.6 | 5.7 | 62.9 |
| | 15 | 20.3 | 19.8 | 9.5 | 50.4 | | 15 | 35.5 | 33.8 | 1.0 | 29.8 |
| | 30 | 31.0 | 27.7 | 5.9 | 35.4 | | 30 | 46.0 | 36.4 | 0.7 | 16.9 |
| | 50 | 41.6 | 33.7 | 3.1 | 21.6 | | 50 | 53.1 | 37.0 | 0.7 | 9.2 |
| | inf. | 47.5 | 35.6 | 2.2 | 14.7 | | inf. | 56.9 | 37.2 | 0.6 | 5.2 |
| 4 | 5 | 0.6 | 1.0 | 18.3 | 80.1 | 36 | 5 | 20.7 | 22.3 | 7.0 | 50.1 |
| | 15 | 15.3 | 29.2 | 1.1 | 54.5 | | 15 | 62.0 | 36.5 | 0.2 | 1.3 |
| | 30 | 31.8 | 33.5 | 0.7 | 33.9 | | 30 | 61.2 | 36.4 | 0.4 | 2.0 |
| | 50 | 43.2 | 35.8 | 0.6 | 20.5 | | 50 | 61.4 | 37.1 | 0.3 | 1.2 |
| | inf. | 49.8 | 36.7 | 0.5 | 13.0 | | inf. | 60.6 | 37.2 | 0.4 | 1.8 |
| 12 | 5 | 4.3 | 18.3 | 6.5 | 70.9 | 44 | 5 | 44.6 | 35.3 | 1.8 | 18.2 |
| | 15 | 20.2 | 30.7 | 0.9 | 48.1 | | 15 | 59.5 | 37.7 | 0.6 | 2.2 |
| | 30 | 36.6 | 35.0 | 0.6 | 27.9 | | 30 | 59.9 | 38.1 | 0.4 | 1.6 |
| | 50 | 47.7 | 36.7 | 0.4 | 15.1 | | 50 | 59.4 | 37.8 | 0.5 | 2.3 |
| | inf. | 52.7 | 37.2 | 0.4 | 9.7 | | inf. | 59.4 | 37.6 | 0.6 | 2.3 |
| 20 | 5 | 16.5 | 19.7 | 5.9 | 57.9 | 48 | 5 | 51.0 | 32.1 | 2.3 | 14.6 |
| | 15 | 27.5 | 32.3 | 0.7 | 39.6 | | 15 | 60.6 | 38.1 | 0.3 | 1.0 |
| | 30 | 40.9 | 35.3 | 0.6 | 23.2 | | 30 | 60.2 | 38.0 | 0.4 | 1.5 |
| | 50 | 50.5 | 37.0 | 0.4 | 12.1 | | 50 | 59.9 | 38.0 | 0.4 | 1.6 |
| | inf. | 54.5 | 37.0 | 0.5 | 7.9 | | inf. | 60.5 | 38.4 | 0.2 | 0.9 |

**Appendix Table B2** Cont'd

| Day | Depth (cm) | Gas concentrations | | | | Day | Depth (cm) | Gas concentrations | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | %$CH_4$ | %$CO_2$ | %$O_2$ | %$N_2$ | | | %$CH_4$ | %$CO_2$ | %$O_2$ | %$N_2$ |
| 56 | 5 | 59.7 | 37.0 | 0.7 | 2.6 | 96 | 5 | 59.7 | 37.4 | 0.5 | 2.4 |
| | 15 | 59.9 | 37.2 | 0.7 | 2.2 | | 15 | 59.1 | 37.9 | 0.7 | 2.3 |
| | 30 | 58.6 | 36.7 | 0.9 | 3.8 | | 30 | 59.1 | 37.6 | 0.7 | 2.6 |
| | 50 | 59.0 | 37.2 | 0.8 | 3.0 | | 50 | 60.4 | 38.5 | 0.3 | 0.7 |
| | inf. | 59.3 | 37.3 | 0.8 | 2.5 | | inf. | 60.3 | 38.3 | 0.4 | 1.0 |
| 68 | 5 | 59.4 | 37.3 | 0.7 | 2.7 | 128 | 5 | 58.5 | 37.2 | 0.9 | 3.4 |
| | 15 | 58.9 | 37.0 | 0.9 | 3.3 | | 15 | 58.8 | 37.8 | 0.6 | 2.8 |
| | 30 | 58.2 | 36.7 | 1.1 | 4.0 | | 30 | 59.0 | 37.9 | 0.6 | 2.5 |
| | 50 | 59.0 | 37.3 | 0.7 | 3.0 | | 50 | 59.1 | 38.1 | 0.5 | 2.3 |
| | inf. | 59.2 | 37.3 | 0.7 | 2.8 | | inf. | 59.5 | 37.8 | 0.5 | 2.3 |
| 82 | 5 | 59.6 | 37.1 | 0.7 | 2.6 | 136 | 5 | 58.3 | 36.3 | 0.8 | 4.6 |
| | 15 | 59.6 | 37.2 | 0.7 | 2.5 | | 15 | 58.4 | 37.6 | 0.7 | 3.2 |
| | 30 | 59.8 | 37.5 | 0.6 | 2.0 | | 30 | 59.2 | 37.7 | 0.7 | 2.4 |
| | 50 | 59.6 | 37.4 | 0.7 | 2.3 | | 50 | 59.4 | 38.3 | 0.4 | 1.9 |
| | inf. | 59.7 | 37.5 | 0.6 | 2.2 | | inf. | 59.9 | 38.1 | 0.4 | 1.6 |
| 92 | 5 | 59.7 | 37.3 | 0.5 | 2.5 | 144 | 5 | 57.4 | 36.6 | 0.9 | 5.2 |
| | 15 | 60.5 | 38.1 | 0.4 | 1.1 | | 15 | 58.8 | 37.9 | 0.6 | 2.7 |
| | 30 | 59.8 | 37.8 | 0.5 | 1.9 | | 30 | 59.6 | 37.9 | 0.6 | 1.9 |
| | 50 | 59.8 | 37.9 | 0.5 | 1.8 | | 50 | 59.8 | 38.5 | 0.3 | 1.4 |
| | inf. | 60.0 | 37.9 | 0.4 | 1.6 | | inf. | 60.3 | 38.4 | 0.2 | 1.0 |

**Appendix Table B3** Gas concentrations in non-vegetated compost column with rainwater irrigation

| Day | Depth (cm) | Gas concentrations | | | | Day | Depth (cm) | Gas concentrations | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | %$CH_4$ | %$CO_2$ | %$O_2$ | %$N_2$ | | | %$CH_4$ | %$CO_2$ | %$O_2$ | %$N_2$ |
| 0 | 5 | 7.5 | 7.7 | 16.0 | 68.8 | 28 | 5 | 3.7 | 14.6 | 9.0 | 72.7 |
| | 15 | 17.1 | 16.3 | 12.1 | 54.5 | | 15 | 24.5 | 32.0 | 0.9 | 42.7 |
| | 30 | 27.5 | 24.3 | 8.4 | 39.8 | | 30 | 38.2 | 35.8 | 0.5 | 25.5 |
| | 50 | 38.7 | 31.5 | 5.0 | 24.7 | | 50 | 46.8 | 37.1 | 0.7 | 15.5 |
| | inf. | 45.2 | 34.3 | 3.8 | 16.7 | | inf. | 52.8 | 38.1 | 0.5 | 8.6 |
| 4 | 5 | 8.5 | 8.8 | 15.1 | 67.6 | 36 | 5 | 2.3 | 3.2 | 17.6 | 76.9 |
| | 15 | 19.2 | 18.4 | 10.8 | 51.5 | | 15 | 40.3 | 35.3 | 1.0 | 23.3 |
| | 30 | 29.9 | 26.4 | 7.2 | 36.6 | | 30 | 48.7 | 37.7 | 0.5 | 13.1 |
| | 50 | 40.2 | 32.7 | 4.2 | 23.0 | | 50 | 53.2 | 38.4 | 0.5 | 7.9 |
| | inf. | 46.3 | 35.2 | 3.0 | 15.5 | | inf. | 55.9 | 37.9 | 0.7 | 5.5 |
| 8 | 5 | 6.0 | 10.6 | 13.1 | 70.3 | 44 | 5 | 0.9 | 5.8 | 14.3 | 79.0 |
| | 15 | 16.7 | 21.7 | 7.9 | 53.7 | | 15 | 59.3 | 37.7 | 0.4 | 2.7 |
| | 30 | 29.1 | 29.8 | 4.4 | 36.7 | | 30 | 59.4 | 37.9 | 0.4 | 2.3 |
| | 50 | 39.4 | 34.1 | 2.7 | 23.8 | | 50 | 59.4 | 38.1 | 0.4 | 2.2 |
| | inf. | 45.9 | 36.1 | 2.0 | 16.0 | | inf. | 59.3 | 38.1 | 0.4 | 2.1 |
| 16 | 5 | 1.9 | 14.7 | 8.5 | 74.9 | 56 | 5 | 0.8 | 13.9 | 12.4 | 72.8 |
| | 15 | 13.1 | 27.5 | 1.8 | 57.7 | | 15 | 61.1 | 35.8 | 0.7 | 2.4 |
| | 30 | 28.4 | 32.2 | 1.6 | 37.8 | | 30 | 60.0 | 36.4 | 0.8 | 2.8 |
| | 50 | 39.4 | 35.1 | 1.2 | 24.3 | | 50 | 59.2 | 36.0 | 1.1 | 3.7 |
| | inf. | 46.0 | 36.2 | 1.2 | 16.6 | | inf. | 59.6 | 36.5 | 1.0 | 2.8 |

**<u>Appendix Table B3</u>** Cont'd

| Day | Depth (cm) | Gas concentrations | | | | Day | Depth (cm) | Gas concentrations | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | %$CH_4$ | %$CO_2$ | %$O_2$ | %$N_2$ | | | %$CH_4$ | %$CO_2$ | %$O_2$ | %$N_2$ |
| 28 | 5 | 3.7 | 14.6 | 9.0 | 72.7 | 108 | 5 | 49.6 | 27.3 | 4.1 | 19.0 |
| | 15 | 24.5 | 32.0 | 0.9 | 42.7 | | 15 | 43.1 | 26.2 | 5.8 | 24.8 |
| | 30 | 38.2 | 35.8 | 0.5 | 25.5 | | 30 | 59.2 | 36.4 | 0.9 | 3.5 |
| | 50 | 46.8 | 37.1 | 0.7 | 15.5 | | 50 | 60.3 | 37.4 | 0.5 | 1.8 |
| | inf. | 52.8 | 38.1 | 0.5 | 8.6 | | inf. | 60.9 | 37.6 | 0.3 | 1.1 |
| 36 | 5 | 2.3 | 3.2 | 17.6 | 76.9 | 116 | 5 | 4.9 | 3.0 | 17.0 | 75.2 |
| | 15 | 40.3 | 35.3 | 1.0 | 23.3 | | 15 | 62.4 | 36.2 | 0.3 | 1.1 |
| | 30 | 48.7 | 37.7 | 0.5 | 13.1 | | 30 | 62.4 | 36.6 | 0.2 | 0.8 |
| | 50 | 53.2 | 38.4 | 0.5 | 7.9 | | 50 | 61.7 | 37.0 | 0.3 | 1.0 |
| | inf. | 55.9 | 37.9 | 0.7 | 5.5 | | inf. | 61.1 | 37.7 | 0.3 | 0.9 |
| 44 | 5 | 0.9 | 5.8 | 14.3 | 79.0 | 124 | 5 | 58.5 | 36.6 | 1.0 | 3.9 |
| | 15 | 59.3 | 37.7 | 0.4 | 2.7 | | 15 | 59.9 | 37.3 | 0.6 | 2.1 |
| | 30 | 59.4 | 37.9 | 0.4 | 2.3 | | 30 | 60.0 | 37.6 | 0.6 | 1.8 |
| | 50 | 59.4 | 38.1 | 0.4 | 2.2 | | 50 | 59.8 | 37.7 | 0.5 | 1.9 |
| | inf. | 59.3 | 38.1 | 0.4 | 2.1 | | inf. | 59.7 | 37.7 | 0.6 | 2.0 |
| 56 | 5 | 0.8 | 13.9 | 12.4 | 72.8 | 132 | 5 | 4.2 | 2.8 | 17.3 | 75.8 |
| | 15 | 61.1 | 35.8 | 0.7 | 2.4 | | 15 | 60.1 | 37.6 | 0.6 | 1.7 |
| | 30 | 60.0 | 36.4 | 0.8 | 2.8 | | 30 | 59.8 | 37.5 | 0.7 | 2.1 |
| | 50 | 59.2 | 36.0 | 1.1 | 3.7 | | 50 | 59.6 | 37.7 | 0.7 | 2.1 |
| | inf. | 59.6 | 36.5 | 1.0 | 2.8 | | inf. | 59.8 | 37.7 | 0.6 | 1.9 |
| 64 | 5 | 49.6 | 42.8 | 0.3 | 7.4 | 140 | 5 | 54.5 | 30.9 | 2.3 | 12.3 |
| | 15 | 58.4 | 39.2 | 0.3 | 2.1 | | 15 | 58.9 | 36.4 | 1.0 | 3.7 |
| | 30 | 58.8 | 39.5 | 0.2 | 1.6 | | 30 | 59.5 | 37.0 | 0.8 | 2.8 |
| | 50 | 58.7 | 38.9 | 0.4 | 2.0 | | 50 | 58.9 | 37.0 | 0.8 | 3.2 |
| | inf. | 59.5 | 39.0 | 0.3 | 1.2 | | inf. | 59.0 | 37.1 | 0.9 | 3.1 |
| 76 | 5 | 12.6 | 27.2 | 1.4 | 58.9 | 148 | 5 | 58.8 | 36.6 | 0.9 | 3.7 |
| | 15 | 58.7 | 39.6 | 0.2 | 1.5 | | 15 | 59.8 | 37.1 | 0.7 | 2.5 |
| | 30 | 58.5 | 39.7 | 0.2 | 1.5 | | 30 | 59.3 | 37.1 | 0.8 | 2.8 |
| | 50 | 58.5 | 39.3 | 0.3 | 1.9 | | 50 | 57.9 | 36.6 | 1.1 | 4.3 |
| | inf. | 59.2 | 38.8 | 0.3 | 1.6 | | inf. | 58.9 | 37.1 | 0.9 | 3.1 |
| 84 | 5 | 12.6 | 28.2 | 1.7 | 57.6 | 176 | 5 | 53.4 | 37.5 | 0.3 | 8.7 |
| | 15 | 59.1 | 38.4 | 0.4 | 2.2 | | 15 | 59.7 | 37.1 | 0.8 | 2.5 |
| | 30 | 59.1 | 38.5 | 0.4 | 2.0 | | 30 | 59.6 | 37.3 | 0.7 | 2.4 |
| | 50 | 59.0 | 38.5 | 0.5 | 2.0 | | 50 | 59.8 | 37.4 | 0.7 | 2.1 |
| | inf. | 59.9 | 37.9 | 0.4 | 1.8 | | inf. | 57.6 | 34.9 | 1.6 | 5.9 |
| 92 | 5 | 13.0 | 25.5 | 3.7 | 57.8 | 208 | 5 | 57.8 | 37.5 | 0.8 | 3.8 |
| | 15 | 61.8 | 37.8 | 0.2 | 0.3 | | 15 | 59.6 | 37.9 | 0.5 | 1.9 |
| | 30 | 61.4 | 37.9 | 0.2 | 0.4 | | 30 | 59.3 | 37.9 | 0.6 | 2.3 |
| | 50 | 61.5 | 37.2 | 0.4 | 0.9 | | 50 | 59.2 | 38.0 | 0.5 | 2.2 |
| | inf. | 61.2 | 38.0 | 0.3 | 0.5 | | inf. | 59.0 | 37.6 | 0.7 | 2.8 |
| 100 | 5 | 33.4 | 21.5 | 8.4 | 36.7 | 224 | 5 | 58.5 | 38.0 | 0.6 | 2.9 |
| | 15 | 61.4 | 37.7 | 0.2 | 0.7 | | 15 | 60.1 | 38.0 | 0.3 | 1.5 |
| | 30 | 61.4 | 37.9 | 0.2 | 0.6 | | 30 | 60.5 | 38.3 | 0.2 | 0.9 |
| | 50 | 60.9 | 37.6 | 0.4 | 1.2 | | 50 | 60.2 | 38.4 | 0.3 | 1.2 |
| | inf. | 61.5 | 38.1 | 0.1 | 0.4 | | inf. | 59.9 | 38.3 | 0.3 | 1.5 |

**Appendix Table B4** Gas concentrations in non-vegetated sandy loam column with leachate irrigation

| Day | Depth (cm) | Gas concentrations | | | | Day | Depth (cm) | Gas concentrations | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | $\%CH_4$ | $\%CO_2$ | $\%O_2$ | $\%N_2$ | | | $\%CH_4$ | $\%CO_2$ | $\%O_2$ | $\%N_2$ |
| 0 | 5 | 25.4 | 21.3 | 11.3 | 42.1 | 76 | 5 | 14.3 | 16.2 | 11.3 | 58.2 |
| | 15 | 38.2 | 29.9 | 7.2 | 24.7 | | 15 | 41.7 | 34.7 | 2.3 | 21.4 |
| | 30 | 50.7 | 36.3 | 3.6 | 9.4 | | 30 | 52.5 | 37.4 | 1.4 | 8.7 |
| | 50 | 56.3 | 37.9 | 2.4 | 3.4 | | 50 | 56.3 | 37.5 | 1.4 | 4.8 |
| | inf. | 57.1 | 37.9 | 2.3 | 2.7 | | inf. | 57.9 | 37.9 | 1.1 | 3.2 |
| 4 | 5 | 22.0 | 22.8 | 9.2 | 46.0 | 84 | 5 | 12.4 | 14.5 | 12.2 | 60.9 |
| | 15 | 34.7 | 32.6 | 4.4 | 28.3 | | 15 | 43.7 | 36.1 | 1.8 | 18.4 |
| | 30 | 48.1 | 37.6 | 2.3 | 12.0 | | 30 | 54.6 | 38.4 | 1.0 | 6.0 |
| | 50 | 56.0 | 38.4 | 2.0 | 3.7 | | 50 | 55.4 | 36.7 | 2.0 | 5.9 |
| | inf. | 56.5 | 37.4 | 2.3 | 3.7 | | inf. | 59.1 | 38.5 | 1.1 | 1.3 |
| 8 | 5 | 20.9 | 23.4 | 8.0 | 47.8 | 92 | 5 | 11.7 | 13.8 | 12.1 | 62.4 |
| | 15 | 36.5 | 35.9 | 1.8 | 25.8 | | 15 | 44.4 | 36.2 | 1.3 | 18.1 |
| | 30 | 50.6 | 39.6 | 0.8 | 9.0 | | 30 | 53.2 | 37.8 | 0.9 | 8.1 |
| | 50 | 58.7 | 40.3 | 0.4 | 0.6 | | 50 | 57.7 | 38.4 | 0.7 | 3.2 |
| | inf. | 59.6 | 39.5 | 0.8 | 0.2 | | inf. | 58.7 | 38.3 | 0.7 | 2.3 |
| 16 | 5 | 20.0 | 22.0 | 7.6 | 50.4 | 100 | 5 | 12.0 | 13.2 | 12.5 | 62.3 |
| | 15 | 34.5 | 33.1 | 2.2 | 30.3 | | 15 | 48.9 | 36.3 | 1.2 | 13.6 |
| | 30 | 48.1 | 37.9 | 0.6 | 13.5 | | 30 | 55.0 | 37.2 | 1.0 | 6.8 |
| | 50 | 57.0 | 39.0 | 0.5 | 3.5 | | 50 | 58.6 | 38.2 | 0.7 | 2.5 |
| | inf. | 59.6 | 39.2 | 0.5 | 0.7 | | inf. | 58.8 | 37.8 | 0.9 | 2.5 |
| 28 | 5 | 20.8 | 22.3 | 8.3 | 48.6 | 104 | 5 | 13.8 | 14.6 | 12.0 | 59.6 |
| | 15 | 37.3 | 34.8 | 2.2 | 25.7 | | 15 | 55.5 | 38.1 | 0.4 | 6.1 |
| | 30 | 51.4 | 39.0 | 0.5 | 9.1 | | 30 | 56.9 | 37.4 | 0.9 | 4.8 |
| | 50 | 57.5 | 39.0 | 0.6 | 2.9 | | 50 | 59.2 | 37.2 | 0.8 | 2.8 |
| | inf. | 59.6 | 39.5 | 0.4 | 0.4 | | inf. | 58.0 | 36.9 | 1.2 | 3.9 |
| 36 | 5 | 26.0 | 26.2 | 6.6 | 41.2 | 112 | 5 | 12.9 | 13.2 | 12.6 | 61.4 |
| | 15 | 43.4 | 37.4 | 1.2 | 18.0 | | 15 | 53.1 | 37.8 | 0.5 | 8.6 |
| | 30 | 54.5 | 39.2 | 0.6 | 5.7 | | 30 | 56.5 | 37.8 | 0.7 | 5.0 |
| | 50 | 58.5 | 39.2 | 0.6 | 1.7 | | 50 | 59.1 | 38.4 | 0.5 | 2.0 |
| | inf. | 59.7 | 39.4 | 0.5 | 0.5 | | inf. | 59.4 | 38.5 | 0.5 | 1.6 |
| 44 | 5 | 21.7 | 23.5 | 7.6 | 47.1 | 120 | 5 | 14.8 | 14.6 | 12.0 | 58.6 |
| | 15 | 40.6 | 36.1 | 1.6 | 21.7 | | 15 | 53.9 | 38.1 | 0.6 | 7.5 |
| | 30 | 52.3 | 38.2 | 1.0 | 8.4 | | 30 | 57.2 | 38.5 | 0.6 | 3.7 |
| | 50 | 57.7 | 38.7 | 0.7 | 2.9 | | 50 | 57.2 | 37.6 | 0.9 | 4.3 |
| | inf. | 57.9 | 38.1 | 1.1 | 2.8 | | inf. | 58.9 | 38.2 | 0.6 | 2.3 |
| 56 | 5 | 20.8 | 22.9 | 7.7 | 48.6 | 132 | 5 | 0.1 | 0.3 | 17.9 | 81.7 |
| | 15 | 40.1 | 35.5 | 1.6 | 22.7 | | 15 | 55.2 | 37.8 | 0.5 | 6.4 |
| | 30 | 50.8 | 37.4 | 1.2 | 10.6 | | 30 | 57.7 | 38.0 | 0.6 | 3.7 |
| | 50 | 55.4 | 37.6 | 1.3 | 5.7 | | 50 | 59.3 | 38.6 | 0.4 | 1.7 |
| | inf. | 58.1 | 38.6 | 0.8 | 2.5 | | inf. | 59.6 | 38.4 | 0.4 | 1.5 |
| 64 | 5 | 18.2 | 20.2 | 9.1 | 52.6 | 140 | 5 | 31.8 | 26.6 | 5.9 | 35.6 |
| | 15 | 39.6 | 34.5 | 2.2 | 23.8 | | 15 | 54.2 | 36.7 | 0.6 | 8.5 |
| | 30 | 52.4 | 38.1 | 0.9 | 8.5 | | 30 | 56.9 | 36.8 | 0.8 | 5.5 |
| | 50 | 57.3 | 38.7 | 0.7 | 3.3 | | 50 | 58.5 | 37.1 | 0.9 | 3.5 |
| | inf. | 58.0 | 38.4 | 0.9 | 2.7 | | inf. | 59.6 | 38.3 | 0.3 | 1.8 |

**Appendix Table B4** Cont'd

| Day | Depth (cm) | Gas concentrations | | | | Day | Depth (cm) | Gas concentrations | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | $\%CH_4$ | $\%CO_2$ | $\%O_2$ | $\%N_2$ | | | $\%CH_4$ | $\%CO_2$ | $\%O_2$ | $\%N_2$ |
| 148 | 5 | 27.4 | 25.2 | 6.9 | 40.5 | 224 | 5 | 33.0 | 27.8 | 5.6 | 33.6 |
| | 15 | 56.0 | 38.4 | 0.3 | 5.3 | | 15 | 57.8 | 36.6 | 1.0 | 4.6 |
| | 30 | 59.2 | 38.8 | 0.2 | 1.8 | | 30 | 58.4 | 37.1 | 0.8 | 3.6 |
| | 50 | 59.6 | 38.8 | 0.3 | 1.3 | | 50 | 58.6 | 37.1 | 0.9 | 3.4 |
| | inf. | 59.9 | 38.6 | 0.4 | 1.1 | | inf. | 59.0 | 37.4 | 0.8 | 2.9 |
| 152 | 5 | 33.3 | 28.7 | 5.3 | 32.7 | 232 | 5 | 30.4 | 26.4 | 6.7 | 36.5 |
| | 15 | 55.5 | 38.0 | 0.7 | 5.7 | | 15 | 58.3 | 37.3 | 0.7 | 3.7 |
| | 30 | 58.3 | 38.5 | 0.4 | 2.8 | | 30 | 58.5 | 37.3 | 0.8 | 3.3 |
| | 50 | 59.1 | 38.4 | 0.5 | 2.1 | | 50 | 51.6 | 32.7 | 3.0 | 12.7 |
| | inf. | 59.2 | 38.2 | 0.6 | 2.0 | | inf. | 58.2 | 36.7 | 1.1 | 4.1 |
| 164 | 5 | 32.0 | 28.7 | 4.9 | 34.4 | 236 | 5 | 36.0 | 29.8 | 4.7 | 29.6 |
| | 15 | 56.4 | 38.3 | 0.4 | 4.9 | | 15 | 59.7 | 38.1 | 0.4 | 1.9 |
| | 30 | 58.3 | 38.2 | 0.5 | 3.0 | | 30 | 59.7 | 37.9 | 0.5 | 1.9 |
| | 50 | 58.9 | 38.2 | 0.5 | 2.4 | | 50 | 59.6 | 37.9 | 0.4 | 2.1 |
| | inf. | 59.6 | 38.4 | 0.4 | 1.6 | | inf. | 60.0 | 37.9 | 0.4 | 1.7 |
| 176 | 5 | 32.7 | 26.7 | 5.9 | 34.7 | 248 | 5 | 58.3 | 38.3 | 0.4 | 3.0 |
| | 15 | 59.4 | 37.3 | 0.3 | 3.0 | | 15 | 58.9 | 37.1 | 0.8 | 3.2 |
| | 30 | 60.9 | 37.6 | 0.3 | 1.2 | | 30 | 59.2 | 37.4 | 0.8 | 2.7 |
| | 50 | 61.1 | 37.7 | 0.3 | 0.9 | | 50 | 59.2 | 37.3 | 0.8 | 2.7 |
| | inf. | 61.6 | 37.8 | 0.2 | 0.3 | | inf. | 58.8 | 37.1 | 0.9 | 3.3 |
| 184 | 5 | 37.8 | 30.9 | 3.9 | 27.4 | 252 | 5 | 59.5 | 38.3 | 0.4 | 1.8 |
| | 15 | 59.3 | 37.4 | 0.3 | 2.9 | | 15 | 57.6 | 36.2 | 1.2 | 5.0 |
| | 30 | 60.6 | 37.7 | 0.2 | 1.4 | | 30 | 60.5 | 38.0 | 0.4 | 1.2 |
| | 50 | 60.0 | 37.2 | 0.5 | 2.3 | | 50 | 60.2 | 37.9 | 0.4 | 1.5 |
| | inf. | 60.9 | 37.6 | 0.3 | 1.1 | | inf. | 60.4 | 38.1 | 0.3 | 1.2 |
| 192 | 5 | 37.5 | 30.9 | 4.0 | 27.6 | 272 | 5 | 58.1 | 37.3 | 1.0 | 3.6 |
| | 15 | 59.1 | 37.2 | 0.5 | 3.2 | | 15 | 56.3 | 35.3 | 1.8 | 6.6 |
| | 30 | 59.7 | 37.2 | 0.6 | 2.6 | | 30 | 59.0 | 37.0 | 1.0 | 2.9 |
| | 50 | 60.0 | 37.4 | 0.5 | 2.1 | | 50 | 58.7 | 37.0 | 1.0 | 3.2 |
| | inf. | 60.3 | 37.4 | 0.5 | 1.8 | | inf. | 58.9 | 37.2 | 0.9 | 2.9 |
| 200 | 5 | 34.5 | 27.5 | 5.1 | 32.8 | 280 | 5 | 57.2 | 38.3 | 0.7 | 3.8 |
| | 15 | 60.6 | 36.8 | 0.3 | 2.3 | | 15 | 57.8 | 37.0 | 1.2 | 4.0 |
| | 30 | 60.9 | 36.8 | 0.4 | 1.9 | | 30 | 58.1 | 36.9 | 1.1 | 3.9 |
| | 50 | 59.7 | 36.7 | 0.6 | 2.9 | | 50 | 58.6 | 36.9 | 1.1 | 3.4 |
| | inf. | 60.7 | 37.6 | 0.3 | 1.4 | | inf. | 58.6 | 37.0 | 1.1 | 3.3 |
| 208 | 5 | 29.2 | 26.5 | 6.1 | 38.3 | 288 | 5 | 57.9 | 36.6 | 1.9 | 3.6 |
| | 15 | 58.2 | 37.5 | 0.6 | 3.7 | | 15 | 58.5 | 37.1 | 1.3 | 3.2 |
| | 30 | 59.0 | 37.5 | 0.6 | 2.8 | | 30 | 58.7 | 37.3 | 1.0 | 3.0 |
| | 50 | 59.5 | 38.0 | 0.4 | 2.1 | | 50 | 58.6 | 37.2 | 1.0 | 3.2 |
| | inf. | 59.8 | 37.8 | 0.5 | 1.9 | | inf. | 58.7 | 37.5 | 0.9 | 2.9 |
| 216 | 5 | 28.7 | 25.6 | 6.6 | 39.0 | 308 | 5 | 58.7 | 37.0 | 1.6 | 2.7 |
| | 15 | 57.8 | 37.2 | 0.8 | 4.1 | | 15 | 58.7 | 36.4 | 0.9 | 4.1 |
| | 30 | 59.0 | 37.5 | 0.7 | 2.8 | | 30 | 59.7 | 38.3 | 0.3 | 1.6 |
| | 50 | 59.3 | 37.6 | 0.7 | 2.4 | | 50 | 59.3 | 38.0 | 0.4 | 2.2 |
| | inf. | 59.8 | 37.8 | 0.6 | 1.8 | | inf. | 59.8 | 38.1 | 0.4 | 1.7 |

**Appendix Table B5** Gas concentrations in non-vegetated sandy loam/compost mixture column with leachate irrigation

| Day | Depth (cm) | Gas concentrations | | | | Day | Depth (cm) | Gas concentrations | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | $\%CH_4$ | $\%CO_2$ | $\%O_2$ | $\%N_2$ | | | $\%CH_4$ | $\%CO_2$ | $\%O_2$ | $\%N_2$ |
| 0 | 5 | 10.0 | 9.4 | 16.2 | 64.4 | 76 | 5 | 9.1 | 15.3 | 10.9 | 64.8 |
| | 15 | 20.9 | 18.5 | 12.2 | 48.5 | | 15 | 54.8 | 37.4 | 1.2 | 6.6 |
| | 30 | 32.5 | 26.8 | 8.4 | 32.3 | | 30 | 54.2 | 36.6 | 1.8 | 7.4 |
| | 50 | 42.5 | 32.5 | 5.4 | 19.5 | | 50 | 56.3 | 38.0 | 1.3 | 4.4 |
| | inf. | 48.3 | 35.0 | 4.1 | 12.6 | | inf. | 57.3 | 37.4 | 1.4 | 3.9 |
| 4 | 5 | 20.9 | 20.9 | 10.4 | 47.8 | 84 | 5 | 2.2 | 7.3 | 14.9 | 75.7 |
| | 15 | 30.8 | 27.1 | 7.8 | 34.3 | | 15 | 58.4 | 38.0 | 1.2 | 2.5 |
| | 30 | 41.8 | 33.6 | 5.0 | 19.6 | | 30 | 56.0 | 36.5 | 2.0 | 5.5 |
| | 50 | 48.9 | 36.5 | 3.5 | 11.1 | | 50 | 56.2 | 36.8 | 2.0 | 5.0 |
| | inf. | 53.0 | 37.4 | 2.8 | 6.9 | | inf. | 57.8 | 37.5 | 1.5 | 3.1 |
| 8 | 5 | 4.7 | 25.1 | 2.2 | 68.0 | 92 | 5 | 7.8 | 15.9 | 9.5 | 66.8 |
| | 15 | 22.5 | 32.7 | 0.9 | 43.9 | | 15 | 57.1 | 37.4 | 1.0 | 4.5 |
| | 30 | 36.5 | 36.4 | 0.9 | 26.1 | | 30 | 57.3 | 37.7 | 1.0 | 4.0 |
| | 50 | 46.1 | 38.0 | 0.9 | 15.0 | | 50 | 58.4 | 38.6 | 0.7 | 2.3 |
| | inf. | 52.5 | 39.3 | 0.7 | 7.4 | | inf. | 58.8 | 38.3 | 0.7 | 2.2 |
| 16 | 5 | 5.5 | 19.5 | 6.0 | 69.0 | 100 | 5 | 21.6 | 26.7 | 4.2 | 47.6 |
| | 15 | 21.5 | 31.1 | 1.2 | 46.2 | | 15 | 59.5 | 38.2 | 0.5 | 1.7 |
| | 30 | 38.5 | 36.1 | 0.7 | 24.7 | | 30 | 59.5 | 38.4 | 0.6 | 1.5 |
| | 50 | 48.5 | 38.1 | 0.6 | 12.7 | | 50 | 59.1 | 38.2 | 0.6 | 2.0 |
| | inf. | 54.3 | 38.9 | 0.4 | 6.3 | | inf. | 59.2 | 38.4 | 0.6 | 1.8 |
| 28 | 5 | 9.6 | 20.9 | 6.3 | 63.1 | 104 | 5 | 12.5 | 24.9 | 3.6 | 59.0 |
| | 15 | 26.3 | 33.8 | 0.9 | 39.0 | | 15 | 58.8 | 37.9 | 0.7 | 2.6 |
| | 30 | 42.3 | 37.6 | 0.7 | 19.4 | | 30 | 59.6 | 38.2 | 0.5 | 1.7 |
| | 50 | 52.4 | 39.3 | 0.4 | 7.9 | | 50 | 60.3 | 37.6 | 0.5 | 1.6 |
| | inf. | 57.2 | 39.0 | 0.7 | 3.1 | | inf. | 60.6 | 37.5 | 0.4 | 1.4 |
| 36 | 5 | 15.7 | 25.9 | 4.1 | 54.3 | 112 | 5 | 35.1 | 31.5 | 3.3 | 30.0 |
| | 15 | 31.8 | 35.0 | 0.8 | 32.4 | | 15 | 61.1 | 37.6 | 0.3 | 1.0 |
| | 30 | 45.4 | 38.2 | 0.6 | 15.9 | | 30 | 60.8 | 38.7 | 0.2 | 0.3 |
| | 50 | 53.4 | 39.3 | 0.4 | 6.9 | | 50 | 60.3 | 38.6 | 0.3 | 0.8 |
| | inf. | 56.7 | 38.2 | 1.0 | 4.2 | | inf. | 60.2 | 39.2 | 0.2 | 0.3 |
| 44 | 5 | 12.2 | 22.2 | 6.0 | 59.5 | 120 | 5 | 39.9 | 33.4 | 1.7 | 25.0 |
| | 15 | 30.1 | 34.1 | 1.2 | 34.6 | | 15 | 59.5 | 38.1 | 0.4 | 1.9 |
| | 30 | 43.8 | 37.2 | 1.0 | 17.9 | | 30 | 59.6 | 38.2 | 0.4 | 1.8 |
| | 50 | 52.4 | 38.7 | 0.8 | 8.2 | | 50 | 59.0 | 38.2 | 0.6 | 2.2 |
| | inf. | 57.7 | 38.7 | 0.8 | 2.8 | | inf. | 59.2 | 38.6 | 0.4 | 1.8 |
| 56 | 5 | 9.0 | 17.8 | 8.4 | 64.8 | 128 | 5 | 42.3 | 34.7 | 1.6 | 21.4 |
| | 15 | 31.5 | 33.6 | 1.4 | 33.5 | | 15 | 60.2 | 37.9 | 0.3 | 1.6 |
| | 30 | 42.7 | 36.6 | 1.1 | 19.7 | | 30 | 60.2 | 38.0 | 0.3 | 1.5 |
| | 50 | 50.5 | 37.7 | 1.0 | 10.7 | | 50 | 59.8 | 38.0 | 0.4 | 1.7 |
| | inf. | 57.2 | 38.5 | 0.8 | 3.5 | | inf. | 59.7 | 38.3 | 0.4 | 1.5 |
| 64 | 5 | 10.8 | 17.7 | 9.0 | 62.5 | 132 | 5 | 52.8 | 37.1 | 0.9 | 9.2 |
| | 15 | 44.1 | 36.7 | 1.0 | 18.2 | | 15 | 60.1 | 38.2 | 0.3 | 1.4 |
| | 30 | 51.0 | 38.2 | 0.8 | 10.0 | | 30 | 60.0 | 38.2 | 0.4 | 1.4 |
| | 50 | 55.3 | 38.8 | 0.7 | 5.3 | | 50 | 59.8 | 38.4 | 0.4 | 1.4 |
| | inf. | 57.6 | 38.2 | 1.0 | 3.2 | | inf. | 58.9 | 38.0 | 0.6 | 2.4 |

**Appendix Table B5** Cont'd

| Day | Depth (cm) | Gas concentrations | | | | Day | Depth (cm) | Gas concentrations | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | $\%CH_4$ | $\%CO_2$ | $\%O_2$ | $\%N_2$ | | | $\%CH_4$ | $\%CO_2$ | $\%O_2$ | $\%N_2$ |
| 144 | 5 | 50.6 | 36.7 | 1.0 | 11.8 | 220 | 5 | 57.7 | 36.5 | 0.8 | 4.9 |
| | 15 | 60.4 | 38.2 | 0.3 | 1.0 | | 15 | 59.7 | 37.2 | 0.7 | 2.4 |
| | 30 | 60.5 | 38.5 | 0.3 | 0.8 | | 30 | 59.4 | 37.4 | 0.6 | 2.5 |
| | 50 | 60.4 | 38.8 | 0.3 | 0.6 | | 50 | 58.8 | 37.2 | 0.8 | 3.2 |
| | inf. | 60.4 | 39.0 | 0.2 | 0.3 | | inf. | 59.5 | 37.6 | 0.7 | 2.3 |
| 148 | 5 | 42.3 | 33.6 | 2.4 | 21.8 | 228 | 5 | 60.1 | 36.8 | 0.6 | 2.5 |
| | 15 | 60.2 | 38.2 | 0.3 | 1.2 | | 15 | 58.7 | 36.2 | 1.0 | 4.2 |
| | 30 | 60.5 | 38.6 | 0.2 | 0.8 | | 30 | 60.3 | 37.2 | 0.5 | 2.0 |
| | 50 | 60.1 | 38.6 | 0.3 | 1.0 | | 50 | 59.9 | 36.8 | 0.6 | 2.6 |
| | inf. | 60.3 | 38.9 | 0.2 | 0.5 | | inf. | 60.3 | 37.0 | 0.6 | 2.1 |
| 164 | 5 | 51.2 | 35.4 | 1.6 | 11.8 | 246 | 5 | 60.1 | 37.1 | 0.6 | 2.2 |
| | 15 | 59.3 | 38.0 | 0.5 | 2.1 | | 15 | 59.3 | 36.9 | 0.9 | 2.9 |
| | 30 | 59.2 | 38.0 | 0.5 | 2.2 | | 30 | 59.2 | 37.2 | 0.8 | 2.8 |
| | 50 | 59.1 | 38.0 | 0.5 | 2.3 | | 50 | 59.5 | 37.6 | 0.7 | 2.2 |
| | inf. | 59.3 | 38.1 | 0.5 | 2.1 | | inf. | 59.6 | 37.8 | 0.6 | 2.1 |
| 176 | 5 | 42.2 | 33.6 | 2.1 | 22.2 | 256 | 5 | 51.8 | 36.0 | 1.0 | 11.2 |
| | 15 | 61.3 | 37.6 | 0.2 | 0.9 | | 15 | 57.5 | 37.5 | 0.6 | 4.4 |
| | 30 | 61.8 | 37.7 | 0.2 | 0.4 | | 30 | 54.6 | 35.8 | 1.7 | 7.9 |
| | 50 | 61.4 | 37.7 | 0.2 | 0.7 | | 50 | 59.5 | 37.9 | 0.5 | 2.0 |
| | inf. | 61.7 | 37.9 | 0.2 | 0.2 | | inf. | 59.6 | 37.7 | 0.6 | 2.1 |
| 184 | 5 | 49.3 | 36.0 | 1.0 | 13.7 | 264 | 5 | 52.8 | 33.9 | 1.4 | 12.0 |
| | 15 | 60.9 | 37.7 | 0.2 | 1.2 | | 15 | 56.5 | 36.2 | 1.4 | 5.9 |
| | 30 | 61.0 | 37.6 | 0.3 | 1.2 | | 30 | 57.2 | 36.3 | 1.4 | 5.2 |
| | 50 | 60.6 | 37.4 | 0.4 | 1.6 | | 50 | 58.8 | 37.1 | 1.0 | 3.2 |
| | inf. | 69.2 | 6.8 | 23.4 | 0.6 | | inf. | 59.0 | 37.2 | 1.0 | 2.8 |
| 188 | 5 | 57.0 | 36.3 | 0.5 | 6.2 | 272 | 5 | 57.3 | 37.3 | 1.0 | 4.4 |
| | 15 | 60.9 | 36.8 | 0.4 | 1.9 | | 15 | 58.6 | 36.5 | 1.2 | 3.6 |
| | 30 | 58.4 | 35.4 | 1.2 | 5.0 | | 30 | 58.5 | 36.8 | 1.1 | 3.5 |
| | 50 | 60.7 | 37.2 | 0.4 | 1.8 | | 50 | 58.9 | 37.2 | 1.0 | 2.9 |
| | inf. | 60.5 | 37.3 | 0.4 | 1.8 | | inf. | 59.0 | 37.4 | 0.9 | 2.8 |
| 196 | 5 | 60.3 | 38.1 | 0.4 | 1.2 | 288 | 5 | 50.8 | 35.3 | 1.5 | 12.4 |
| | 15 | 60.7 | 38.4 | 0.2 | 0.7 | | 15 | 56.4 | 36.8 | 1.1 | 5.7 |
| | 30 | 60.8 | 38.4 | 0.2 | 0.7 | | 30 | 53.5 | 35.1 | 2.2 | 9.1 |
| | 50 | 60.8 | 38.4 | 0.2 | 0.6 | | 50 | 58.4 | 37.2 | 1.1 | 3.4 |
| | inf. | 61.0 | 37.9 | 0.3 | 0.8 | | inf. | 58.5 | 37.0 | 1.1 | 3.4 |
| 204 | 5 | 60.9 | 37.5 | 0.3 | 1.3 | 292 | 5 | 51.9 | 34.5 | 1.5 | 12.2 |
| | 15 | 61.0 | 37.6 | 0.2 | 1.2 | | 15 | 58.7 | 37.6 | 0.6 | 3.1 |
| | 30 | 60.9 | 37.7 | 0.2 | 1.1 | | 30 | 58.6 | 37.7 | 0.7 | 3.0 |
| | 50 | 60.7 | 37.7 | 0.3 | 1.4 | | 50 | 58.9 | 38.0 | 0.4 | 2.7 |
| | inf. | 60.6 | 37.7 | 0.3 | 1.3 | | inf. | 59.9 | 38.1 | 0.4 | 1.7 |
| 212 | 5 | 60.5 | 37.7 | 0.4 | 1.4 | 308 | 5 | 52.7 | 36.4 | 0.8 | 10.1 |
| | 15 | 60.6 | 37.9 | 0.3 | 1.2 | | 15 | 59.2 | 37.8 | 0.4 | 2.5 |
| | 30 | 60.5 | 38.0 | 0.3 | 1.2 | | 30 | 59.6 | 38.0 | 0.4 | 2.0 |
| | 50 | 60.5 | 38.3 | 0.3 | 0.9 | | 50 | 59.8 | 38.3 | 0.3 | 1.6 |
| | inf. | 60.4 | 38.2 | 0.3 | 1.1 | | inf. | 59.9 | 38.3 | 0.3 | 1.4 |

**Appendix Table B6** Gas concentrations in non-vegetated compost column with leachate irrigation

| Day | Depth (cm) | Gas concentrations | | | | Day | Depth (cm) | Gas concentrations | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | $\%CH_4$ | $\%CO_2$ | $\%O_2$ | $\%N_2$ | | | $\%CH_4$ | $\%CO_2$ | $\%O_2$ | $\%N_2$ |
| 0 | 5 | 4.5 | 4.9 | 17.7 | 72.9 | 72 | 5 | 6.3 | 19.2 | 6.3 | 68.3 |
| | 15 | 9.2 | 9.1 | 15.7 | 66.0 | | 15 | 30.6 | 33.1 | 1.2 | 35.1 |
| | 30 | 16.7 | 15.3 | 12.9 | 55.2 | | 30 | 39.5 | 34.5 | 1.8 | 24.3 |
| | 50 | 24.5 | 20.6 | 10.4 | 44.4 | | 50 | 48.7 | 37.4 | 0.9 | 12.9 |
| | inf. | 32.9 | 26.2 | 8.2 | 32.8 | | inf. | 55.5 | 38.6 | 0.6 | 5.4 |
| 4 | 5 | 9.2 | 9.4 | 15.9 | 65.6 | 84 | 5 | 2.1 | 7.2 | 14.6 | 76.1 |
| | 15 | 15.0 | 14.2 | 13.4 | 57.4 | | 15 | 40.2 | 34.9 | 2.5 | 22.4 |
| | 30 | 22.9 | 20.3 | 10.9 | 46.0 | | 30 | 40.6 | 32.8 | 3.9 | 22.6 |
| | 50 | 30.1 | 25.0 | 8.7 | 36.2 | | 50 | 51.9 | 37.9 | 1.2 | 9.1 |
| | inf. | 36.9 | 28.9 | 7.0 | 27.2 | | inf. | 56.0 | 37.8 | 1.3 | 4.8 |
| 8 | 5 | 1.3 | 18.7 | 5.9 | 74.1 | 92 | 5 | 2.0 | 5.7 | 14.5 | 77.9 |
| | 15 | 9.4 | 27.7 | 1.5 | 61.4 | | 15 | 42.6 | 35.3 | 1.0 | 21.1 |
| | 30 | 21.2 | 31.9 | 1.1 | 45.9 | | 30 | 47.2 | 36.4 | 1.0 | 15.4 |
| | 50 | 32.2 | 34.6 | 1.1 | 32.0 | | 50 | 51.6 | 37.4 | 0.9 | 10.2 |
| | inf. | 40.9 | 36.8 | 0.9 | 21.4 | | inf. | 56.9 | 38.3 | 0.7 | 4.1 |
| 20 | 5 | 1.8 | 20.6 | 4.5 | 73.2 | 100 | 5 | 1.6 | 5.2 | 14.4 | 78.8 |
| | 15 | 12.9 | 27.2 | 2.9 | 57.0 | | 15 | 44.9 | 35.8 | 0.9 | 18.4 |
| | 30 | 26.1 | 31.7 | 1.9 | 40.3 | | 30 | 48.6 | 36.9 | 0.7 | 13.7 |
| | 50 | 35.5 | 33.1 | 2.3 | 29.1 | | 50 | 51.7 | 37.1 | 1.0 | 10.3 |
| | inf. | 42.5 | 34.9 | 2.1 | 20.5 | | inf. | 56.5 | 38.0 | 0.8 | 4.8 |
| 28 | 5 | 1.1 | 18.3 | 5.8 | 74.8 | 104 | 5 | 4.3 | 15.9 | 6.8 | 73.0 |
| | 15 | 10.8 | 27.8 | 1.2 | 60.2 | | 15 | 54.6 | 36.3 | 1.3 | 7.9 |
| | 30 | 25.1 | 32.4 | 1.0 | 41.5 | | 30 | 56.0 | 36.4 | 1.2 | 6.4 |
| | 50 | 36.2 | 34.4 | 1.6 | 27.8 | | 50 | 56.9 | 37.1 | 1.1 | 4.9 |
| | inf. | 46.3 | 37.7 | 0.6 | 15.4 | | inf. | 58.3 | 37.3 | 1.0 | 3.4 |
| 36 | 5 | 3.2 | 16.5 | 7.7 | 72.6 | 112 | 5 | 16.6 | 19.1 | 5.7 | 58.6 |
| | 15 | 14.3 | 29.3 | 1.0 | 55.4 | | 15 | 60.7 | 37.8 | 0.3 | 1.2 |
| | 30 | 29.6 | 34.3 | 0.8 | 35.4 | | 30 | 60.9 | 38.0 | 0.2 | 0.9 |
| | 50 | 42.1 | 37.0 | 0.8 | 20.2 | | 50 | 59.9 | 37.9 | 0.4 | 1.8 |
| | inf. | 51.9 | 38.9 | 0.5 | 8.8 | | inf. | 59.8 | 38.5 | 0.4 | 1.3 |
| 44 | 5 | 1.8 | 13.4 | 9.6 | 75.3 | 120 | 5 | 9.0 | 18.6 | 6.3 | 66.1 |
| | 15 | 10.7 | 26.8 | 1.9 | 60.6 | | 15 | 57.8 | 36.6 | 1.1 | 4.6 |
| | 30 | 25.9 | 32.4 | 1.3 | 40.4 | | 30 | 59.8 | 38.2 | 0.4 | 1.5 |
| | 50 | 38.7 | 35.5 | 1.2 | 24.6 | | 50 | 59.1 | 38.1 | 0.5 | 2.2 |
| | inf. | 48.9 | 37.3 | 1.1 | 12.7 | | inf. | 59.3 | 38.4 | 0.5 | 1.8 |
| 56 | 5 | 4.5 | 19.1 | 5.8 | 70.6 | 132 | 5 | 6.4 | 20.3 | 5.0 | 68.3 |
| | 15 | 16.1 | 28.2 | 1.8 | 54.0 | | 15 | 59.6 | 37.4 | 0.5 | 2.6 |
| | 30 | 27.0 | 31.3 | 1.8 | 39.9 | | 30 | 58.9 | 37.0 | 0.7 | 3.4 |
| | 50 | 39.1 | 35.3 | 1.2 | 24.4 | | 50 | 58.6 | 37.4 | 0.7 | 3.4 |
| | inf. | 47.8 | 36.6 | 1.4 | 14.3 | | inf. | 58.6 | 37.8 | 0.7 | 3.0 |
| 64 | 5 | 4.7 | 19.5 | 5.5 | 70.2 | 144 | 5 | 5.5 | 21.3 | 4.4 | 68.8 |
| | 15 | 21.3 | 28.7 | 2.6 | 47.3 | | 15 | 60.3 | 38.0 | 0.2 | 1.4 |
| | 30 | 34.0 | 34.0 | 1.4 | 30.6 | | 30 | 60.4 | 38.1 | 0.3 | 1.2 |
| | 50 | 43.5 | 36.5 | 1.2 | 18.8 | | 50 | 59.2 | 37.7 | 0.5 | 2.5 |
| | inf. | 49.9 | 36.6 | 1.5 | 12.0 | | inf. | 59.9 | 38.8 | 0.2 | 1.1 |

**Appendix Table B6** Cont'd

| Day | Depth (cm) | Gas concentrations | | | | Day | Depth (cm) | Gas concentrations | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | %$CH_4$ | %$CO_2$ | %$O_2$ | %$N_2$ | | | %$CH_4$ | %$CO_2$ | %$O_2$ | %$N_2$ |
| 148 | 5 | 0.3 | 2.1 | 17.3 | 80.3 | 236 | 5 | 4.3 | 22.6 | 3.1 | 70.0 |
| | 15 | 60.1 | 37.9 | 0.3 | 1.7 | | 15 | 55.6 | 36.4 | 0.5 | 7.5 |
| | 30 | 60.4 | 38.3 | 0.2 | 1.1 | | 30 | 57.5 | 37.5 | 0.3 | 4.7 |
| | 50 | 59.4 | 37.9 | 0.5 | 2.2 | | 50 | 58.5 | 37.6 | 0.5 | 3.3 |
| | inf. | 59.9 | 38.6 | 0.3 | 1.2 | | inf. | 60.0 | 38.0 | 0.4 | 1.6 |
| 160 | 5 | 7.2 | 24.3 | 7.3 | 61.2 | 252 | 5 | 3.7 | 20.6 | 4.4 | 71.3 |
| | 15 | 59.9 | 38.0 | 0.3 | 1.9 | | 15 | 57.3 | 37.0 | 0.3 | 5.4 |
| | 30 | 60.1 | 38.4 | 0.2 | 1.3 | | 30 | 58.6 | 37.4 | 0.3 | 3.7 |
| | 50 | 59.4 | 38.2 | 0.4 | 2.0 | | 50 | 59.2 | 37.8 | 0.4 | 2.7 |
| | inf. | 59.7 | 38.4 | 0.3 | 1.5 | | inf. | 59.5 | 37.5 | 0.7 | 2.3 |
| 164 | 5 | 7.2 | 24.1 | 7.5 | 61.2 | 260 | 5 | 7.2 | 30.9 | 3.7 | 58.2 |
| | 15 | 59.9 | 37.7 | 0.4 | 2.0 | | 15 | 57.1 | 36.7 | 0.7 | 5.6 |
| | 30 | 59.7 | 37.8 | 0.4 | 2.1 | | 30 | 58.8 | 37.6 | 0.4 | 3.2 |
| | 50 | 59.3 | 38.1 | 0.4 | 2.2 | | 50 | 59.4 | 38.2 | 0.3 | 2.1 |
| | inf. | 59.3 | 38.2 | 0.4 | 2.0 | | inf. | 59.5 | 38.2 | 0.5 | 1.8 |
| 176 | 5 | 2.3 | 17.2 | 6.9 | 73.6 | 264 | 5 | 26.1 | 29.3 | 2.4 | 42.2 |
| | 15 | 61.2 | 36.6 | 0.4 | 1.9 | | 15 | 55.4 | 36.1 | 1.0 | 7.5 |
| | 30 | 61.4 | 37.0 | 0.2 | 1.3 | | 30 | 56.7 | 36.5 | 1.1 | 5.8 |
| | 50 | 60.4 | 36.7 | 0.5 | 2.3 | | 50 | 57.8 | 36.9 | 1.0 | 4.3 |
| | inf. | 61.1 | 37.6 | 0.3 | 1.0 | | inf. | 58.7 | 37.1 | 1.0 | 3.2 |
| 184 | 5 | 16.9 | 28.1 | 2.0 | 52.9 | 272 | 5 | 50.1 | 43.6 | 1.2 | 5.2 |
| | 15 | 60.1 | 36.6 | 0.4 | 2.9 | | 15 | 58.6 | 36.5 | 1.2 | 3.6 |
| | 30 | 60.9 | 37.1 | 0.3 | 1.8 | | 30 | 58.5 | 36.8 | 1.1 | 3.5 |
| | 50 | 59.5 | 36.7 | 0.6 | 3.3 | | 50 | 58.9 | 37.2 | 1.0 | 2.9 |
| | inf. | 60.9 | 37.7 | 0.3 | 1.2 | | inf. | 59.0 | 37.4 | 0.9 | 2.8 |
| 192 | 5 | 27.2 | 30.2 | 1.7 | 40.9 | 280 | 5 | 52.9 | 33.8 | 1.4 | 11.9 |
| | 15 | 60.6 | 36.9 | 0.5 | 2.0 | | 15 | 58.4 | 37.0 | 1.0 | 3.7 |
| | 30 | 60.1 | 36.6 | 0.7 | 2.6 | | 30 | 57.3 | 37.7 | 0.8 | 4.2 |
| | 50 | 60.5 | 37.1 | 0.5 | 1.9 | | 50 | 58.8 | 37.1 | 1.1 | 3.1 |
| | inf. | 60.1 | 37.3 | 0.5 | 2.1 | | inf. | 59.2 | 37.3 | 0.9 | 2.6 |
| 200 | 5 | 4.5 | 21.0 | 3.3 | 71.2 | 288 | 5 | 55.2 | 36.0 | 0.7 | 8.0 |
| | 15 | 61.2 | 35.5 | 0.6 | 2.8 | | 15 | 56.1 | 36.7 | 0.7 | 6.5 |
| | 30 | 62.0 | 36.3 | 0.2 | 1.5 | | 30 | 58.1 | 36.4 | 0.7 | 4.8 |
| | 50 | 61.6 | 36.6 | 0.2 | 1.6 | | 50 | 58.2 | 37.2 | 0.5 | 4.1 |
| | inf. | 60.9 | 37.7 | 0.2 | 1.3 | | inf. | 59.5 | 37.1 | 0.4 | 3.0 |
| 208 | 5 | 3.5 | 21.9 | 3.7 | 70.9 | 292 | 5 | 60.1 | 37.0 | 0.6 | 2.4 |
| | 15 | 56.4 | 37.0 | 0.5 | 6.1 | | 15 | 59.4 | 37.1 | 0.7 | 2.9 |
| | 30 | 57.3 | 37.1 | 0.6 | 5.0 | | 30 | 59.2 | 37.1 | 0.7 | 3.0 |
| | 50 | 57.8 | 37.3 | 0.6 | 4.3 | | 50 | 59.7 | 37.8 | 0.5 | 2.0 |
| | inf. | 59.4 | 37.7 | 0.5 | 2.3 | | inf. | 58.9 | 37.4 | 0.7 | 3.0 |
| 224 | 5 | 3.9 | 21.4 | 3.4 | 71.3 | 308 | 5 | 57.0 | 35.9 | 1.3 | 5.9 |
| | 15 | 54.3 | 35.5 | 1.0 | 9.2 | | 15 | 60.1 | 37.6 | 0.4 | 1.9 |
| | 30 | 56.0 | 36.1 | 1.0 | 6.9 | | 30 | 60.0 | 37.5 | 0.5 | 2.0 |
| | 50 | 56.9 | 36.5 | 1.0 | 5.6 | | 50 | 60.5 | 38.3 | 0.2 | 1.1 |
| | inf. | 58.8 | 37.3 | 0.7 | 3.2 | | inf. | 59.7 | 37.9 | 0.4 | 2.0 |

**<u>Appendix Table B7</u>** Gas concentrations in vegetated compost (*S. virginicus*) column with rainwater irrigation

| Day | Depth (cm) | Gas concentrations | | | | Day | Depth (cm) | Gas concentrations | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | $\%CH_4$ | $\%CO_2$ | $\%O_2$ | $\%N_2$ | | | $\%CH_4$ | $\%CO_2$ | $\%O_2$ | $\%N_2$ |
| 0 | 5 | 16.9 | 19.3 | 9.4 | 54.4 | 60 | 5 | 44.9 | 37.1 | 0.5 | 17.5 |
| | 15 | 28.4 | 28.7 | 5.1 | 37.7 | | 15 | 51.3 | 38.5 | 0.4 | 9.8 |
| | 30 | 36.1 | 32.5 | 3.5 | 28.0 | | 30 | 54.6 | 38.6 | 0.6 | 6.2 |
| | 50 | 43.8 | 35.9 | 2.1 | 18.2 | | 50 | 57.5 | 39.0 | 0.4 | 3.1 |
| | inf. | 45.2 | 34.1 | 3.0 | 17.8 | | inf. | 58.2 | 38.7 | 0.6 | 2.5 |
| 8 | 5 | 1.1 | 20.1 | 4.9 | 73.9 | 64 | 5 | 18.0 | 30.8 | 0.6 | 50.6 |
| | 15 | 16.3 | 29.7 | 2.0 | 52.0 | | 15 | 31.3 | 31.1 | 2.9 | 34.8 |
| | 30 | 31.7 | 34.7 | 0.8 | 32.8 | | 30 | 46.5 | 37.6 | 0.3 | 15.5 |
| | 50 | 41.5 | 37.0 | 0.6 | 20.9 | | 50 | 52.2 | 37.9 | 0.5 | 9.4 |
| | inf. | 47.2 | 37.9 | 0.7 | 14.3 | | inf. | 55.2 | 37.8 | 0.7 | 6.3 |
| 16 | 5 | 6.4 | 23.4 | 3.2 | 67.0 | 68 | 5 | 7.4 | 22.8 | 3.6 | 66.2 |
| | 15 | 24.0 | 31.9 | 1.3 | 42.9 | | 15 | 27.6 | 31.3 | 1.4 | 39.6 |
| | 30 | 37.9 | 34.6 | 1.5 | 26.0 | | 30 | 41.5 | 35.9 | 0.4 | 22.2 |
| | 50 | 46.0 | 37.2 | 0.9 | 16.0 | | 50 | 48.6 | 36.9 | 0.6 | 13.9 |
| | inf. | 50.0 | 37.4 | 1.0 | 11.7 | | inf. | 55.8 | 38.6 | 0.1 | 5.5 |
| 20 | 5 | 11.7 | 26.8 | 2.0 | 59.5 | 76 | 5 | 8.2 | 24.4 | 2.8 | 64.6 |
| | 15 | 24.0 | 31.9 | 1.3 | 42.9 | | 15 | 29.3 | 33.1 | 0.8 | 36.8 |
| | 30 | 37.9 | 34.6 | 1.5 | 26.0 | | 30 | 43.5 | 36.4 | 0.5 | 19.5 |
| | 50 | 48.6 | 37.4 | 0.5 | 13.5 | | 50 | 52.2 | 38.0 | 0.4 | 9.4 |
| | inf. | 50.9 | 37.2 | 1.3 | 10.6 | | inf. | 57.8 | 39.0 | 0.1 | 3.1 |
| 24 | 5 | 43.5 | 30.9 | 4.1 | 21.5 | 84 | 5 | 4.9 | 16.7 | 8.0 | 70.4 |
| | 15 | 42.6 | 37.0 | 0.9 | 19.5 | | 15 | 27.9 | 31.6 | 1.9 | 38.6 |
| | 30 | 49.1 | 37.9 | 0.8 | 12.1 | | 30 | 41.9 | 35.1 | 1.6 | 21.4 |
| | 50 | 53.3 | 38.5 | 0.7 | 7.5 | | 50 | 51.3 | 37.0 | 1.0 | 10.7 |
| | inf. | 55.4 | 38.7 | 0.7 | 5.1 | | inf. | 55.4 | 37.5 | 1.0 | 6.1 |
| 28 | 5 | 57.0 | 37.9 | 1.0 | 4.0 | 96 | 5 | 8.1 | 20.4 | 5.8 | 65.8 |
| | 15 | 57.0 | 37.7 | 1.1 | 4.3 | | 15 | 25.3 | 26.9 | 4.5 | 43.2 |
| | 30 | 58.3 | 38.5 | 0.6 | 2.5 | | 30 | 42.0 | 34.7 | 1.5 | 21.7 |
| | 50 | 58.4 | 38.4 | 0.6 | 2.6 | | 50 | 51.3 | 37.3 | 1.5 | 9.9 |
| | inf. | 57.9 | 38.2 | 0.8 | 3.1 | | inf. | 54.5 | 36.8 | 1.3 | 7.4 |
| 36 | 5 | 58.0 | 39.0 | 0.6 | 2.4 | 108 | 5 | 11.2 | 23.9 | 4.1 | 60.8 |
| | 15 | 57.9 | 38.9 | 0.6 | 2.6 | | 15 | 42.6 | 35.7 | 0.9 | 20.8 |
| | 30 | 56.6 | 38.1 | 1.0 | 4.3 | | 30 | 50.8 | 37.0 | 0.8 | 11.4 |
| | 50 | 58.1 | 38.8 | 0.6 | 2.5 | | 50 | 54.4 | 37.2 | 0.9 | 7.5 |
| | inf. | 55.2 | 36.7 | 1.5 | 6.5 | | inf. | 57.0 | 37.8 | 0.7 | 4.5 |
| 44 | 5 | 57.0 | 37.7 | 1.1 | 4.2 | 120 | 5 | 12.3 | 26.1 | 3.2 | 58.3 |
| | 15 | 60.2 | 39.6 | 0.2 | 0.0 | | 15 | 48.0 | 37.3 | 0.6 | 14.1 |
| | 30 | 60.1 | 39.7 | 0.2 | 0.0 | | 30 | 52.5 | 37.6 | 0.8 | 9.1 |
| | 50 | 60.0 | 39.7 | 0.2 | 0.1 | | 50 | 55.8 | 38.2 | 0.7 | 5.3 |
| | inf. | 60.0 | 39.7 | 0.2 | 0.2 | | inf. | 58.0 | 38.9 | 0.5 | 2.6 |
| 56 | 5 | 58.0 | 40.2 | 0.3 | 1.4 | 128 | 5 | 13.9 | 23.1 | 5.3 | 57.7 |
| | 15 | 59.8 | 38.3 | 0.3 | 1.6 | | 15 | 48.3 | 35.1 | 1.8 | 14.8 |
| | 30 | 59.8 | 38.4 | 0.4 | 1.4 | | 30 | 52.2 | 36.0 | 1.5 | 10.3 |
| | 50 | 59.8 | 38.8 | 0.3 | 1.1 | | 50 | 55.7 | 37.4 | 1.0 | 5.9 |
| | inf. | 60.0 | 38.7 | 0.3 | 1.0 | | inf. | 56.4 | 37.6 | 1.2 | 4.9 |

**Appendix Table B7** Cont'd

| Day | Depth (cm) | Gas concentrations | | | | Day | Depth (cm) | Gas concentrations | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | %$CH_4$ | %$CO_2$ | %$O_2$ | %$N_2$ | | | %$CH_4$ | %$CO_2$ | %$O_2$ | %$N_2$ |
| 132 | 5 | 20.0 | 30.3 | 2.1 | 47.5 | 200 | 5 | 50.5 | 33.0 | 2.1 | 14.4 |
| | 15 | 50.8 | 36.0 | 1.8 | 11.4 | | 15 | 55.2 | 35.6 | 1.4 | 7.8 |
| | 30 | 56.5 | 38.7 | 0.7 | 4.1 | | 30 | 54.3 | 34.9 | 1.9 | 9.0 |
| | 50 | 57.9 | 39.0 | 0.6 | 2.5 | | 50 | 56.7 | 36.4 | 1.2 | 5.6 |
| | inf. | 58.4 | 38.9 | 0.5 | 2.2 | | inf. | 57.9 | 37.1 | 0.9 | 4.1 |
| 136 | 5 | 29.0 | 30.3 | 1.9 | 38.8 | 212 | 5 | 41.8 | 28.6 | 4.8 | 24.8 |
| | 15 | 57.0 | 36.6 | 0.8 | 5.6 | | 15 | 55.4 | 37.3 | 1.1 | 6.2 |
| | 30 | 57.4 | 36.5 | 1.2 | 4.9 | | 30 | 55.6 | 37.3 | 1.2 | 5.8 |
| | 50 | 57.4 | 36.8 | 1.0 | 4.8 | | 50 | 57.4 | 38.1 | 0.8 | 3.7 |
| | inf. | 59.6 | 37.9 | 0.5 | 2.0 | | inf. | 57.0 | 36.8 | 1.2 | 5.0 |
| 144 | 5 | 47.8 | 36.8 | 0.6 | 14.8 | 220 | 5 | 22.4 | 30.7 | 2.0 | 45.0 |
| | 15 | 59.5 | 39.2 | 0.2 | 1.1 | | 15 | 51.1 | 37.6 | 1.1 | 10.3 |
| | 30 | 59.8 | 39.4 | 0.2 | 0.6 | | 30 | 53.7 | 38.0 | 1.1 | 7.3 |
| | 50 | 60.1 | 39.8 | 0.1 | 0.1 | | 50 | 54.9 | 38.0 | 1.1 | 6.0 |
| | inf. | 60.0 | 39.6 | 0.2 | 0.2 | | inf. | 57.1 | 38.3 | 0.9 | 3.7 |
| 148 | 5 | 51.8 | 36.9 | 0.6 | 10.7 | 224 | 5 | 21.1 | 28.3 | 3.2 | 47.3 |
| | 15 | 59.6 | 38.8 | 0.2 | 1.4 | | 15 | 55.1 | 37.4 | 1.1 | 6.4 |
| | 30 | 58.7 | 38.3 | 0.6 | 2.4 | | 30 | 56.1 | 37.8 | 1.1 | 5.1 |
| | 50 | 59.9 | 39.3 | 0.2 | 0.6 | | 50 | 56.1 | 37.7 | 1.1 | 5.1 |
| | inf. | 59.8 | 39.8 | 0.1 | 0.3 | | inf. | 55.7 | 37.2 | 1.4 | 5.8 |
| 156 | 5 | 55.8 | 35.0 | 1.8 | 7.3 | 232 | 5 | 30.6 | 31.0 | 3.3 | 35.2 |
| | 15 | 57.1 | 36.4 | 1.3 | 5.2 | | 15 | 55.0 | 37.1 | 1.4 | 6.5 |
| | 30 | 57.6 | 35.9 | 1.3 | 5.2 | | 30 | 56.3 | 37.8 | 1.1 | 4.8 |
| | 50 | 57.7 | 35.8 | 0.9 | 5.6 | | 50 | 56.3 | 37.8 | 1.1 | 4.7 |
| | inf. | 59.3 | 36.9 | 0.7 | 3.1 | | inf. | 56.0 | 37.3 | 1.3 | 5.3 |
| 160 | 5 | 56.2 | 36.1 | 0.8 | 6.8 | 236 | 5 | 29.3 | 30.7 | 3.3 | 36.8 |
| | 15 | 58.8 | 36.9 | 0.8 | 3.5 | | 15 | 55.6 | 37.9 | 1.1 | 5.4 |
| | 30 | 59.5 | 37.6 | 0.6 | 2.3 | | 30 | 55.6 | 37.4 | 1.3 | 5.7 |
| | 50 | 58.9 | 37.4 | 0.8 | 2.9 | | 50 | 55.4 | 37.3 | 1.5 | 5.8 |
| | inf. | 58.5 | 37.2 | 1.0 | 3.4 | | inf. | 57.3 | 38.3 | 0.9 | 3.5 |
| 172 | 5 | 54.1 | 35.3 | 1.6 | 9.0 | 248 | 5 | 41.7 | 34.6 | 2.2 | 21.5 |
| | 15 | 55.6 | 35.7 | 1.3 | 7.4 | | 15 | 56.4 | 37.4 | 1.1 | 5.1 |
| | 30 | 56.6 | 36.1 | 1.3 | 6.1 | | 30 | 57.1 | 38.0 | 0.9 | 4.0 |
| | 50 | 57.6 | 36.7 | 1.2 | 4.6 | | 50 | 57.1 | 38.2 | 0.9 | 3.8 |
| | inf. | 58.2 | 37.2 | 0.9 | 3.6 | | inf. | 57.2 | 38.3 | 0.8 | 3.6 |
| 184 | 5 | 53.7 | 36.4 | 0.9 | 9.1 | 260 | 5 | 44.7 | 34.8 | 2.0 | 18.5 |
| | 15 | 57.5 | 37.4 | 1.0 | 4.1 | | 15 | 57.7 | 37.8 | 0.9 | 3.7 |
| | 30 | 57.9 | 37.5 | 1.0 | 3.6 | | 30 | 57.0 | 37.4 | 1.1 | 4.6 |
| | 50 | 56.8 | 36.8 | 1.3 | 5.0 | | 50 | 57.2 | 37.7 | 1.0 | 4.1 |
| | inf. | 58.4 | 37.5 | 1.0 | 3.2 | | inf. | 57.4 | 37.9 | 0.9 | 3.8 |
| 192 | 5 | 54.3 | 35.5 | 1.5 | 8.7 | 268 | 5 | 51.1 | 36.4 | 1.4 | 11.0 |
| | 15 | 56.4 | 36.2 | 1.8 | 5.7 | | 15 | 57.3 | 38.1 | 0.9 | 3.7 |
| | 30 | 56.3 | 36.2 | 1.8 | 5.7 | | 30 | 56.6 | 37.6 | 1.2 | 4.7 |
| | 50 | 55.9 | 36.1 | 1.9 | 6.1 | | 50 | 57.1 | 38.1 | 0.9 | 3.8 |
| | inf. | 57.4 | 36.9 | 1.5 | 4.2 | | inf. | 57.3 | 38.0 | 0.9 | 3.8 |

**Appendix Table B7** Cont'd

| Day | Depth (cm) | Gas concentrations | | | | Day | Depth (cm) | Gas concentrations | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | %$CH_4$ | %$CO_2$ | %$O_2$ | %$N_2$ | | | %$CH_4$ | %$CO_2$ | %$O_2$ | %$N_2$ |
| 272 | 5 | 52.6 | 37.2 | 1.2 | 9.0 | 340 | 5 | 53.2 | 36.5 | 1.8 | 8.4 |
| | 15 | 56.7 | 37.9 | 1.0 | 4.4 | | 15 | 54.8 | 37.3 | 1.6 | 6.2 |
| | 30 | 57.9 | 38.8 | 0.7 | 2.7 | | 30 | 54.9 | 37.5 | 1.6 | 6.1 |
| | 50 | 57.8 | 38.8 | 0.7 | 2.7 | | 50 | 55.3 | 37.7 | 1.5 | 5.5 |
| | inf. | 57.6 | 38.0 | 0.9 | 3.5 | | inf. | 54.9 | 36.9 | 1.7 | 6.4 |
| 280 | 5 | 55.3 | 37.4 | 1.1 | 6.2 | 356 | 5 | 50.4 | 36.3 | 1.7 | 11.6 |
| | 15 | 57.3 | 38.4 | 0.8 | 3.5 | | 15 | 51.1 | 36.6 | 1.5 | 10.8 |
| | 30 | 57.4 | 38.2 | 0.9 | 3.5 | | 30 | 51.1 | 36.5 | 1.6 | 10.7 |
| | 50 | 56.5 | 38.0 | 1.1 | 4.4 | | 50 | 51.8 | 36.9 | 1.5 | 9.8 |
| | inf. | 58.0 | 37.9 | 0.8 | 3.3 | | inf. | 53.1 | 37.3 | 1.3 | 8.3 |
| 304 | 5 | 55.3 | 35.4 | 1.8 | 7.5 | 376 | 5 | 52.6 | 36.6 | 1.7 | 9.1 |
| | 15 | 57.0 | 37.3 | 1.2 | 4.5 | | 15 | 54.9 | 37.2 | 1.8 | 6.1 |
| | 30 | 56.3 | 36.9 | 1.4 | 5.4 | | 30 | 55.7 | 37.7 | 1.6 | 5.1 |
| | 50 | 56.7 | 37.5 | 1.2 | 4.6 | | 50 | 55.7 | 37.6 | 1.6 | 5.0 |
| | inf. | 56.6 | 37.8 | 1.3 | 4.4 | | inf. | 56.5 | 37.7 | 1.3 | 4.5 |
| 316 | 5 | 56.5 | 37.3 | 1.4 | 4.8 | 388 | 5 | 54.6 | 37.7 | 1.8 | 6.0 |
| | 15 | 56.4 | 37.4 | 1.4 | 4.8 | | 15 | 55.6 | 37.4 | 1.6 | 5.3 |
| | 30 | 56.7 | 37.7 | 1.3 | 4.3 | | 30 | 55.8 | 37.2 | 1.6 | 5.4 |
| | 50 | 56.3 | 37.4 | 1.4 | 4.8 | | 50 | 56.5 | 37.3 | 1.5 | 4.7 |
| | inf. | 56.7 | 37.7 | 1.3 | 4.3 | | inf. | 57.0 | 37.3 | 1.5 | 4.2 |

**Appendix Table B8** Gas concentrations in vegetated compost (*P. repens*) column with rainwater irrigation

| Day | Depth (cm) | Gas concentrations | | | | Day | Depth (cm) | Gas concentrations | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | %$CH_4$ | %$CO_2$ | %$O_2$ | %$N_2$ | | | %$CH_4$ | %$CO_2$ | %$O_2$ | %$N_2$ |
| 0 | 5 | 13.9 | 15.3 | 11.7 | 59.2 | 28 | 5 | 26.4 | 33.2 | 1.0 | 39.5 |
| | 15 | 25.4 | 24.8 | 7.4 | 42.3 | | 15 | 37.8 | 35.6 | 0.8 | 25.8 |
| | 30 | 35.1 | 31.2 | 4.5 | 29.2 | | 30 | 45.8 | 37.5 | 0.7 | 15.9 |
| | 50 | 43.3 | 35.1 | 2.7 | 18.9 | | 50 | 51.4 | 38.2 | 0.6 | 9.8 |
| | inf. | 47.8 | 35.9 | 2.2 | 14.1 | | inf. | 52.6 | 37.5 | 1.2 | 8.8 |
| 8 | 5 | 1.1 | 18.8 | 5.9 | 74.2 | 36 | 5 | 46.9 | 36.3 | 1.2 | 15.7 |
| | 15 | 15.7 | 29.8 | 1.3 | 53.2 | | 15 | 51.5 | 38.0 | 0.7 | 9.8 |
| | 30 | 30.7 | 34.2 | 0.9 | 34.2 | | 30 | 54.1 | 38.6 | 0.6 | 6.6 |
| | 50 | 42.1 | 37.1 | 0.6 | 20.2 | | 50 | 55.0 | 38.2 | 0.6 | 6.1 |
| | inf. | 48.5 | 38.1 | 0.6 | 12.9 | | inf. | 55.8 | 38.2 | 0.4 | 5.6 |
| 16 | 5 | 3.0 | 23.8 | 2.5 | 70.6 | 44 | 5 | 58.8 | 38.8 | 0.6 | 1.8 |
| | 15 | 25.9 | 30.4 | 1.7 | 42.1 | | 15 | 59.4 | 39.2 | 0.4 | 1.0 |
| | 30 | 32.8 | 34.2 | 1.2 | 31.8 | | 30 | 59.3 | 39.4 | 0.3 | 0.9 |
| | 50 | 42.7 | 36.4 | 1.0 | 19.9 | | 50 | 60.1 | 39.6 | 0.1 | 0.2 |
| | inf. | 48.3 | 37.2 | 1.0 | 13.5 | | inf. | 60.0 | 39.7 | 0.1 | 0.2 |
| 24 | 5 | 6.9 | 24.3 | 3.3 | 65.6 | 52 | 5 | 59.0 | 38.1 | 0.6 | 2.3 |
| | 15 | 23.8 | 32.7 | 1.1 | 42.5 | | 15 | 59.2 | 38.4 | 0.5 | 1.8 |
| | 30 | 35.7 | 35.2 | 1.2 | 27.9 | | 30 | 59.9 | 38.7 | 0.4 | 1.0 |
| | 50 | 45.5 | 37.6 | 0.8 | 16.1 | | 50 | 59.6 | 39.6 | 0.4 | 0.4 |
| | inf. | 51.1 | 37.4 | 1.0 | 10.5 | | inf. | 60.6 | 39.0 | 0.3 | 0.2 |

**Appendix Table B8** Cont'd

| Day | Depth (cm) | Gas concentrations | | | | Day | Depth (cm) | Gas concentrations | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | $\%CH_4$ | $\%CO_2$ | $\%O_2$ | $\%N_2$ | | | $\%CH_4$ | $\%CO_2$ | $\%O_2$ | $\%N_2$ |
| 56 | 5 | 51.5 | 42.7 | 4.2 | 30.6 | 128 | 5 | 7.4 | 14.7 | 10.1 | 67.9 |
| | 15 | 54.8 | 41.6 | 4.1 | 24.9 | | 15 | 29.3 | 32.7 | 1.2 | 36.7 |
| | 30 | 54.9 | 38.3 | 0.5 | 6.4 | | 30 | 42.6 | 35.7 | 1.2 | 20.6 |
| | 50 | 57.9 | 38.8 | 0.3 | 3.0 | | 50 | 51.4 | 37.3 | 1.0 | 10.4 |
| | inf. | 59.0 | 38.7 | 0.3 | 1.9 | | inf. | 57.2 | 39.2 | 0.4 | 3.2 |
| 60 | 5 | 32.4 | 34.6 | 0.6 | 32.3 | 144 | 5 | 8.3 | 18.2 | 8.0 | 65.5 |
| | 15 | 36.6 | 32.7 | 2.9 | 27.8 | | 15 | 35.4 | 35.7 | 0.6 | 28.3 |
| | 30 | 47.4 | 37.3 | 1.2 | 14.2 | | 30 | 46.8 | 38.1 | 0.4 | 14.6 |
| | 50 | 53.5 | 38.0 | 0.9 | 7.7 | | 50 | 53.5 | 39.0 | 0.4 | 7.1 |
| | inf. | 54.7 | 37.0 | 1.3 | 7.0 | | inf. | 58.4 | 39.7 | 0.2 | 1.7 |
| 68 | 5 | 14.2 | 28.0 | 1.3 | 56.5 | 156 | 5 | 8.8 | 18.4 | 7.7 | 65.1 |
| | 15 | 33.9 | 33.9 | 0.4 | 31.8 | | 15 | 34.1 | 32.4 | 1.7 | 31.8 |
| | 30 | 45.1 | 36.7 | 0.3 | 17.9 | | 30 | 46.3 | 36.1 | 0.9 | 16.7 |
| | 50 | 52.3 | 37.3 | 0.4 | 9.9 | | 50 | 54.4 | 37.9 | 0.7 | 6.9 |
| | inf. | 57.7 | 38.7 | 0.1 | 3.5 | | inf. | 56.4 | 36.9 | 1.1 | 5.7 |
| 76 | 5 | 3.2 | 14.5 | 8.8 | 73.5 | 168 | 5 | 8.5 | 19.2 | 7.0 | 65.3 |
| | 15 | 27.8 | 32.1 | 1.1 | 39.0 | | 15 | 36.1 | 33.6 | 1.5 | 28.8 |
| | 30 | 43.4 | 36.7 | 0.3 | 19.6 | | 30 | 45.0 | 35.3 | 1.5 | 18.3 |
| | 50 | 52.4 | 38.1 | 0.2 | 9.2 | | 50 | 53.3 | 37.6 | 0.7 | 8.3 |
| | inf. | 58.3 | 39.1 | 0.1 | 2.6 | | inf. | 57.1 | 37.5 | 0.9 | 4.5 |
| 84 | 5 | 4.2 | 14.6 | 9.2 | 72.0 | 184 | 5 | 8.9 | 27.9 | 5.6 | 57.6 |
| | 15 | 23.9 | 30.9 | 1.7 | 43.5 | | 15 | 41.8 | 35.4 | 1.3 | 21.6 |
| | 30 | 32.2 | 28.6 | 4.4 | 34.8 | | 30 | 48.1 | 36.4 | 1.3 | 14.2 |
| | 50 | 48.6 | 36.4 | 1.2 | 13.8 | | 50 | 53.6 | 37.5 | 1.0 | 7.9 |
| | inf. | 48.9 | 36.4 | 1.2 | 13.5 | | inf. | 56.7 | 37.2 | 1.1 | 4.9 |
| 96 | 5 | 4.1 | 10.6 | 12.3 | 73.0 | 232 | 5 | 10.2 | 24.0 | 3.7 | 62.1 |
| | 15 | 25.2 | 30.8 | 1.7 | 42.4 | | 15 | 47.1 | 36.9 | 1.2 | 14.8 |
| | 30 | 41.0 | 35.3 | 1.2 | 22.5 | | 30 | 51.1 | 37.4 | 1.2 | 10.3 |
| | 50 | 49.9 | 36.1 | 1.3 | 12.7 | | 50 | 54.6 | 38.2 | 1.0 | 6.2 |
| | inf. | 53.9 | 36.3 | 1.6 | 8.2 | | inf. | 56.7 | 38.2 | 1.0 | 4.1 |
| 104 | 5 | 2.7 | 65.1 | 3.7 | 28.5 | 248 | 5 | 7.7 | 17.7 | 8.2 | 66.4 |
| | 15 | 25.8 | 32.9 | 1.1 | 40.2 | | 15 | 49.2 | 37.1 | 1.0 | 12.7 |
| | 30 | 40.2 | 36.6 | 0.8 | 22.4 | | 30 | 52.5 | 37.5 | 1.1 | 9.0 |
| | 50 | 48.9 | 37.5 | 0.8 | 12.7 | | 50 | 54.9 | 37.9 | 1.0 | 6.3 |
| | inf. | 55.1 | 38.3 | 0.6 | 6.0 | | inf. | 55.9 | 37.4 | 1.2 | 5.5 |
| 112 | 5 | 7.9 | 18.1 | 8.0 | 66.0 | 256 | 5 | 6.7 | 17.2 | 9.4 | 66.7 |
| | 15 | 28.4 | 34.3 | 0.9 | 36.4 | | 15 | 46.0 | 35.5 | 2.4 | 16.0 |
| | 30 | 42.3 | 37.8 | 0.6 | 19.3 | | 30 | 50.6 | 36.7 | 2.2 | 10.5 |
| | 50 | 51.1 | 39.1 | 0.5 | 9.3 | | 50 | 53.0 | 36.9 | 2.2 | 8.0 |
| | inf. | 57.2 | 39.6 | 0.3 | 2.9 | | inf. | 54.2 | 36.4 | 2.4 | 6.9 |
| 120 | 5 | 7.4 | 15.9 | 9.4 | 67.3 | 268 | 5 | 7.9 | 18.6 | 8.7 | 64.8 |
| | 15 | 28.0 | 32.2 | 1.5 | 38.3 | | 15 | 47.4 | 34.5 | 2.3 | 15.8 |
| | 30 | 42.8 | 36.4 | 1.0 | 19.8 | | 30 | 53.5 | 37.2 | 1.2 | 8.1 |
| | 50 | 50.2 | 36.7 | 1.3 | 11.9 | | 50 | 55.8 | 38.0 | 1.0 | 5.2 |
| | inf. | 55.1 | 37.7 | 1.1 | 6.1 | | inf. | 57.1 | 38.0 | 1.0 | 3.9 |

**Appendix Table B8** Cont'd

| Day | Depth (cm) | Gas concentrations | | | | Day | Depth (cm) | Gas concentrations | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | $\%CH_4$ | $\%CO_2$ | $\%O_2$ | $\%N_2$ | | | $\%CH_4$ | $\%CO_2$ | $\%O_2$ | $\%N_2$ |
| 280 | 5 | 11.1 | 25.6 | 5.8 | 57.5 | 404 | 5 | 11.8 | 21.1 | 7.0 | 60.1 |
| | 15 | 55.9 | 38.6 | 0.7 | 4.9 | | 15 | 33.9 | 33.2 | 2.1 | 30.8 |
| | 30 | 56.8 | 38.3 | 0.8 | 4.1 | | 30 | 45.2 | 35.9 | 1.9 | 17.1 |
| | 50 | 57.9 | 38.5 | 0.7 | 2.9 | | 50 | 51.2 | 36.5 | 2.0 | 10.4 |
| | inf. | 57.9 | 37.9 | 0.9 | 3.3 | | inf. | 55.5 | 37.1 | 1.8 | 5.6 |
| 296 | 5 | 5.2 | 17.2 | 7.9 | 69.6 | 412 | 5 | 11.8 | 21.1 | 7.1 | 60.0 |
| | 15 | 52.9 | 36.6 | 1.2 | 9.3 | | 15 | 31.7 | 32.9 | 2.3 | 33.1 |
| | 30 | 54.3 | 36.6 | 1.4 | 7.8 | | 30 | 44.2 | 36.1 | 1.9 | 17.7 |
| | 50 | 55.9 | 37.3 | 1.2 | 5.6 | | 50 | 51.5 | 37.2 | 1.7 | 9.6 |
| | inf. | 56.9 | 37.9 | 1.1 | 4.1 | | inf. | 55.9 | 37.6 | 1.6 | 4.9 |
| 308 | 5 | 5.4 | 21.0 | 5.5 | 68.1 | 420 | 5 | 11.1 | 19.2 | 8.7 | 61.1 |
| | 15 | 50.6 | 36.3 | 1.6 | 11.6 | | 15 | 31.3 | 32.9 | 2.2 | 33.6 |
| | 30 | 52.8 | 36.6 | 1.7 | 8.9 | | 30 | 43.0 | 35.4 | 2.1 | 19.5 |
| | 50 | 54.7 | 37.2 | 1.5 | 6.6 | | 50 | 50.9 | 37.0 | 1.8 | 10.2 |
| | inf. | 55.0 | 36.6 | 1.8 | 6.5 | | inf. | 55.6 | 37.4 | 1.7 | 5.3 |
| 324 | 5 | 7.1 | 24.7 | 3.0 | 65.2 | 448 | 5 | 8.6 | 16.4 | 10.4 | 64.6 |
| | 15 | 51.3 | 35.8 | 1.9 | 11.0 | | 15 | 19.0 | 28.7 | 4.1 | 48.1 |
| | 30 | 54.6 | 37.4 | 1.4 | 6.5 | | 30 | 35.2 | 34.7 | 2.5 | 27.6 |
| | 50 | 55.4 | 37.4 | 1.5 | 5.7 | | 50 | 54.3 | 38.1 | 1.8 | 5.9 |
| | inf. | 55.8 | 36.8 | 1.7 | 5.8 | | inf. | 55.6 | 37.7 | 1.8 | 4.9 |
| 356 | 5 | 10.3 | 21.8 | 5.9 | 62.0 | 456 | 5 | 3.9 | 12.3 | 12.8 | 70.9 |
| | 15 | 51.6 | 37.2 | 1.6 | 9.5 | | 15 | 10.9 | 27.3 | 3.4 | 58.3 |
| | 30 | 53.9 | 37.6 | 1.5 | 7.0 | | 30 | 28.2 | 33.3 | 2.7 | 35.8 |
| | 50 | 55.1 | 37.6 | 1.5 | 5.8 | | 50 | 41.5 | 37.1 | 2.2 | 19.1 |
| | inf. | 56.0 | 37.4 | 1.6 | 5.0 | | inf. | 54.7 | 37.8 | 1.8 | 5.7 |
| 372 | 5 | 9.6 | 20.6 | 6.8 | 63.0 | 464 | 5 | 11.6 | 18.5 | 9.0 | 60.9 |
| | 15 | 47.0 | 36.6 | 1.7 | 14.7 | | 15 | 23.9 | 30.9 | 2.4 | 42.8 |
| | 30 | 51.4 | 37.0 | 1.6 | 9.9 | | 30 | 42.3 | 37.3 | 1.3 | 19.1 |
| | 50 | 54.2 | 37.6 | 1.5 | 6.7 | | 50 | 54.3 | 38.4 | 1.2 | 6.1 |
| | inf. | 56.0 | 37.5 | 1.5 | 4.9 | | inf. | 55.6 | 37.8 | 1.3 | 5.2 |
| 388 | 5 | 7.7 | 19.4 | 7.0 | 65.8 | 472 | 5 | 11.4 | 21.2 | 6.9 | 60.5 |
| | 15 | 33.3 | 32.8 | 2.3 | 31.6 | | 15 | 22.4 | 30.2 | 2.1 | 45.3 |
| | 30 | 43.6 | 34.9 | 2.4 | 19.2 | | 30 | 42.6 | 35.9 | 1.5 | 20.0 |
| | 50 | 50.4 | 36.3 | 2.0 | 11.3 | | 50 | 55.9 | 38.0 | 1.0 | 5.0 |
| | inf. | 55.4 | 36.4 | 1.9 | 6.3 | | inf. | 57.0 | 38.2 | 1.0 | 3.9 |

**<u>Appendix Table B9</u>** Gas concentrations in vegetated compost (*S. virginicus*) column with leachate irrigation

| Day | Depth (cm) | Gas concentrations | | | | Day | Depth (cm) | Gas concentrations | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | %$CH_4$ | %$CO_2$ | %$O_2$ | %$N_2$ | | | %$CH_4$ | %$CO_2$ | %$O_2$ | %$N_2$ |
| 0 | 5 | 13.2 | 17.1 | 10.0 | 59.7 | 80 | 5 | 13.5 | 25.7 | 3.7 | 57.0 |
| | 15 | 28.5 | 33.6 | 1.7 | 36.3 | | 15 | 57.9 | 37.2 | 1.1 | 3.7 |
| | 30 | 36.2 | 34.1 | 2.2 | 27.4 | | 30 | 58.6 | 37.9 | 0.9 | 2.7 |
| | 50 | 49.0 | 37.6 | 1.3 | 12.1 | | 50 | 59.3 | 38.3 | 0.6 | 1.9 |
| | inf. | 52.3 | 37.9 | 1.2 | 8.6 | | inf. | 60.5 | 38.6 | 0.4 | 0.5 |
| 8 | 5 | 4.3 | 13.1 | 11.2 | 71.4 | 84 | 5 | 7.1 | 16.1 | 8.4 | 68.4 |
| | 15 | 28.0 | 33.7 | 1.0 | 37.4 | | 15 | 54.0 | 35.2 | 2.1 | 8.7 |
| | 30 | 41.5 | 36.6 | 1.0 | 20.9 | | 30 | 57.1 | 37.1 | 1.2 | 4.6 |
| | 50 | 50.2 | 38.1 | 0.7 | 11.0 | | 50 | 57.4 | 37.2 | 1.1 | 4.3 |
| | inf. | 54.8 | 39.1 | 0.4 | 5.6 | | inf. | 57.3 | 37.1 | 1.1 | 4.4 |
| 16 | 5 | 8.9 | 20.8 | 5.9 | 64.4 | 92 | 5 | 51.4 | 32.8 | 3.1 | 12.8 |
| | 15 | 27.2 | 31.8 | 1.7 | 39.2 | | 15 | 58.7 | 37.5 | 0.8 | 3.0 |
| | 30 | 40.7 | 35.4 | 1.3 | 22.6 | | 30 | 58.3 | 37.9 | 0.8 | 3.0 |
| | 50 | 48.0 | 36.7 | 1.4 | 14.0 | | 50 | 59.2 | 37.8 | 0.8 | 2.2 |
| | inf. | 53.6 | 38.3 | 0.8 | 7.3 | | inf. | 59.1 | 38.3 | 0.7 | 1.8 |
| 24 | 5 | 11.9 | 23.1 | 5.6 | 59.5 | 100 | 5 | 54.8 | 34.9 | 2.0 | 8.2 |
| | 15 | 32.0 | 34.9 | 1.0 | 32.1 | | 15 | 57.1 | 37.1 | 1.2 | 4.6 |
| | 30 | 42.7 | 36.6 | 1.3 | 19.4 | | 30 | 57.7 | 37.4 | 0.8 | 4.1 |
| | 50 | 51.6 | 38.5 | 0.7 | 9.2 | | 50 | 57.3 | 37.1 | 1.1 | 4.4 |
| | inf. | 54.8 | 38.5 | 0.7 | 5.9 | | inf. | 57.4 | 37.2 | 1.1 | 4.3 |
| 36 | 5 | 12.3 | 22.8 | 5.6 | 59.3 | 108 | 5 | 52.7 | 37.2 | 0.8 | 9.3 |
| | 15 | 37.2 | 35.7 | 1.1 | 26.1 | | 15 | 56.9 | 38.6 | 0.7 | 3.8 |
| | 30 | 46.5 | 37.4 | 1.0 | 15.1 | | 30 | 54.6 | 37.4 | 1.3 | 6.7 |
| | 50 | 52.6 | 38.2 | 0.8 | 8.4 | | 50 | 57.2 | 38.7 | 0.7 | 3.4 |
| | inf. | 56.1 | 38.4 | 0.7 | 4.8 | | inf. | 59.8 | 39.5 | 0.2 | 0.5 |
| 44 | 5 | 12.1 | 23.3 | 5.7 | 58.8 | 112 | 5 | 41.3 | 37.2 | 0.9 | 20.7 |
| | 15 | 41.6 | 34.2 | 2.1 | 22.1 | | 15 | 58.2 | 40.1 | 0.4 | 1.3 |
| | 30 | 53.3 | 39.1 | 0.2 | 7.4 | | 30 | 58.8 | 40.3 | 0.3 | 0.6 |
| | 50 | 56.4 | 38.9 | 0.4 | 4.3 | | 50 | 58.8 | 40.1 | 0.3 | 0.9 |
| | inf. | 58.7 | 39.4 | 0.3 | 1.6 | | inf. | 59.5 | 39.5 | 0.2 | 0.7 |
| 56 | 5 | 7.4 | 17.4 | 8.4 | 66.8 | 124 | 5 | 44.3 | 35.4 | 1.7 | 18.6 |
| | 15 | 55.2 | 38.0 | 0.5 | 6.3 | | 15 | 58.7 | 38.4 | 0.6 | 2.3 |
| | 30 | 57.8 | 38.5 | 0.4 | 3.3 | | 30 | 58.0 | 38.1 | 0.8 | 3.1 |
| | 50 | 59.5 | 39.1 | 0.2 | 1.2 | | 50 | 58.4 | 38.6 | 0.7 | 2.3 |
| | inf. | 60.4 | 39.1 | 0.2 | 0.3 | | inf. | 59.0 | 39.1 | 0.5 | 1.4 |
| 64 | 5 | 5.3 | 12.0 | 11.8 | 70.9 | 132 | 5 | 46.2 | 37.5 | 0.9 | 15.4 |
| | 15 | 58.9 | 38.1 | 0.6 | 2.3 | | 15 | 56.5 | 37.7 | 1.2 | 4.6 |
| | 30 | 58.9 | 38.3 | 0.6 | 2.2 | | 30 | 59.8 | 39.9 | 0.2 | 0.1 |
| | 50 | 60.2 | 39.0 | 0.3 | 0.5 | | 50 | 59.6 | 39.7 | 0.3 | 0.5 |
| | inf. | 60.4 | 39.1 | 0.2 | 0.3 | | inf. | 59.8 | 39.3 | 0.3 | 0.5 |
| 72 | 5 | 6.6 | 11.3 | 11.7 | 70.4 | 144 | 5 | 41.8 | 35.7 | 1.4 | 21.1 |
| | 15 | 60.1 | 38.7 | 0.2 | 1.0 | | 15 | 59.1 | 38.2 | 0.6 | 2.0 |
| | 30 | 60.6 | 39.0 | 0.2 | 0.2 | | 30 | 57.3 | 37.4 | 1.0 | 4.2 |
| | 50 | 60.4 | 39.2 | 0.2 | 0.2 | | 50 | 58.0 | 38.0 | 0.8 | 3.1 |
| | inf. | 60.7 | 39.1 | 0.2 | 0.1 | | inf. | 60.2 | 39.5 | 0.1 | 0.2 |

**<u>Appendix Table B9</u>** Cont'd

| Day | Depth (cm) | Gas concentrations | | | | Day | Depth (cm) | Gas concentrations | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | $\%CH_4$ | $\%CO_2$ | $\%O_2$ | $\%N_2$ | | | $\%CH_4$ | $\%CO_2$ | $\%O_2$ | $\%N_2$ |
| 156 | 5 | 38.1 | 32.5 | 2.3 | 27.2 | 232 | 5 | 15.1 | 22.0 | 6.6 | 56.2 |
| | 15 | 56.1 | 35.7 | 1.7 | 6.5 | | 15 | 39.7 | 35.7 | 1.3 | 23.3 |
| | 30 | 58.9 | 37.2 | 0.9 | 3.1 | | 30 | 49.5 | 37.5 | 1.1 | 11.9 |
| | 50 | 59.2 | 36.7 | 0.8 | 3.3 | | 50 | 53.8 | 37.8 | 1.2 | 7.2 |
| | inf. | 59.8 | 37.3 | 0.7 | 2.2 | | inf. | 57.1 | 38.1 | 1.0 | 3.8 |
| 160 | 5 | 27.0 | 27.8 | 4.0 | 41.2 | 248 | 5 | 13.0 | 19.7 | 7.9 | 59.3 |
| | 15 | 59.4 | 37.4 | 0.7 | 2.5 | | 15 | 34.2 | 35.0 | 1.2 | 29.6 |
| | 30 | 58.3 | 36.7 | 1.1 | 3.9 | | 30 | 47.5 | 36.8 | 1.2 | 14.6 |
| | 50 | 59.4 | 37.8 | 0.6 | 2.1 | | 50 | 54.0 | 38.0 | 1.0 | 7.0 |
| | inf. | 59.2 | 37.9 | 0.7 | 2.2 | | inf. | 54.2 | 36.0 | 1.8 | 8.0 |
| 168 | 5 | 21.5 | 25.7 | 4.9 | 47.9 | 252 | 5 | 11.8 | 18.8 | 8.4 | 61.0 |
| | 15 | 57.4 | 36.5 | 1.3 | 4.8 | | 15 | 30.2 | 32.9 | 1.8 | 35.2 |
| | 30 | 57.8 | 36.8 | 1.2 | 4.2 | | 30 | 46.7 | 37.1 | 1.0 | 15.2 |
| | 50 | 57.8 | 36.8 | 1.1 | 4.3 | | 50 | 53.8 | 38.2 | 0.9 | 7.1 |
| | inf. | 58.5 | 37.4 | 0.9 | 3.2 | | inf. | 57.3 | 38.3 | 0.9 | 3.6 |
| 176 | 5 | 18.4 | 24.0 | 5.7 | 51.9 | 260 | 5 | 11.6 | 18.1 | 9.3 | 61.0 |
| | 15 | 58.9 | 37.2 | 0.9 | 3.0 | | 15 | 31.4 | 33.8 | 1.5 | 33.3 |
| | 30 | 57.3 | 36.3 | 1.4 | 5.0 | | 30 | 46.9 | 36.9 | 1.1 | 15.1 |
| | 50 | 58.2 | 37.1 | 1.1 | 3.6 | | 50 | 53.7 | 37.5 | 1.1 | 7.8 |
| | inf. | 58.5 | 37.4 | 0.9 | 3.2 | | inf. | 58.0 | 38.2 | 0.8 | 3.0 |
| 184 | 5 | 19.0 | 24.9 | 5.2 | 50.9 | 268 | 5 | 10.0 | 15.8 | 10.7 | 63.6 |
| | 15 | 57.5 | 37.4 | 1.1 | 4.0 | | 15 | 30.5 | 34.1 | 1.5 | 34.0 |
| | 30 | 58.4 | 37.8 | 0.9 | 2.9 | | 30 | 44.9 | 36.3 | 1.5 | 17.3 |
| | 50 | 57.2 | 37.0 | 1.2 | 4.6 | | 50 | 53.7 | 38.1 | 1.0 | 7.2 |
| | inf. | 58.3 | 37.4 | 1.0 | 3.3 | | inf. | 56.3 | 37.3 | 1.3 | 5.2 |
| 188 | 5 | 15.6 | 23.9 | 5.3 | 55.3 | 276 | 5 | 13.1 | 18.1 | 9.8 | 59.0 |
| | 15 | 56.4 | 36.3 | 1.5 | 5.8 | | 15 | 35.1 | 35.4 | 1.3 | 28.2 |
| | 30 | 58.4 | 37.8 | 0.9 | 2.8 | | 30 | 47.4 | 37.3 | 1.3 | 13.9 |
| | 50 | 58.1 | 37.6 | 1.0 | 3.3 | | 50 | 54.4 | 37.9 | 1.0 | 6.7 |
| | inf. | 58.8 | 37.7 | 0.9 | 2.7 | | inf. | 57.6 | 37.8 | 1.0 | 3.6 |
| 200 | 5 | 21.0 | 24.5 | 5.5 | 49.0 | 288 | 5 | 10.9 | 15.7 | 10.6 | 62.8 |
| | 15 | 55.6 | 35.5 | 1.7 | 7.3 | | 15 | 31.6 | 33.9 | 1.5 | 32.9 |
| | 30 | 57.1 | 36.6 | 1.2 | 5.1 | | 30 | 46.4 | 36.4 | 1.4 | 15.8 |
| | 50 | 57.3 | 36.8 | 1.1 | 4.8 | | 50 | 53.5 | 38.0 | 1.1 | 7.4 |
| | inf. | 57.5 | 36.8 | 1.1 | 4.6 | | inf. | 56.4 | 37.7 | 1.2 | 4.7 |
| 208 | 5 | 19.9 | 22.4 | 6.6 | 51.1 | 304 | 5 | 10.3 | 14.1 | 11.6 | 64.1 |
| | 15 | 56.0 | 36.8 | 1.1 | 6.1 | | 15 | 35.0 | 33.7 | 2.0 | 29.3 |
| | 30 | 57.5 | 37.3 | 0.9 | 4.3 | | 30 | 48.2 | 36.3 | 1.4 | 14.0 |
| | 50 | 57.5 | 37.2 | 1.0 | 4.2 | | 50 | 53.9 | 37.4 | 1.3 | 7.5 |
| | inf. | 58.0 | 37.1 | 1.0 | 3.9 | | inf. | 56.6 | 37.6 | 1.2 | 4.5 |
| 220 | 5 | 16.4 | 22.0 | 6.9 | 54.7 | 316 | 5 | 10.4 | 14.2 | 11.7 | 63.6 |
| | 15 | 47.7 | 37.3 | 1.1 | 13.9 | | 15 | 36.5 | 33.9 | 2.2 | 27.4 |
| | 30 | 53.2 | 38.5 | 0.9 | 7.4 | | 30 | 49.8 | 36.9 | 1.6 | 11.7 |
| | 50 | 55.7 | 38.7 | 0.9 | 4.7 | | 50 | 53.0 | 36.8 | 1.8 | 8.4 |
| | inf. | 56.8 | 38.1 | 1.0 | 4.1 | | inf. | 56.4 | 37.6 | 1.3 | 4.7 |

**<u>Appendix Table B9</u>** Cont'd

| Day | Depth (cm) | Gas concentrations | | | | Day | Depth (cm) | Gas concentrations | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | %$CH_4$ | %$CO_2$ | %$O_2$ | %$N_2$ | | | %$CH_4$ | %$CO_2$ | %$O_2$ | %$N_2$ |
| 332 | 5 | 12.3 | 15.0 | 11.7 | 60.9 | 396 | 5 | 9.0 | 17.3 | 9.9 | 63.7 |
| | 15 | 44.5 | 35.8 | 1.8 | 18.0 | | 15 | 49.2 | 34.9 | 2.1 | 13.7 |
| | 30 | 51.8 | 36.7 | 1.8 | 9.7 | | 30 | 55.0 | 37.0 | 1.8 | 6.1 |
| | 50 | 54.9 | 37.5 | 1.5 | 6.0 | | 50 | 55.3 | 37.2 | 1.8 | 5.7 |
| | inf. | 56.0 | 37.2 | 1.5 | 5.3 | | inf. | 56.4 | 37.7 | 1.5 | 4.4 |
| 344 | 5 | 13.2 | 15.8 | 11.4 | 59.6 | 412 | 5 | 18.4 | 27.2 | 4.5 | 49.9 |
| | 15 | 46.2 | 35.0 | 2.0 | 16.8 | | 15 | 55.7 | 36.8 | 1.7 | 5.7 |
| | 30 | 55.0 | 37.5 | 1.4 | 6.2 | | 30 | 56.5 | 37.6 | 1.5 | 4.4 |
| | 50 | 56.4 | 37.9 | 1.3 | 4.5 | | 50 | 56.4 | 37.6 | 1.6 | 4.4 |
| | inf. | 56.3 | 37.5 | 1.5 | 4.6 | | inf. | 56.5 | 37.6 | 1.6 | 4.4 |
| 348 | 5 | 11.7 | 14.9 | 11.9 | 61.5 | 420 | 5 | 21.4 | 28.7 | 4.0 | 45.9 |
| | 15 | 45.9 | 36.5 | 1.6 | 15.9 | | 15 | 56.2 | 37.2 | 1.6 | 5.0 |
| | 30 | 53.4 | 37.7 | 1.5 | 7.4 | | 30 | 56.4 | 37.1 | 1.7 | 4.8 |
| | 50 | 55.6 | 38.1 | 1.3 | 4.9 | | 50 | 56.5 | 37.5 | 1.6 | 4.4 |
| | inf. | 56.6 | 37.6 | 1.4 | 4.4 | | inf. | 56.0 | 37.5 | 1.7 | 4.8 |
| 368 | 5 | 13.9 | 10.5 | 12.4 | 63.3 | 448 | 5 | 11.4 | 24.3 | 4.8 | 59.5 |
| | 15 | 26.5 | 29.4 | 2.5 | 41.6 | | 15 | 45.8 | 34.7 | 2.6 | 16.8 |
| | 30 | 43.5 | 35.9 | 1.9 | 18.6 | | 30 | 50.8 | 35.8 | 2.3 | 11.0 |
| | 50 | 53.9 | 37.9 | 1.5 | 6.7 | | 50 | 53.9 | 37.2 | 2.0 | 6.9 |
| | inf. | 55.8 | 37.4 | 1.6 | 5.2 | | inf. | 55.5 | 37.7 | 1.8 | 5.0 |
| 376 | 5 | 9.5 | 12.5 | 13.6 | 64.4 | 464 | 5 | 11.6 | 25.8 | 3.6 | 59.1 |
| | 15 | 46.1 | 35.3 | 2.1 | 16.6 | | 15 | 54.2 | 38.1 | 1.2 | 6.5 |
| | 30 | 54.2 | 37.4 | 1.7 | 6.7 | | 30 | 54.1 | 37.7 | 1.5 | 6.6 |
| | 50 | 55.6 | 37.9 | 1.5 | 4.9 | | 50 | 56.2 | 38.8 | 0.9 | 4.0 |
| | inf. | 56.2 | 37.6 | 1.5 | 4.6 | | inf. | 55.1 | 37.3 | 1.4 | 6.1 |
| 388 | 5 | 12.4 | 17.5 | 10.3 | 59.8 | 472 | 5 | 12.9 | 21.5 | 7.3 | 58.3 |
| | 15 | 48.9 | 35.2 | 2.2 | 13.8 | | 15 | 55.3 | 38.1 | 1.0 | 5.6 |
| | 30 | 55.8 | 37.4 | 1.6 | 5.2 | | 30 | 55.0 | 37.6 | 1.3 | 6.1 |
| | 50 | 55.5 | 38.1 | 1.6 | 4.8 | | 50 | 55.1 | 37.2 | 1.4 | 6.2 |
| | inf. | 56.7 | 36.9 | 1.7 | 4.7 | | inf. | 56.5 | 37.8 | 1.1 | 4.6 |

**Appendix Table B10** Gas concentrations in vegetated compost (*P. repens*) column with leachate irrigation

| Day | Depth (cm) | Gas concentrations | | | | Day | Depth (cm) | Gas concentrations | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | $\%CH_4$ | $\%CO_2$ | $\%O_2$ | $\%N_2$ | | | $\%CH_4$ | $\%CO_2$ | $\%O_2$ | $\%N_2$ |
| 0 | 5 | 7.1 | 17.1 | 8.6 | 67.2 | 76 | 5 | 7.1 | 22.5 | 4.1 | 66.4 |
| | 15 | 19.0 | 27.7 | 3.6 | 49.7 | | 15 | 52.1 | 37.4 | 0.3 | 10.3 |
| | 30 | 29.3 | 31.7 | 2.6 | 36.4 | | 30 | 52.2 | 36.6 | 1.3 | 9.9 |
| | 50 | 36.9 | 33.7 | 2.4 | 27.0 | | 50 | 58.2 | 38.9 | 0.2 | 2.8 |
| | inf. | 43.7 | 35.9 | 1.7 | 18.7 | | inf. | 58.7 | 38.7 | 0.2 | 2.4 |
| 8 | 5 | 0.2 | 12.7 | 9.9 | 77.3 | 84 | 5 | 6.0 | 21.0 | 5.1 | 67.8 |
| | 15 | 7.5 | 27.3 | 1.3 | 63.9 | | 15 | 44.4 | 33.4 | 2.6 | 19.6 |
| | 30 | 18.8 | 30.6 | 1.3 | 49.2 | | 30 | 51.3 | 36.0 | 1.5 | 11.2 |
| | 50 | 32.4 | 30.6 | 4.2 | 32.8 | | 50 | 55.0 | 37.0 | 1.1 | 6.9 |
| | inf. | 35.8 | 35.8 | 0.7 | 27.7 | | inf. | 57.0 | 37.5 | 0.9 | 4.6 |
| 16 | 5 | 0.6 | 12.1 | 10.0 | 77.3 | 96 | 5 | 8.1 | 20.2 | 5.6 | 66.0 |
| | 15 | 13.0 | 28.1 | 1.6 | 57.2 | | 15 | 44.9 | 34.5 | 1.5 | 19.1 |
| | 30 | 27.4 | 32.9 | 1.1 | 38.6 | | 30 | 47.2 | 34.4 | 2.1 | 16.3 |
| | 50 | 36.2 | 32.9 | 2.3 | 28.5 | | 50 | 52.3 | 36.5 | 1.7 | 9.6 |
| | inf. | 42.6 | 36.3 | 1.1 | 20.0 | | inf. | 55.2 | 36.4 | 1.3 | 7.0 |
| 24 | 5 | 4.2 | 13.9 | 10.0 | 71.8 | 104 | 5 | 8.0 | 21.7 | 5.2 | 65.1 |
| | 15 | 23.5 | 32.9 | 1.1 | 42.5 | | 15 | 48.3 | 37.5 | 0.7 | 13.5 |
| | 30 | 36.5 | 36.1 | 0.8 | 26.6 | | 30 | 52.1 | 37.9 | 0.8 | 9.2 |
| | 50 | 43.8 | 35.4 | 2.1 | 18.7 | | 50 | 54.9 | 38.6 | 0.6 | 5.9 |
| | inf. | 49.9 | 37.9 | 0.9 | 11.3 | | inf. | 56.9 | 38.2 | 0.7 | 4.3 |
| 32 | 5 | 4.3 | 15.3 | 9.4 | 71.0 | 112 | 5 | 4.8 | 17.5 | 7.4 | 70.3 |
| | 15 | 17.9 | 24.0 | 5.8 | 52.4 | | 15 | 50.1 | 38.4 | 0.6 | 11.0 |
| | 30 | 37.9 | 34.5 | 2.0 | 25.6 | | 30 | 52.9 | 38.4 | 0.5 | 8.2 |
| | 50 | 45.3 | 36.8 | 1.3 | 16.7 | | 50 | 56.8 | 39.9 | 0.2 | 3.0 |
| | inf. | 51.5 | 37.5 | 1.0 | 10.1 | | inf. | 57.9 | 38.8 | 0.6 | 2.6 |
| 40 | 5 | 3.9 | 17.0 | 7.7 | 71.4 | 124 | 5 | 7.1 | 17.3 | 7.7 | 67.9 |
| | 15 | 40.0 | 36.6 | 0.5 | 22.8 | | 15 | 49.3 | 37.3 | 0.5 | 12.9 |
| | 30 | 45.6 | 38.2 | 0.4 | 15.8 | | 30 | 52.6 | 37.5 | 0.7 | 9.2 |
| | 50 | 50.0 | 38.7 | 0.4 | 11.0 | | 50 | 56.0 | 38.8 | 0.5 | 4.7 |
| | inf. | 54.2 | 39.1 | 0.3 | 6.3 | | inf. | 57.8 | 38.9 | 0.5 | 2.7 |
| 52 | 5 | 4.2 | 21.6 | 5.0 | 69.2 | 132 | 5 | 10.0 | 22.4 | 5.1 | 62.5 |
| | 15 | 52.0 | 35.4 | 0.6 | 12.0 | | 15 | 54.8 | 39.0 | 0.4 | 5.8 |
| | 30 | 55.1 | 37.6 | 0.6 | 6.7 | | 30 | 55.6 | 38.5 | 0.8 | 5.1 |
| | 50 | 57.1 | 38.1 | 0.5 | 4.3 | | 50 | 57.6 | 38.8 | 0.6 | 2.9 |
| | inf. | 59.4 | 38.8 | 0.3 | 1.5 | | inf. | 59.8 | 39.5 | 0.3 | 0.4 |
| 60 | 5 | 2.4 | 21.4 | 4.5 | 71.7 | 144 | 5 | 12.1 | 24.8 | 3.5 | 59.6 |
| | 15 | 57.9 | 38.5 | 0.6 | 3.0 | | 15 | 55.6 | 36.6 | 1.5 | 6.3 |
| | 30 | 58.1 | 38.6 | 0.6 | 2.7 | | 30 | 57.5 | 37.8 | 0.5 | 4.2 |
| | 50 | 57.1 | 37.6 | 1.0 | 4.2 | | 50 | 59.5 | 39.0 | 0.3 | 1.2 |
| | inf. | 59.2 | 38.4 | 0.5 | 1.9 | | inf. | 59.8 | 39.3 | 0.1 | 0.8 |
| 68 | 5 | 4.0 | 15.3 | 8.3 | 72.4 | 160 | 5 | 22.7 | 28.2 | 2.2 | 46.9 |
| | 15 | 41.1 | 34.8 | 0.5 | 23.6 | | 15 | 53.4 | 36.1 | 1.4 | 9.0 |
| | 30 | 47.7 | 36.9 | 0.3 | 15.2 | | 30 | 55.8 | 36.8 | 1.0 | 6.4 |
| | 50 | 51.7 | 37.1 | 0.5 | 10.7 | | 50 | 56.3 | 36.7 | 0.8 | 6.3 |
| | inf. | 55.3 | 37.4 | 0.7 | 6.7 | | inf. | 56.8 | 36.5 | 0.6 | 6.1 |

**<u>Appendix Table B10</u>** Cont'd

| Day | Depth (cm) | Gas concentrations | | | | Day | Depth (cm) | Gas concentrations | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | %$CH_4$ | %$CO_2$ | %$O_2$ | %$N_2$ | | | %$CH_4$ | %$CO_2$ | %$O_2$ | %$N_2$ |
| 164 | 5 | 14.6 | 22.9 | 4.8 | 57.8 | 236 | 5 | 16.5 | 26.0 | 2.9 | 54.6 |
| | 15 | 45.2 | 33.7 | 1.7 | 19.5 | | 15 | 51.9 | 36.4 | 1.2 | 10.4 |
| | 30 | 54.0 | 38.0 | 1.1 | 6.9 | | 30 | 54.2 | 37.2 | 1.1 | 7.5 |
| | 50 | 55.4 | 37.3 | 0.8 | 6.5 | | 50 | 55.9 | 37.9 | 1.0 | 5.1 |
| | inf. | 56.0 | 36.9 | 0.7 | 6.5 | | inf. | 56.2 | 37.4 | 1.3 | 5.2 |
| 172 | 5 | 10.1 | 17.9 | 8.0 | 64.0 | 248 | 5 | 57.5 | 35.7 | 1.0 | 5.8 |
| | 15 | 38.4 | 34.6 | 1.8 | 25.1 | | 15 | 57.1 | 37.1 | 1.1 | 4.8 |
| | 30 | 47.2 | 35.9 | 1.4 | 15.5 | | 30 | 57.8 | 37.9 | 0.9 | 3.4 |
| | 50 | 51.3 | 35.7 | 1.0 | 12.0 | | 50 | 54.9 | 36.3 | 1.7 | 7.1 |
| | inf. | 56.2 | 36.8 | 1.0 | 6.0 | | inf. | 57.3 | 37.9 | 1.0 | 3.8 |
| 184 | 5 | 13.2 | 20.2 | 7.5 | 59.1 | 252 | 5 | 57.4 | 36.9 | 1.1 | 4.5 |
| | 15 | 47.9 | 35.9 | 1.4 | 14.7 | | 15 | 57.8 | 37.8 | 0.9 | 3.6 |
| | 30 | 52.8 | 36.3 | 1.6 | 9.4 | | 30 | 57.9 | 38.0 | 0.8 | 3.4 |
| | 50 | 54.2 | 35.9 | 1.8 | 8.1 | | 50 | 57.5 | 38.0 | 0.9 | 3.6 |
| | inf. | 55.9 | 35.9 | 1.6 | 6.6 | | inf. | 57.0 | 37.8 | 1.0 | 4.2 |
| 192 | 5 | 7.7 | 17.6 | 8.1 | 66.5 | 260 | 5 | 58.0 | 36.0 | 1.2 | 4.9 |
| | 15 | 43.6 | 33.8 | 2.2 | 20.3 | | 15 | 58.8 | 37.2 | 0.8 | 3.2 |
| | 30 | 48.6 | 35.3 | 2.0 | 14.0 | | 30 | 58.9 | 37.5 | 0.7 | 2.9 |
| | 50 | 52.8 | 36.1 | 1.8 | 9.4 | | 50 | 58.0 | 36.9 | 1.0 | 4.0 |
| | inf. | 56.0 | 36.6 | 1.6 | 5.7 | | inf. | 58.2 | 37.1 | 1.0 | 3.8 |
| 200 | 5 | 7.9 | 18.0 | 7.2 | 67.0 | 276 | 5 | 58.0 | 37.9 | 0.9 | 3.3 |
| | 15 | 44.6 | 33.8 | 1.5 | 20.1 | | 15 | 57.1 | 37.3 | 1.2 | 4.4 |
| | 30 | 48.0 | 33.9 | 1.8 | 16.3 | | 30 | 58.1 | 38.0 | 0.8 | 3.0 |
| | 50 | 50.7 | 34.3 | 2.0 | 13.1 | | 50 | 57.7 | 38.1 | 0.9 | 3.2 |
| | inf. | 54.1 | 35.2 | 1.7 | 9.0 | | inf. | 57.1 | 37.2 | 1.2 | 4.5 |
| 208 | 5 | 9.7 | 21.8 | 4.6 | 63.9 | 304 | 5 | 57.8 | 36.7 | 1.2 | 4.3 |
| | 15 | 48.5 | 35.0 | 1.1 | 15.4 | | 15 | 57.9 | 37.0 | 1.2 | 4.0 |
| | 30 | 52.6 | 36.2 | 1.0 | 10.2 | | 30 | 57.9 | 37.2 | 1.1 | 3.8 |
| | 50 | 55.5 | 37.1 | 0.9 | 6.5 | | 50 | 57.4 | 37.1 | 1.3 | 4.3 |
| | inf. | 57.4 | 37.2 | 0.9 | 4.5 | | inf. | 56.3 | 36.9 | 1.5 | 5.3 |
| 220 | 5 | 11.5 | 24.2 | 3.6 | 60.7 | 324 | 5 | 57.0 | 37.4 | 1.3 | 4.3 |
| | 15 | 49.5 | 36.7 | 1.1 | 12.7 | | 15 | 56.9 | 37.6 | 1.3 | 4.2 |
| | 30 | 51.7 | 36.8 | 1.4 | 10.1 | | 30 | 56.8 | 37.5 | 1.3 | 4.4 |
| | 50 | 54.5 | 37.7 | 1.1 | 6.7 | | 50 | 56.7 | 37.6 | 1.3 | 4.3 |
| | inf. | 55.9 | 37.5 | 1.2 | 5.4 | | inf. | 56.9 | 37.7 | 1.3 | 4.1 |

**Appendix Table B11** Gas concentrations in non-vegetated sandy loam column without irrigation

| Day | Depth (cm) | Gas concentrations | | | | Day | Depth (cm) | Gas concentrations | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | $\%CH_4$ | $\%CO_2$ | $\%O_2$ | $\%N_2$ | | | $\%CH_4$ | $\%CO_2$ | $\%O_2$ | $\%N_2$ |
| 0 | 5 | 0.8 | 5.5 | 14.9 | 78.8 | 73 | 5 | 2.2 | 4.9 | 15.8 | 77.1 |
| | 15 | 2.5 | 14.5 | 8.7 | 74.2 | | 15 | 6.2 | 12.9 | 11.0 | 69.8 |
| | 30 | 6.7 | 24.9 | 2.2 | 66.2 | | 30 | 15.6 | 25.4 | 3.7 | 55.4 |
| | 50 | 17.2 | 27.8 | 2.0 | 53.0 | | 50 | 28.6 | 32.3 | 1.1 | 38.0 |
| | inf. | 25.1 | 31.1 | 1.1 | 42.7 | | inf. | 35.1 | 33.0 | 1.4 | 30.4 |
| 7 | 5 | 0.9 | 5.6 | 14.9 | 78.6 | 81 | 5 | 2.4 | 4.8 | 15.7 | 77.1 |
| | 15 | 2.2 | 13.9 | 9.5 | 74.4 | | 15 | 8.8 | 14.7 | 10.2 | 66.3 |
| | 30 | 7.0 | 24.5 | 2.7 | 65.7 | | 30 | 17.2 | 24.0 | 5.0 | 53.8 |
| | 50 | 16.9 | 29.5 | 1.2 | 52.4 | | 50 | 35.1 | 34.8 | 0.4 | 29.8 |
| | inf. | 23.4 | 30.9 | 1.2 | 44.4 | | inf. | 41.2 | 35.1 | 0.8 | 22.9 |
| 13 | 5 | 1.2 | 6.3 | 14.4 | 78.1 | 89 | 5 | 2.2 | 4.8 | 15.7 | 77.4 |
| | 15 | 2.7 | 13.4 | 9.7 | 74.2 | | 15 | 6.5 | 13.0 | 10.7 | 69.9 |
| | 30 | 8.4 | 25.1 | 2.4 | 64.1 | | 30 | 9.2 | 15.3 | 7.8 | 67.8 |
| | 50 | 17.8 | 29.0 | 1.4 | 51.7 | | 50 | 15.8 | 22.1 | 6.2 | 55.9 |
| | inf. | 24.7 | 30.9 | 1.3 | 43.1 | | inf. | 29.1 | 26.2 | 4.3 | 40.4 |
| 21 | 5 | 3.4 | 6.6 | 14.8 | 75.2 | 97 | 5 | 3.9 | 6.5 | 14.5 | 75.0 |
| | 15 | 8.4 | 15.6 | 9.6 | 66.4 | | 15 | 8.9 | 14.5 | 10.1 | 66.5 |
| | 30 | 16.8 | 25.4 | 3.9 | 53.9 | | 30 | 14.6 | 23.7 | 5.1 | 56.7 |
| | 50 | 31.7 | 33.1 | 0.9 | 34.3 | | 50 | 34.2 | 34.0 | 0.3 | 31.5 |
| | inf. | 38.6 | 34.4 | 1.1 | 25.9 | | inf. | 39.8 | 34.0 | 1.0 | 25.2 |
| 29 | 5 | 4.3 | 7.5 | 14.4 | 73.9 | 109 | 5 | 2.5 | 5.4 | 15.6 | 76.5 |
| | 15 | 9.4 | 16.7 | 8.8 | 65.1 | | 15 | 5.4 | 11.8 | 11.9 | 70.9 |
| | 30 | 20.3 | 28.4 | 2.6 | 48.8 | | 30 | 14.3 | 24.5 | 3.9 | 57.2 |
| | 50 | 32.4 | 33.5 | 0.5 | 33.6 | | 50 | 27.7 | 32.0 | 1.1 | 39.3 |
| | inf. | 39.8 | 34.1 | 1.1 | 24.9 | | inf. | 39.8 | 32.4 | 0.7 | 27.0 |
| 37 | 5 | 2.8 | 6.4 | 14.8 | 76.0 | 117 | 5 | 2.7 | 5.2 | 15.3 | 76.7 |
| | 15 | 6.4 | 14.0 | 10.1 | 69.4 | | 15 | 7.2 | 13.1 | 10.8 | 68.9 |
| | 30 | 15.9 | 26.6 | 3.0 | 54.4 | | 30 | 16.7 | 25.4 | 3.8 | 54.2 |
| | 50 | 29.2 | 32.3 | 1.0 | 37.6 | | 50 | 26.4 | 30.9 | 1.6 | 41.1 |
| | inf. | 34.8 | 32.4 | 1.8 | 31.1 | | inf. | 31.8 | 29.2 | 3.3 | 35.7 |
| 43 | 5 | 2.4 | 4.6 | 12.8 | 80.1 | 125 | 5 | 3.5 | 5.8 | 15.4 | 75.3 |
| | 15 | 8.9 | 16.3 | 12.1 | 62.7 | | 15 | 8.1 | 13.1 | 11.2 | 67.6 |
| | 30 | 17.5 | 28.0 | 2.3 | 52.3 | | 30 | 15.0 | 22.9 | 5.8 | 56.3 |
| | 50 | 33.1 | 33.1 | 1.0 | 32.8 | | 50 | 32.3 | 32.4 | 1.4 | 33.9 |
| | inf. | 40.7 | 35.0 | 0.7 | 23.5 | | inf. | 40.2 | 34.7 | 0.9 | 24.2 |
| 57 | 5 | 3.1 | 5.9 | 15.2 | 75.8 | 133 | 5 | 2.4 | 5.3 | 15.5 | 76.8 |
| | 15 | 7.4 | 13.9 | 10.3 | 68.4 | | 15 | 6.0 | 12.3 | 11.3 | 70.4 |
| | 30 | 17.1 | 25.4 | 3.7 | 53.9 | | 30 | 14.1 | 24.2 | 4.4 | 57.4 |
| | 50 | 30.4 | 32.1 | 1.0 | 36.6 | | 50 | 28.4 | 32.1 | 1.1 | 38.4 |
| | inf. | 38.3 | 34.1 | 0.7 | 26.9 | | inf. | 35.3 | 33.5 | 1.2 | 30.0 |
| 65 | 5 | 1.2 | 3.3 | 16.8 | 78.8 | 149 | 5 | 1.7 | 3.6 | 16.8 | 77.8 |
| | 15 | 6.6 | 13.2 | 10.8 | 69.4 | | 15 | 6.9 | 13.0 | 11.5 | 68.6 |
| | 30 | 15.9 | 25.3 | 3.6 | 55.2 | | 30 | 15.5 | 25.0 | 4.7 | 54.8 |
| | 50 | 27.8 | 31.0 | 1.5 | 39.7 | | 50 | 27.7 | 30.9 | 2.8 | 38.7 |
| | inf. | 35.3 | 32.9 | 1.5 | 30.3 | | inf. | 36.1 | 33.8 | 1.9 | 28.2 |

**Appendix Table B11** Cont'd

| Day | Depth (cm) | Gas concentrations | | | | Day | Depth (cm) | Gas concentrations | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | $\%CH_4$ | $\%CO_2$ | $\%O_2$ | $\%N_2$ | | | $\%CH_4$ | $\%CO_2$ | $\%O_2$ | $\%N_2$ |
| 157 | 5 | 2.8 | 5.8 | 15.4 | 76.1 | 225 | 5 | 3.9 | 5.7 | 15.8 | 74.5 |
| | 15 | 6.7 | 13.6 | 10.8 | 68.9 | | 15 | 8.2 | 12.0 | 12.3 | 67.5 |
| | 30 | 15.2 | 25.9 | 3.8 | 55.1 | | 30 | 18.2 | 24.0 | 5.6 | 52.1 |
| | 50 | 28.0 | 32.7 | 1.5 | 37.8 | | 50 | 33.1 | 33.4 | 1.4 | 32.1 |
| | inf. | 36.5 | 35.8 | 0.8 | 26.9 | | inf. | 41.3 | 36.3 | 0.9 | 21.5 |
| 165 | 5 | 4.4 | 6.6 | 15.0 | 74.0 | 233 | 5 | 3.3 | 5.1 | 16.4 | 75.3 |
| | 15 | 9.7 | 14.2 | 10.8 | 65.3 | | 15 | 9.0 | 13.2 | 11.5 | 66.2 |
| | 30 | 20.0 | 26.1 | 4.6 | 49.2 | | 30 | 14.6 | 19.9 | 8.0 | 57.4 |
| | 50 | 38.1 | 35.4 | 0.5 | 26.0 | | 50 | 35.3 | 33.7 | 1.2 | 29.7 |
| | inf. | 45.5 | 37.6 | 0.1 | 16.8 | | inf. | 41.1 | 34.3 | 1.3 | 23.3 |
| 173 | 5 | 3.4 | 5.8 | 15.6 | 75.2 | 241 | 5 | 4.1 | 6.2 | 15.5 | 74.2 |
| | 15 | 7.1 | 12.9 | 11.5 | 68.6 | | 15 | 9.6 | 14.2 | 11.2 | 65.0 |
| | 30 | 19.9 | 26.0 | 4.9 | 49.1 | | 30 | 20.6 | 27.3 | 4.2 | 47.9 |
| | 50 | 32.2 | 34.3 | 0.6 | 33.0 | | 50 | 38.4 | 36.6 | 0.4 | 24.6 |
| | inf. | 36.6 | 33.6 | 2.1 | 27.8 | | inf. | 42.4 | 37.3 | 0.9 | 19.4 |
| 181 | 5 | 2.5 | 4.9 | 16.0 | 76.6 | 253 | 5 | 3.6 | 5.7 | 15.7 | 74.9 |
| | 15 | 6.6 | 12.7 | 11.4 | 69.3 | | 15 | 7.9 | 12.5 | 11.9 | 67.7 |
| | 30 | 11.9 | 18.5 | 8.2 | 61.5 | | 30 | 17.3 | 24.7 | 5.5 | 52.6 |
| | 50 | 27.5 | 30.7 | 2.8 | 39.1 | | 50 | 33.2 | 33.4 | 1.6 | 31.8 |
| | inf. | 36.2 | 34.1 | 1.7 | 28.0 | | inf. | 39.4 | 34.7 | 1.7 | 24.2 |
| 193 | 5 | 2.4 | 4.2 | 16.5 | 76.9 | 261 | 5 | 4.6 | 6.1 | 15.9 | 73.4 |
| | 15 | 7.3 | 12.0 | 12.1 | 68.7 | | 15 | 10.2 | 13.3 | 12.1 | 64.4 |
| | 30 | 15.6 | 22.4 | 6.3 | 55.7 | | 30 | 21.2 | 25.5 | 5.8 | 47.5 |
| | 50 | 32.3 | 33.0 | 1.6 | 33.1 | | 50 | 38.0 | 34.0 | 2.1 | 25.9 |
| | inf. | 38.8 | 34.5 | 1.6 | 25.2 | | inf. | 41.8 | 33.7 | 2.7 | 21.8 |
| 201 | 5 | 3.0 | 5.6 | 15.3 | 76.1 | 273 | 5 | 3.6 | 5.8 | 15.7 | 74.9 |
| | 15 | 6.1 | 12.3 | 11.4 | 70.2 | | 15 | 7.9 | 12.4 | 12.1 | 67.7 |
| | 30 | 14.1 | 24.7 | 4.6 | 56.6 | | 30 | 17.3 | 23.9 | 5.6 | 53.2 |
| | 50 | 27.5 | 32.4 | 1.4 | 38.6 | | 50 | 35.1 | 34.4 | 1.4 | 29.1 |
| | inf. | 35.2 | 34.9 | 1.0 | 29.0 | | inf. | 41.2 | 35.6 | 1.3 | 21.9 |
| 209 | 5 | 3.2 | 6.0 | 15.5 | 75.3 | 289 | 5 | 2.4 | 5.1 | 16.2 | 76.2 |
| | 15 | 7.1 | 13.7 | 11.2 | 68.0 | | 15 | 5.3 | 11.7 | 12.4 | 70.5 |
| | 30 | 16.1 | 26.6 | 4.2 | 53.1 | | 30 | 11.9 | 23.1 | 5.9 | 59.1 |
| | 50 | 30.8 | 34.7 | 0.9 | 33.6 | | 50 | 27.3 | 32.8 | 2.0 | 37.9 |
| | inf. | 38.2 | 36.5 | 0.7 | 24.7 | | inf. | 33.1 | 33.2 | 2.5 | 31.3 |

**Appendix Table B12** Gas concentrations and MOR in vegetated sandy loam (*P. repens*) column without irrigation

| Day | Depth (cm) | Gas concentrations | | | | Day | Depth (cm) | Gas concentrations | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | % $CH_4$ | % $CO_2$ | % $O_2$ | % $N_2$ | | | % $CH_4$ | % $CO_2$ | % $O_2$ | % $N_2$ |
| 0 | 5 | 4.6 | 4.8 | 17.2 | 73.5 | 74 | 5 | 6.0 | 5.6 | 17.0 | 71.4 |
| | 15 | 11.7 | 11.0 | 14.6 | 62.7 | | 15 | 15.6 | 13.9 | 13.6 | 56.9 |
| | 30 | 21.9 | 19.6 | 10.8 | 47.7 | | 30 | 27.5 | 23.0 | 9.6 | 39.9 |
| | 50 | 32.4 | 27.1 | 7.5 | 33.0 | | 50 | 38.8 | 30.3 | 6.2 | 24.7 |
| | inf. | 38.4 | 30.9 | 5.7 | 25.0 | | inf. | 44.1 | 33.4 | 4.6 | 18.0 |
| 2 | 5 | 3.7 | 6.4 | 15.7 | 74.2 | 94 | 5 | 4.0 | 4.2 | 17.6 | 74.3 |
| | 15 | 9.4 | 15.7 | 10.4 | 64.5 | | 15 | 10.1 | 9.6 | 15.4 | 64.9 |
| | 30 | 20.8 | 29.5 | 3.1 | 46.7 | | 30 | 19.2 | 17.3 | 12.3 | 51.2 |
| | 50 | 37.0 | 35.3 | 1.6 | 26.1 | | 50 | 28.5 | 24.2 | 8.7 | 38.5 |
| | inf. | 44.4 | 36.5 | 1.6 | 17.4 | | inf. | 35.0 | 28.8 | 6.6 | 29.6 |
| 14 | 5 | 3.8 | 5.9 | 16.0 | 74.3 | 102 | 5 | 5.3 | 5.1 | 16.6 | 73.0 |
| | 15 | 10.0 | 15.0 | 11.3 | 63.7 | | 15 | 13.3 | 12.3 | 13.7 | 60.7 |
| | 30 | 19.7 | 27.3 | 4.6 | 48.3 | | 30 | 23.4 | 20.2 | 10.4 | 46.0 |
| | 50 | 34.1 | 34.7 | 1.8 | 29.4 | | 50 | 34.6 | 28.3 | 6.9 | 30.2 |
| | inf. | 41.3 | 36.0 | 1.7 | 21.0 | | inf. | 39.7 | 31.2 | 5.4 | 23.7 |
| 22 | 5 | 5.3 | 6.9 | 15.9 | 72.0 | 118 | 5 | 4.6 | 4.5 | 16.9 | 74.0 |
| | 15 | 13.2 | 16.2 | 11.3 | 59.3 | | 15 | 11.7 | 10.9 | 14.3 | 63.1 |
| | 30 | 24.7 | 28.2 | 5.1 | 42.1 | | 30 | 21.6 | 18.9 | 11.0 | 48.5 |
| | 50 | 38.5 | 35.6 | 1.8 | 24.1 | | 50 | 31.6 | 26.0 | 7.9 | 34.5 |
| | inf. | 45.4 | 36.9 | 1.6 | 16.1 | | inf. | 37.5 | 29.9 | 6.1 | 26.5 |
| 30 | 5 | 5.1 | 6.4 | 16.1 | 72.4 | 126 | 5 | 6.7 | 6.5 | 16.1 | 70.7 |
| | 15 | 13.6 | 15.9 | 11.6 | 58.9 | | 15 | 16.0 | 14.2 | 13.0 | 56.9 |
| | 30 | 25.2 | 27.7 | 5.6 | 41.5 | | 30 | 27.5 | 23.0 | 9.2 | 40.3 |
| | 50 | 37.8 | 35.5 | 1.9 | 24.8 | | 50 | 38.4 | 30.3 | 5.9 | 25.4 |
| | inf. | 44.8 | 37.0 | 1.6 | 16.7 | | inf. | 44.9 | 34.1 | 3.9 | 17.1 |
| 38 | 5 | 4.7 | 5.9 | 16.3 | 73.1 | 142 | 5 | 7.7 | 7.4 | 15.9 | 69.0 |
| | 15 | 11.8 | 14.3 | 12.3 | 61.5 | | 15 | 17.7 | 15.9 | 12.4 | 54.1 |
| | 30 | 22.1 | 25.2 | 7.0 | 45.7 | | 30 | 31.1 | 25.8 | 8.2 | 34.9 |
| | 50 | 33.3 | 33.7 | 2.5 | 30.4 | | 50 | 40.2 | 31.8 | 5.3 | 22.8 |
| | inf. | 40.8 | 36.3 | 1.7 | 21.2 | | inf. | 46.2 | 35.0 | 3.6 | 15.1 |
| 50 | 5 | 5.5 | 5.6 | 16.7 | 72.2 | 154 | 5 | 8.1 | 7.7 | 15.7 | 68.5 |
| | 15 | 13.7 | 13.1 | 13.6 | 59.6 | | 15 | 18.0 | 16.2 | 12.3 | 53.5 |
| | 30 | 24.3 | 21.9 | 9.8 | 44.0 | | 30 | 30.0 | 25.1 | 8.5 | 36.4 |
| | 50 | 36.1 | 30.3 | 5.6 | 28.0 | | 50 | 41.3 | 32.4 | 5.0 | 21.3 |
| | inf. | 41.2 | 32.8 | 4.4 | 21.6 | | inf. | 47.6 | 35.5 | 3.3 | 13.6 |
| 58 | 5 | 4.6 | 4.8 | 17.2 | 73.5 | 160 | 5 | 8.7 | 8.3 | 15.5 | 67.5 |
| | 15 | 11.7 | 11.0 | 14.6 | 62.7 | | 15 | 19.8 | 17.6 | 11.7 | 50.9 |
| | 30 | 21.9 | 19.6 | 10.8 | 47.7 | | 30 | 30.5 | 25.3 | 8.3 | 35.9 |
| | 50 | 32.4 | 27.1 | 7.5 | 33.0 | | 50 | 42.5 | 33.2 | 4.6 | 19.7 |
| | inf. | 38.4 | 30.9 | 5.7 | 25.0 | | inf. | 47.7 | 35.4 | 3.3 | 13.6 |
| 66 | 5 | 6.9 | 6.7 | 16.5 | 69.9 | 164 | 5 | 8.2 | 8.5 | 15.2 | 68.2 |
| | 15 | 16.7 | 14.9 | 13.0 | 55.4 | | 15 | 20.2 | 18.8 | 10.8 | 50.1 |
| | 30 | 29.7 | 24.7 | 8.8 | 36.7 | | 30 | 34.6 | 24.9 | 7.2 | 33.3 |
| | 50 | 40.8 | 31.6 | 5.5 | 22.1 | | 50 | 41.2 | 32.3 | 4.9 | 21.7 |
| | inf. | 46.2 | 34.5 | 3.9 | 15.4 | | inf. | 46.9 | 35.0 | 3.4 | 14.7 |

**Appendix Table B12** Cont'd

| Day | Depth (cm) | Gas concentrations | | | | Day | Depth (cm) | Gas concentrations | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | $\%CH_4$ | $\%CO_2$ | $\%O_2$ | $\%N_2$ | | | $\%CH_4$ | $\%CO_2$ | $\%O_2$ | $\%N_2$ |
| 168 | 5 | 9.6 | 10.3 | 14.4 | 65.7 | 184 | 5 | 8.5 | 11.0 | 14.5 | 66.1 |
| | 15 | 22.6 | 21.6 | 9.5 | 46.3 | | 15 | 21.0 | 22.5 | 9.6 | 46.9 |
| | 30 | 35.2 | 28.2 | 6.3 | 30.4 | | 30 | 35.5 | 25.7 | 6.7 | 32.1 |
| | 50 | 43.0 | 33.8 | 4.1 | 19.1 | | 50 | 42.2 | 34.0 | 4.2 | 19.6 |
| | inf. | 48.0 | 35.7 | 3.0 | 13.3 | | inf. | 49.2 | 35.1 | 2.9 | 12.8 |
| 172 | 5 | 8.7 | 10.9 | 14.4 | 65.9 | 188 | 5 | 8.7 | 10.8 | 14.5 | 66.1 |
| | 15 | 21.8 | 22.3 | 9.5 | 46.4 | | 15 | 21.5 | 20.0 | 9.9 | 48.6 |
| | 30 | 35.4 | 28.4 | 6.2 | 30.0 | | 30 | 35.4 | 28.2 | 6.2 | 30.1 |
| | 50 | 42.9 | 33.8 | 4.1 | 19.2 | | 50 | 41.8 | 35.5 | 4.0 | 18.7 |
| | inf. | 48.4 | 35.5 | 3.0 | 13.1 | | inf. | 49.1 | 34.6 | 3.0 | 13.3 |
| 176 | 5 | 8.8 | 10.9 | 14.4 | 65.8 | 192 | 5 | 8.9 | 10.9 | 14.4 | 65.8 |
| | 15 | 22.4 | 23.2 | 9.2 | 45.2 | | 15 | 21.8 | 22.3 | 9.5 | 46.4 |
| | 30 | 36.0 | 28.1 | 6.2 | 29.7 | | 30 | 36.0 | 28.1 | 6.2 | 29.7 |
| | 50 | 42.9 | 33.8 | 4.1 | 19.2 | | 50 | 42.9 | 33.9 | 4.1 | 19.1 |
| | inf. | 48.4 | 35.5 | 3.0 | 13.1 | | inf. | 48.5 | 35.4 | 3.0 | 13.1 |
| 180 | 5 | 9.8 | 10.8 | 14.3 | 65.2 | 200 | 5 | 9.2 | 10.9 | 14.4 | 65.6 |
| | 15 | 22.6 | 21.6 | 9.5 | 46.3 | | 15 | 22.6 | 22.0 | 9.4 | 45.9 |
| | 30 | 35.3 | 28.4 | 6.2 | 30.0 | | 30 | 37.4 | 27.5 | 6.0 | 29.1 |
| | 50 | 42.9 | 33.8 | 4.1 | 19.2 | | 50 | 42.9 | 34.2 | 4.0 | 18.8 |
| | inf. | 48.4 | 35.5 | 3.0 | 13.1 | | inf. | 48.4 | 35.5 | 3.0 | 13.1 |

**Appendix Table B13** Gas concentrations and MOR in non-vegetated compost column without irrigation

| Day | Depth (cm) | Gas concentrations | | | | Day | Depth (cm) | Gas concentrations | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | $\%CH_4$ | $\%CO_2$ | $\%O_2$ | $\%N_2$ | | | $\%CH_4$ | $\%CO_2$ | $\%O_2$ | $\%N_2$ |
| 0 | 5 | 3.3 | 5.6 | 15.7 | 75.4 | 30 | 5 | 8.1 | 8.0 | 15.8 | 68.1 |
| | 15 | 6.7 | 11.6 | 12.2 | 69.6 | | 15 | 18.4 | 17.2 | 11.9 | 52.5 |
| | 30 | 15.4 | 23.5 | 5.4 | 55.7 | | 30 | 31.2 | 27.0 | 7.5 | 34.3 |
| | 50 | 31.2 | 33.9 | 1.0 | 33.8 | | 50 | 41.4 | 33.1 | 4.6 | 20.8 |
| | inf. | 36.6 | 34.1 | 1.5 | 27.8 | | inf. | 47.2 | 35.1 | 3.4 | 14.3 |
| 3 | 5 | 7.3 | 7.5 | 15.9 | 69.3 | 38 | 5 | 8.2 | 8.1 | 15.8 | 67.9 |
| | 15 | 18.2 | 17.3 | 11.8 | 52.7 | | 15 | 19.5 | 18.1 | 11.6 | 50.8 |
| | 30 | 30.4 | 26.6 | 7.6 | 35.5 | | 30 | 32.1 | 27.4 | 7.4 | 33.0 |
| | 50 | 39.9 | 32.2 | 4.8 | 23.0 | | 50 | 42.3 | 33.4 | 4.4 | 19.9 |
| | inf. | 46.1 | 35.0 | 3.5 | 15.4 | | inf. | 48.6 | 36.0 | 3.0 | 12.5 |
| 10 | 5 | 7.8 | 8.0 | 15.8 | 68.4 | 46 | 5 | 7.6 | 7.6 | 16.0 | 68.9 |
| | 15 | 18.7 | 17.5 | 11.7 | 52.0 | | 15 | 18.3 | 17.2 | 12.0 | 52.5 |
| | 30 | 31.8 | 27.5 | 7.2 | 33.4 | | 30 | 30.9 | 27.0 | 7.7 | 34.5 |
| | 50 | 41.7 | 33.3 | 4.4 | 20.6 | | 50 | 41.1 | 33.0 | 4.7 | 21.2 |
| | inf. | 47.6 | 35.5 | 3.1 | 13.8 | | inf. | 46.5 | 35.3 | 3.5 | 14.8 |
| 22 | 5 | 7.5 | 7.6 | 15.9 | 69.0 | 58 | 5 | 8.7 | 8.5 | 15.7 | 67.1 |
| | 15 | 18.2 | 17.2 | 11.9 | 52.7 | | 15 | 19.8 | 17.9 | 11.6 | 50.7 |
| | 30 | 30.5 | 26.6 | 7.7 | 35.2 | | 30 | 32.9 | 27.5 | 7.3 | 32.3 |
| | 50 | 40.9 | 32.8 | 4.7 | 21.7 | | 50 | 43.5 | 33.6 | 4.3 | 18.6 |
| | inf. | 47.2 | 35.3 | 3.3 | 14.3 | | inf. | 48.8 | 35.4 | 3.2 | 12.6 |

**<u>Appendix Table B13</u>** Cont'd

| Day | Depth (cm) | Gas concentrations | | | | Day | Depth (cm) | Gas concentrations | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | $\%CH_4$ | $\%CO_2$ | $\%O_2$ | $\%N_2$ | | | $\%CH_4$ | $\%CO_2$ | $\%O_2$ | $\%N_2$ |
| 66 | 5 | 8.2 | 7.9 | 16.0 | 67.9 | 162 | 5 | 10.1 | 9.7 | 14.8 | 65.3 |
| | 15 | 18.7 | 17.1 | 12.1 | 52.2 | | 15 | 21.7 | 19.6 | 10.8 | 48.0 |
| | 30 | 32.0 | 27.0 | 7.6 | 33.4 | | 30 | 34.8 | 29.2 | 6.5 | 29.6 |
| | 50 | 41.9 | 32.9 | 4.7 | 20.5 | | 50 | 45.2 | 35.2 | 3.4 | 16.2 |
| | inf. | 48.5 | 35.8 | 3.1 | 12.5 | | inf. | 50.8 | 37.3 | 2.2 | 9.8 |
| 74 | 5 | 8.1 | 8.0 | 16.0 | 67.9 | 168 | 5 | 10.9 | 10.4 | 14.5 | 64.2 |
| | 15 | 19.0 | 17.4 | 12.0 | 51.5 | | 15 | 22.4 | 20.1 | 10.5 | 47.0 |
| | 30 | 32.4 | 27.4 | 7.5 | 32.7 | | 30 | 34.6 | 28.8 | 6.6 | 30.1 |
| | 50 | 42.7 | 33.3 | 4.6 | 19.4 | | 50 | 44.8 | 34.6 | 3.7 | 16.9 |
| | inf. | 48.4 | 35.5 | 3.2 | 12.9 | | inf. | 50.3 | 36.7 | 2.4 | 10.6 |
| 102 | 5 | 7.6 | 7.6 | 16.2 | 68.5 | 172 | 5 | 11.5 | 11.5 | 13.9 | 63.1 |
| | 15 | 18.3 | 17.2 | 12.3 | 52.3 | | 15 | 23.4 | 21.3 | 9.8 | 45.5 |
| | 30 | 31.5 | 27.1 | 7.8 | 33.6 | | 30 | 36.3 | 30.4 | 5.6 | 27.6 |
| | 50 | 42.2 | 33.6 | 4.6 | 19.6 | | 50 | 46.8 | 35.7 | 2.9 | 14.6 |
| | inf. | 47.7 | 35.5 | 3.5 | 13.4 | | inf. | 51.7 | 37.4 | 1.9 | 9.0 |
| 110 | 5 | 6.6 | 6.8 | 16.6 | 70.0 | 176 | 5 | 8.9 | 14.8 | 11.1 | 65.2 |
| | 15 | 16.9 | 16.0 | 12.7 | 54.4 | | 15 | 21.6 | 24.8 | 6.3 | 47.3 |
| | 30 | 29.4 | 25.6 | 8.5 | 36.5 | | 30 | 34.9 | 33.1 | 2.4 | 29.5 |
| | 50 | 40.7 | 32.9 | 5.1 | 21.4 | | 50 | 44.1 | 36.5 | 1.9 | 17.5 |
| | inf. | 46.8 | 35.2 | 3.6 | 14.4 | | inf. | 49.8 | 37.3 | 1.7 | 11.2 |
| 118 | 5 | 6.8 | 7.1 | 15.8 | 70.3 | 180 | 5 | 8.2 | 15.6 | 11.0 | 65.1 |
| | 15 | 17.7 | 16.8 | 11.8 | 53.7 | | 15 | 21.1 | 25.8 | 6.2 | 46.9 |
| | 30 | 31.2 | 27.2 | 7.2 | 34.4 | | 30 | 34.9 | 33.1 | 2.4 | 29.5 |
| | 50 | 41.4 | 33.2 | 4.3 | 21.1 | | 50 | 43.9 | 36.6 | 1.9 | 17.5 |
| | inf. | 48.6 | 36.3 | 2.5 | 12.5 | | inf. | 49.8 | 37.3 | 1.7 | 11.2 |
| 126 | 5 | 9.6 | 9.6 | 14.8 | 66.0 | 184 | 5 | 8.1 | 15.2 | 11.1 | 65.5 |
| | 15 | 20.6 | 18.8 | 10.9 | 49.7 | | 15 | 21.4 | 25.4 | 6.3 | 47.0 |
| | 30 | 34.1 | 28.8 | 6.5 | 30.6 | | 30 | 36.3 | 32.5 | 2.3 | 28.9 |
| | 50 | 44.0 | 34.3 | 3.7 | 18.1 | | 50 | 44.1 | 36.5 | 1.9 | 17.5 |
| | inf. | 48.5 | 35.7 | 2.7 | 13.1 | | inf. | 51.0 | 36.6 | 1.6 | 10.8 |
| 134 | 5 | 10.7 | 10.2 | 14.5 | 64.6 | 188 | 5 | 8.3 | 15.8 | 11.0 | 64.9 |
| | 15 | 22.3 | 20.0 | 10.4 | 47.3 | | 15 | 21.9 | 25.7 | 6.2 | 46.2 |
| | 30 | 36.1 | 29.9 | 6.0 | 28.0 | | 30 | 36.7 | 32.4 | 2.3 | 28.6 |
| | 50 | 46.2 | 35.1 | 3.2 | 15.5 | | 50 | 44.4 | 36.4 | 1.9 | 17.2 |
| | inf. | 51.2 | 37.1 | 2.0 | 9.7 | | inf. | 50.6 | 37.0 | 1.6 | 10.8 |
| 141 | 5 | 10.2 | 9.7 | 14.7 | 65.4 | 192 | 5 | 8.4 | 16.5 | 10.9 | 64.2 |
| | 15 | 21.7 | 19.4 | 10.7 | 48.2 | | 15 | 22.1 | 25.6 | 6.2 | 46.1 |
| | 30 | 34.8 | 29.0 | 6.5 | 29.8 | | 30 | 36.5 | 32.7 | 2.3 | 28.5 |
| | 50 | 45.2 | 35.0 | 3.4 | 16.3 | | 50 | 45.0 | 35.9 | 1.9 | 17.2 |
| | inf. | 50.6 | 37.1 | 2.2 | 10.1 | | inf. | 50.0 | 37.5 | 1.6 | 10.9 |
| 150 | 5 | 11.1 | 11.0 | 14.4 | 63.5 | 200 | 5 | 8.5 | 16.2 | 10.9 | 64.4 |
| | 15 | 23.4 | 20.6 | 10.4 | 45.6 | | 15 | 22.0 | 25.6 | 6.2 | 46.3 |
| | 30 | 37.4 | 30.2 | 5.9 | 26.5 | | 30 | 36.5 | 32.7 | 2.3 | 28.5 |
| | 50 | 46.1 | 34.9 | 3.5 | 15.6 | | 50 | 45.0 | 35.9 | 1.9 | 17.2 |
| | inf. | 52.7 | 37.2 | 2.0 | 8.1 | | inf. | 51.1 | 36.6 | 1.6 | 10.7 |

**Appendix Table B14** Gas concentrations and MOR in vegetated compost (*P. repens*) column without irrigation

| Day | Depth (cm) | Gas concentrations | | | | Day | Depth (cm) | Gas concentrations | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | %$CH_4$ | %$CO_2$ | %$O_2$ | %$N_2$ | | | %$CH_4$ | %$CO_2$ | %$O_2$ | %$N_2$ |
| 0 | 5 | 2.1 | 3.2 | 17.6 | 77.1 | 72 | 5 | 7.2 | 7.2 | 16.3 | 69.3 |
| | 15 | 4.3 | 6.3 | 16.2 | 73.3 | | 15 | 15.0 | 14.2 | 13.2 | 57.5 |
| | 30 | 8.6 | 10.8 | 14.1 | 66.6 | | 30 | 26.3 | 23.5 | 9.2 | 41.0 |
| | 50 | 15.5 | 16.0 | 11.7 | 56.9 | | 50 | 35.7 | 29.5 | 6.3 | 28.4 |
| | inf. | 25.1 | 22.4 | 9.0 | 43.4 | | inf. | 42.5 | 33.2 | 4.5 | 19.8 |
| 3 | 5 | 6.1 | 6.2 | 16.4 | 71.2 | 100 | 5 | 5.3 | 5.6 | 16.9 | 72.1 |
| | 15 | 14.6 | 14.1 | 13.1 | 58.1 | | 15 | 11.6 | 11.5 | 14.5 | 62.5 |
| | 30 | 26.0 | 23.3 | 9.0 | 41.6 | | 30 | 21.8 | 20.2 | 10.7 | 47.3 |
| | 50 | 35.7 | 29.8 | 6.1 | 28.5 | | 50 | 31.7 | 27.2 | 7.5 | 33.6 |
| | inf. | 44.1 | 34.4 | 3.9 | 17.6 | | inf. | 38.2 | 30.6 | 5.9 | 25.3 |
| 8 | 5 | 5.9 | 6.2 | 16.4 | 71.5 | 108 | 5 | 4.8 | 5.4 | 17.1 | 72.7 |
| | 15 | 13.8 | 13.6 | 13.3 | 59.4 | | 15 | 10.3 | 10.9 | 14.8 | 64.0 |
| | 30 | 24.4 | 22.4 | 9.4 | 43.9 | | 30 | 19.1 | 18.8 | 11.3 | 50.8 |
| | 50 | 34.7 | 29.5 | 6.2 | 29.6 | | 50 | 28.2 | 25.5 | 8.3 | 38.0 |
| | inf. | 42.0 | 33.4 | 4.3 | 20.3 | | inf. | 36.1 | 30.3 | 6.2 | 27.5 |
| 20 | 5 | 5.7 | 6.1 | 16.6 | 71.7 | 116 | 5 | 7.5 | 7.7 | 15.5 | 69.2 |
| | 15 | 13.7 | 13.5 | 13.3 | 59.5 | | 15 | 16.0 | 15.5 | 12.3 | 56.3 |
| | 30 | 24.9 | 22.8 | 9.2 | 43.1 | | 30 | 28.0 | 25.1 | 8.1 | 38.7 |
| | 50 | 35.0 | 29.8 | 6.0 | 29.2 | | 50 | 38.8 | 32.3 | 4.8 | 24.1 |
| | inf. | 41.6 | 33.2 | 4.5 | 20.7 | | inf. | 45.2 | 35.3 | 3.2 | 16.3 |
| 28 | 5 | 6.7 | 6.9 | 16.2 | 70.3 | 124 | 5 | 7.5 | 7.7 | 15.5 | 69.3 |
| | 15 | 13.6 | 13.3 | 13.5 | 59.7 | | 15 | 16.2 | 15.5 | 12.2 | 56.0 |
| | 30 | 24.5 | 22.3 | 9.5 | 43.7 | | 30 | 27.8 | 24.7 | 8.2 | 39.3 |
| | 50 | 34.4 | 29.2 | 6.4 | 30.1 | | 50 | 37.7 | 31.2 | 5.2 | 25.9 |
| | inf. | 41.0 | 32.6 | 4.7 | 21.7 | | inf. | 40.8 | 31.8 | 4.7 | 22.7 |
| 36 | 5 | 6.4 | 6.7 | 16.4 | 70.5 | 132 | 5 | 9.7 | 9.5 | 14.9 | 66.0 |
| | 15 | 13.6 | 13.3 | 13.5 | 59.6 | | 15 | 19.4 | 17.9 | 11.3 | 51.4 |
| | 30 | 24.9 | 22.8 | 9.4 | 43.0 | | 30 | 32.4 | 27.8 | 6.9 | 32.8 |
| | 50 | 34.5 | 29.4 | 6.4 | 29.7 | | 50 | 42.5 | 33.9 | 4.0 | 19.6 |
| | inf. | 41.5 | 33.1 | 4.5 | 20.8 | | inf. | 48.7 | 36.5 | 2.5 | 12.3 |
| 44 | 5 | 6.4 | 6.7 | 16.3 | 70.6 | 139 | 5 | 6.7 | 7.0 | 15.8 | 70.4 |
| | 15 | 13.7 | 13.5 | 13.5 | 59.3 | | 15 | 13.6 | 13.3 | 13.2 | 59.8 |
| | 30 | 24.4 | 22.4 | 9.5 | 43.7 | | 30 | 23.7 | 21.7 | 9.7 | 45.0 |
| | 50 | 34.5 | 29.4 | 6.3 | 29.7 | | 50 | 33.5 | 28.7 | 6.5 | 31.3 |
| | inf. | 41.4 | 33.1 | 4.5 | 21.0 | | inf. | 41.3 | 33.2 | 4.4 | 21.0 |
| 56 | 5 | 7.8 | 7.8 | 15.9 | 68.5 | 148 | 5 | 6.7 | 6.3 | 16.3 | 70.7 |
| | 15 | 16.3 | 15.2 | 12.8 | 55.7 | | 15 | 11.2 | 10.2 | 14.4 | 64.2 |
| | 30 | 29.0 | 25.1 | 8.5 | 37.5 | | 30 | 22.9 | 19.6 | 10.6 | 47.0 |
| | 50 | 39.0 | 31.4 | 5.4 | 24.2 | | 50 | 29.9 | 24.3 | 8.1 | 37.6 |
| | inf. | 45.2 | 34.3 | 3.9 | 16.7 | | inf. | 38.4 | 30.0 | 5.6 | 26.0 |
| 64 | 5 | 7.3 | 7.4 | 16.1 | 69.2 | 160 | 5 | 8.8 | 8.6 | 15.3 | 67.3 |
| | 15 | 14.9 | 14.2 | 13.2 | 57.7 | | 15 | 17.8 | 16.7 | 12.0 | 53.5 |
| | 30 | 26.0 | 23.1 | 9.3 | 41.5 | | 30 | 29.8 | 26.0 | 7.9 | 36.3 |
| | 50 | 36.0 | 29.8 | 6.2 | 28.0 | | 50 | 40.2 | 32.7 | 4.7 | 22.4 |
| | inf. | 42.6 | 33.3 | 4.4 | 19.7 | | inf. | 46.3 | 35.1 | 3.3 | 15.2 |

**<u>Appendix Table B12</u>** Cont'd

| Day | Depth (cm) | Gas concentrations | | | | Day | Depth (cm) | Gas concentrations | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | $\%CH_4$ | $\%CO_2$ | $\%O_2$ | $\%N_2$ | | | $\%CH_4$ | $\%CO_2$ | $\%O_2$ | $\%N_2$ |
| 166 | 5 | 9.6 | 9.4 | 15.0 | 66.1 | 182 | 5 | 6.6 | 13.6 | 13.8 | 66.0 |
| | 15 | 19.3 | 17.7 | 11.5 | 51.5 | | 15 | 19.0 | 23.6 | 8.6 | 48.7 |
| | 30 | 31.9 | 27.4 | 7.3 | 33.4 | | 30 | 33.4 | 29.2 | 3.9 | 33.5 |
| | 50 | 42.2 | 33.5 | 4.3 | 20.0 | | 50 | 42.5 | 32.4 | 2.6 | 22.5 |
| | inf. | 48.3 | 36.2 | 2.8 | 12.7 | | inf. | 49.8 | 36.3 | 2.3 | 11.6 |
| 170 | 5 | 9.3 | 9.3 | 15.0 | 66.4 | 186 | 5 | 6.3 | 13.4 | 13.9 | 66.4 |
| | 15 | 19.2 | 17.9 | 11.4 | 51.5 | | 15 | 19.0 | 23.9 | 8.6 | 48.5 |
| | 30 | 31.2 | 27.1 | 7.2 | 34.4 | | 30 | 33.2 | 29.8 | 3.8 | 33.2 |
| | 50 | 41.8 | 33.6 | 4.1 | 20.5 | | 50 | 42.4 | 32.6 | 2.6 | 22.4 |
| | inf. | 48.5 | 36.6 | 2.5 | 12.4 | | inf. | 49.7 | 36.5 | 2.3 | 11.5 |
| 174 | 5 | 7.3 | 13.1 | 13.8 | 65.8 | 190 | 5 | 6.2 | 13.5 | 13.9 | 66.4 |
| | 15 | 19.0 | 23.6 | 8.6 | 48.8 | | 15 | 19.1 | 23.5 | 8.6 | 48.7 |
| | 30 | 33.7 | 28.5 | 3.9 | 34.0 | | 30 | 33.0 | 30.2 | 3.8 | 33.0 |
| | 50 | 41.6 | 32.8 | 2.7 | 22.9 | | 50 | 42.7 | 32.5 | 2.6 | 22.2 |
| | inf. | 49.6 | 36.4 | 2.3 | 11.7 | | inf. | 49.6 | 36.6 | 2.3 | 11.5 |
| 178 | 5 | 6.5 | 14.1 | 13.8 | 65.6 | 198 | 5 | 6.6 | 13.4 | 13.9 | 66.1 |
| | 15 | 19.0 | 23.4 | 8.7 | 49.0 | | 15 | 19.2 | 23.5 | 8.6 | 48.7 |
| | 30 | 33.7 | 28.7 | 3.9 | 33.7 | | 30 | 33.2 | 30.2 | 3.8 | 32.8 |
| | 50 | 41.7 | 32.8 | 2.6 | 22.8 | | 50 | 42.8 | 32.4 | 2.6 | 22.2 |
| | inf. | 49.8 | 36.4 | 2.3 | 11.5 | | inf. | 49.9 | 36.2 | 2.3 | 11.5 |

# Appendix C

## Data of Landfill Cover Materials in Column Experiment

**Appendix Table C1** Physical properties of cover materials in non-vegetated column experiment with rainwater or leachate irrigation

| Experimental Conditions | pH (1:2.5) | | EC (1:2.5), dS/m | | CEC, $cmol_c/kg$ | | MC, %d.w. | | Bulk Density, $kg/m^3$ | |
|---|---|---|---|---|---|---|---|---|---|---|
| | Start | End[a] | Start | End[a] | Start | End[a] | Start | End[a] | Start | End[a] |
| Sandy Loam, | | | | | | | | | | |
| Rainwater irrigation | | | | | | | | | | |
| depth 0-5 cm | 7.30* | 7.53 | 0.24* | 0.21 | 4.8* | 8.9 | 15.2* | 18.9 | 1,236* | 1,280 |
| 5-15 cm | | 7.39 | | 0.17 | | 8.3 | | 23.0 | | 1,323 |
| 15-30 cm | | 7.46 | | 0.15 | | 7.6 | | 18.7 | | 1,287 |
| 30-50 cm | | 7.55 | | 0.12 | | 6.9 | | 18.7 | | 1,295 |
| 50-60 cm | | 7.70 | | 0.11 | | 7.6 | | 21.6 | | 1,315 |
| SL+Compost, | | | | | | | | | | |
| Rainwater irrigation | | | | | | | | | | |
| depth 0-5 cm | 6.86* | 6.88 | 3.40* | 0.88 | 11.8* | 17.1 | 24.2* | 55.2 | 830* | 1,087 |
| 5-15 cm | | 7.24 | | 0.83 | | 14.2 | | 48.8 | | 1,034 |
| 15-30 cm | | 7.60 | | 0.67 | | 14.3 | | 38.0 | | 944 |
| 30-50 cm | | 7.87 | | 0.71 | | 13.8 | | 38.5 | | 948 |
| 50-60 cm | | 8.01 | | 0.79 | | 13.1 | | 43.3 | | 989 |
| Compost, | | | | | | | | | | |
| Rainwater irrigation | | | | | | | | | | |
| depth 0-5 cm | 6.36* | 6.98 | 7.15* | 1.95 | 22.3* | 30.3 | 42.9* | 80.3 | 566* | 800 |
| 5-15 cm | | 6.82 | | 1.90 | | 25.4 | | 99.8 | | 945 |
| 15-30 cm | | 7.31 | | 1.46 | | 24.0 | | 84.3 | | 801 |
| 30-50 cm | | 8.00 | | 1.96 | | 23.7 | | 81.4 | | 818 |
| 50-60 cm | | 8.19 | | 2.27 | | 24.2 | | 85.4 | | 826 |

**Appendix Table C1** Cont'd

| Experimental Conditions | pH (1:2.5) | | EC (1:2.5), dS/m | | CEC, $cmol_c/kg$ | | MC, %d.w. | | Bulk Density, $kg/m^3$ | |
|---|---|---|---|---|---|---|---|---|---|---|
| | Start | End[a] | Start | End[a] | Start | End[a] | Start | End[a] | Start | End[a] |
| Sandy Loam, Leachate irrigation | | | | | | | | | | |
| depth 0-5 cm | 7.30* | 7.18 | 0.24* | 0.96 | 4.8* | 8.9 | 13.8* | 19.4 | 1,264* | 1,335 |
| 5-15 cm | | 8.06 | | 0.82 | | 6.7 | | 24.3 | | 1,397 |
| 15-30 cm | | 8.36 | | 0.51 | | 5.7 | | 19.2 | | 1,345 |
| 30-50 cm | | 8.36 | | 0.51 | | 7.3 | | 18.6 | | 1,353 |
| 50-60 cm | | 8.32 | | 0.42 | | 6.5 | | 18.0 | | 1,347 |
| SL+Compost, Leachate irrigation | | | | | | | | | | |
| depth 0-5 cm | 6.86* | 7.16 | 3.40* | 2.84 | 11.8* | 16.3 | 25.9* | 32.3 | 774* | 880 |
| 5-15 cm | | 6.81 | | 2.37 | | 14.1 | | 52.8 | | 982 |
| 15-30 cm | | 7.35 | | 1.27 | | 12.2 | | 41.8 | | 934 |
| 30-50 cm | | 7.51 | | 1.22 | | 13.0 | | 40.8 | | 945 |
| 50-60 cm | | 7.59 | | 1.19 | | 12.4 | | 44.1 | | 954 |
| Compost, Leachate irrigation | | | | | | | | | | |
| depth 0-5 cm | 6.36* | 7.21 | 7.15* | 4.75 | 22.3* | 29.0 | 60.5* | 101.0 | 566* | 918 |
| 5-15 cm | | 6.89 | | 4.46 | | 31.5 | | 123.3 | | 1,006 |
| 15-30 cm | | 7.18 | | 3.50 | | 27.3 | | 103.3 | | 833 |
| 30-50 cm | | 7.31 | | 3.33 | | 26.9 | | 103.2 | | 856 |
| 50-60 cm | | 7.36 | | 3.62 | | 26.5 | | 116.1 | | 909 |

Note: *At total depth

[a] End of the experiment with rainwater irrigation are day 224, 144 and 224 in SL, SL+C and C, respectively

End of the experiment with leachate irrigation is day 308 in all three types of materials

**Appendix Table C2** Chemical properties of cover materials in non-vegetated column experiment with rainwater or leachate irrigation

| Experimental Conditions | Org-C, % | | | TN, mg/kg | | | $NH_4^+$-N, mg/kg | | | $NO_3^-$-N, mg/kg | | | AP, mg/kg | | AK, mg/kg | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Start | During[a] | End[b] | Start | During[a] | End[b] | Start | During[a] | End[b] | Start | During[a] | End[b] | Start | End[b] | Start | End[b] |
| Sandy Loam, Rainwater irrigation | | | | | | | | | | | | | | | | |
| depth 0-5 cm | 0.61* | 0.59 | 1.36 | 1,880* | 912 | 1,262 | 13.3* | 11.5 | n.d. | 16.9* | 1.0 | 0.2 | 8* | 5 | 39* | 52 |
| 5-15 cm | | 0.74 | 1.48 | | 1,263 | 1,159 | | 9.8 | 1.1 | | 0.6 | 3.6 | | 7 | | 39 |
| 15-30 cm | | - | 0.99 | | - | 1,262 | | - | 16.8 | | - | 1.4 | | 6 | | 47 |
| 30-50 cm | | - | 0.97 | | - | 1,268 | | - | 7.7 | | - | 0.7 | | 5 | | 47 |
| 50-60 cm | | - | 0.84 | | - | 1,039 | | - | 6.2 | | - | 0.3 | | 6 | | 55 |
| SL+Compost, Rainwater irrigation | | | | | | | | | | | | | | | | |
| depth 0-5 cm | 6.65* | 7.20 | 6.48 | 4,728* | 4,416 | 7,020 | 26.8* | 29.6 | n.d. | 132.2* | 1.0 | 78.3 | 2,655* | 1,760 | 2,195* | 940 |
| 5-15 cm | | 7.48 | 5.17 | | 5,014 | 4,729 | | 35.3 | 143.1 | | 1.8 | 39.4 | | 1,808 | | 795 |
| 15-30 cm | | - | 5.31 | | - | 3,992 | | - | 134.2 | | - | 9.6 | | 2,112 | | 1,130 |
| 30-50 cm | | - | 6.12 | | - | 3,597 | | - | 62.5 | | - | 2.4 | | 2,200 | | 1,500 |
| 50-60 cm | | - | 6.57 | | - | 3,012 | | - | 34.8 | | - | 1.5 | | 2,311 | | 1,415 |
| Compost, Rainwater irrigation | | | | | | | | | | | | | | | | |
| depth 0-5 cm | 12.22* | 10.00 | 7.28 | 9,645* | 8,704 | 9,952 | 34.1* | 39.1 | 17.6 | 120.4* | 0.8 | 41.2 | 5,845* | 4,286 | 5,780* | 1,730 |
| 5-15 cm | | 8.36 | 7.95 | | 2,609 | 9,069 | | 40.9 | 64.1 | | 1.0 | 74.0 | | 5,260 | | 1,620 |
| 15-30 cm | | - | 8.83 | | - | 8,533 | | - | 139.0 | | - | 20.8 | | 5,452 | | 2,220 |
| 30-50 cm | | - | 8.65 | | - | 8,201 | | - | 86.4 | | - | 5.0 | | 5,131 | | 3,560 |
| 50-60 cm | | - | 8.08 | | - | 7,083 | | - | 46.7 | | - | 5.5 | | 4,767 | | 4,125 |

**Appendix Table C2** Cont'd

| Experimental Conditions | Org-C, % | | | TN, mg/kg | | | $NH_4^+$-N, mg/kg | | | $NO_3^-$-N, mg/kg | | | AP, mg/kg | | AK, mg/kg | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Start | During[a] | End[b] | Start | During[a] | End[b] | Start | During[a] | End[b] | Start | During[a] | End[b] | Start | End[b] | Start | End[b] |
| Sandy Loam, Leachate irrigation | | | | | | | | | | | | | | | | |
| depth 0-5 cm | 0.61* | 0.54 | 1.65 | 1,880* | 1,395 | 1,270 | 13.3* | 12.2 | n.d. | 16.9* | 9.2 | 56.2 | 8* | 11 | 39* | 1,100 |
| 5-15 cm | | 0.86 | 1.54 | | 1,342 | 1,225 | | 8.8 | 46.0 | | 1.1 | 9.8 | | 7 | | 920 |
| 15-30 cm | | - | 0.95 | | - | 914 | | - | 109.3 | | - | 1.1 | | 8 | | 645 |
| 30-50 cm | | - | 0.80 | | - | 791 | | - | 102.9 | | - | 0.7 | | 7 | | 438 |
| 50-60 cm | | - | 0.68 | | - | 1,025 | | - | 127.4 | | - | 0.4 | | 7 | | 350 |
| SL+Compost, Leachate irrigation | | | | | | | | | | | | | | | | |
| depth 0-5 cm | 6.65* | 6.08 | 7.03 | 4,728* | 5,547 | 6,637 | 26.8* | 52.3 | n.d. | 132.2* | 22.9 | 116.1 | 2,655* | 1,878 | 2,195* | 2,150 |
| 5-15 cm | | 7.28 | 6.08 | | 1,094 | 5,485 | | 55.7 | 44.5 | | 2.6 | 126.2 | | 2,216 | | 1,450 |
| 15-30 cm | | - | 6.00 | | - | 4,432 | | - | 117.6 | | - | 49.6 | | 2,882 | | 1,180 |
| 30-50 cm | | - | 6.48 | | - | 4,598 | | - | 109.4 | | - | 25.3 | | 2,679 | | 1,250 |
| 50-60 cm | | - | 5.22 | | - | 4,124 | | - | 63.7 | | - | 24.6 | | 2,983 | | 1,290 |
| Compost, Leachate irrigation | | | | | | | | | | | | | | | | |
| depth 0-5 cm | 12.22* | 14.17 | 8.48 | 9,645* | 8,386 | 13,058 | 34.1* | 14.2 | n.d. | 120.4* | 9.1 | 121.6 | 5,845* | 4,362 | 5,780* | 3,740 |
| 5-15 cm | | 8.81 | 8.31 | | 10,758 | 13,446 | | 20.1 | 45.6 | | 0.6 | 121.8 | | 4,440 | | 3,260 |
| 15-30 cm | | - | 8.77 | | - | 9,615 | | - | 183.3 | | - | 73.1 | | 4,956 | | 2,900 |
| 30-50 cm | | - | 7.85 | | - | 10,368 | | - | 158.0 | | - | 41.1 | | 4,912 | | 3,120 |
| 50-60 cm | | - | 8.37 | | - | 9,581 | | - | 135.5 | | - | 33.1 | | 4,905 | | 3,480 |

Note: *At total depth

[a] During the period of the experiment with rainwater irrigation are day 120, 40 and 120 in SL, SL+C and C, respectively
During the period of the experiment with leachate irrigation is day 204 in all three types of materials

[b] End of the experiment with rainwater irrigation are day 224, 144 and 224 in SL, SL+C and C, respectively
End of the experiment with leachate irrigation is day 308 in all three types of materials

**Appendix Table C3** Physical properties of cover materials in vegetated column experiment with rainwater or leachate irrigation

| Experimental Conditions | pH (1:2.5) | | EC (1:2.5), dS/m | | CEC, $cmol_c/kg$ | | MC, %d.w. | | Bulk Density, $kg/m^3$ | |
|---|---|---|---|---|---|---|---|---|---|---|
| | Start | End[a] | Start | End[a] | Start | End[a] | Start | End[a] | Start | End[a] |
| Compost, Rainwater irrigation | | | | | | | | | | |
| depth 0-5 cm | 6.07* | 7.33 | 6.45* | 1.12 | 21.2* | 28.0 | 45.3* | 80.3 | 613* | 867 |
| 5-15 cm | | 6.66 | | 2.05 | | 23.1 | | 88.9 | | 912 |
| 15-30 cm | | 6.61 | | 1.50 | | 21.3 | | 74.7 | | 831 |
| 30-50 cm | | 6.94 | | 1.63 | | 21.1 | | 74.7 | | 827 |
| 50-60 cm | | 7.74 | | 1.40 | | 17.6 | | 82.1 | | 898 |
| C with *S. virginicus*, Rainwater irrigation | | | | | | | | | | |
| depth 0-5 cm | 6.07* | 6.82 | 6.45* | 2.91 | 21.2* | 24.1 | 45.3* | 68.4 | 642* | 790 |
| 5-15 cm | | 6.91 | | 1.90 | | 20.4 | | 96.6 | | 957 |
| 15-30 cm | | 6.87 | | 1.63 | | 20.2 | | 74.7 | | 816 |
| 30-50 cm | | 6.91 | | 2.46 | | 20.5 | | 77.1 | | 821 |
| 50-60 cm | | 7.09 | | 1.97 | | 20.0 | | 89.5 | | 905 |
| C with *P. repens*, Rainwater irrigation | | | | | | | | | | |
| depth 0-5 cm | 6.07* | 7.01 | 6.45* | 2.26 | 21.2* | 34.9 | 45.3* | 13.9 | 623* | 444 |
| 5-15 cm | | 7.28 | | 2.38 | | 42.5 | | 48.3 | | 565 |
| 15-30 cm | | 6.87 | | 1.58 | | 24.1 | | 84.3 | | 830 |
| 30-50 cm | | 6.92 | | 1.36 | | 22.9 | | 82.1 | | 857 |
| 50-60 cm | | 7.28 | | 1.41 | | 21.3 | | 90.0 | | 902 |

**<u>Appendix Table C3</u>** Cont'd

| Experimental Conditions | pH (1:2.5) | | EC (1:2.5), dS/m | | CEC, $cmol_c/kg$ | | MC, %d.w. | | Bulk Density, $kg/m^3$ | |
|---|---|---|---|---|---|---|---|---|---|---|
| | Start | End[a] | Start | End[a] | Start | End[a] | Start | End[a] | Start | End[a] |
| Compost, Leachate irrigation | | | | | | | | | | |
| depth 0-5 cm | 6.04* | 6.21 | 6.48* | 12.05 | 22.9* | 26.0 | 51.1* | 88.3 | 623* | 900 |
| 5-15 cm | | 5.80 | | 7.09 | | 23.8 | | 90.7 | | 919 |
| 15-30 cm | | 6.04 | | 5.10 | | 23.1 | | 86.3 | | 891 |
| 30-50 cm | | 6.16 | | 4.91 | | 23.2 | | 87.8 | | 901 |
| 50-60 cm | | 6.39 | | 5.87 | | 22.6 | | 90.4 | | 917 |
| C with *S. virginicus*, Leachate irrigation | | | | | | | | | | |
| depth 0-5 cm | 6.04* | 7.10 | 6.48* | 7.58 | 22.9* | 31.3 | 51.1* | 20.2 | 632* | 578 |
| 5-15 cm | | 7.10 | | 7.15 | | 32.0 | | 85.4 | | 814 |
| 15-30 cm | | 7.03 | | 4.71 | | 22.6 | | 85.7 | | 830 |
| 30-50 cm | | 7.20 | | 4.78 | | 22.8 | | 80.1 | | 791 |
| 50-60 cm | | 7.39 | | 5.42 | | 21.9 | | 90.4 | | 905 |
| C with *P. repens*, Leachate irrigation | | | | | | | | | | |
| depth 0-5 cm | 6.04* | 6.98 | 6.48* | 7.67 | 22.9* | 25.7 | 51.1* | 83.0 | 632* | 829 |
| 5-15 cm | | 7.06 | | 6.63 | | 23.0 | | 81.5 | | 816 |
| 15-30 cm | | 7.12 | | 5.29 | | 22.0 | | 78.3 | | 802 |
| 30-50 cm | | 7.14 | | 4.88 | | 22.6 | | 78.2 | | 800 |
| 50-60 cm | | 7.24 | | 5.32 | | 21.3 | | 99.3 | | 927 |

Note: *At total depth

[a] End of the experiment with rainwater irrigation are day 224, 388 and 472 in C, C+*S. virginicus* and C+*P. repens*, respectively

End of the experiment with leachate irrigation are day 308, 472 and 324 in C, C+*S. virginicus* and C+*P. repens*, respectively

**Appendix Table C4** Chemical properties of cover materials in vegetated column experiment with rainwater or leachate irrigation

| Experimental Conditions | Org-C, % | | TN, mg/kg | | $NH_4^+$-N, mg/kg | | $NO_3^-$-N, mg/kg | | AP, mg/kg | | AK, mg/kg | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Start | End[a] | Start | End[a] | Start | End[a] | Start | Start | End[a] | Start | End[a] | End[a] |
| Compost, | | | | | | | | | | | | |
| Rainwater irrigation | | | | | | | | | | | | |
| depth 0-5 cm | 16.62* | 8.05 | 9,113* | 10,367 | 34.1* | 17.6 | 125.1* | 41.2 | 4,283* | 3,527 | 3,740* | 2,040 |
| 5-15 cm | | 7.98 | | 10,103 | | 64.1 | | 74.0 | | 3,883 | | 1,370 |
| 15-30 cm | | 7.57 | | 6,552 | | 139.0 | | 20.8 | | 4,281 | | 1,758 |
| 30-50 cm | | 7.88 | | 7,440 | | 86.4 | | 5.0 | | 4,486 | | 2,460 |
| 50-60 cm | | 8.19 | | 8,660 | | 46.7 | | 5.5 | | 3,987 | | 2,560 |
| C with *S. virginicus*, | | | | | | | | | | | | |
| Rainwater irrigation | | | | | | | | | | | | |
| depth 0-5 cm | 16.62* | 9.55 | 9,113* | 13,591 | 34.1* | 13.3 | 125.1* | 143.9 | 4,283* | 2,986 | 3,740* | 1,355 |
| 5-15 cm | | 8.76 | | 9,032 | | 59.3 | | 125.8 | | 2,894 | | 995 |
| 15-30 cm | | 8.81 | | 7,452 | | 86.7 | | 39.4 | | 3,857 | | 1,270 |
| 30-50 cm | | 8.97 | | 8,255 | | 134.5 | | 56.6 | | 4,189 | | 1,760 |
| 50-60 cm | | 8.97 | | 8,804 | | 91.5 | | 41.9 | | 4,068 | | 2,020 |
| C with *P. repens*, | | | | | | | | | | | | |
| Rainwater irrigation | | | | | | | | | | | | |
| depth 0-5 cm | 16.62* | 9.27 | 9,113* | 14,477 | 34.1* | 8.3 | 125.1* | 63.0 | 4,283* | 3,419 | 3,740* | 1,185 |
| 5-15 cm | | 9.56 | | 16,549 | | 9.4 | | 4.9 | | 2,892 | | 1,185 |
| 15-30 cm | | 8.66 | | 8,712 | | 45.1 | | 98.4 | | 4,004 | | 695 |
| 30-50 cm | | 8.87 | | 7,757 | | 232.1 | | 67.7 | | 3,902 | | 1,285 |
| 50-60 cm | | 8.99 | | 7,386 | | 439.3 | | 11.8 | | 3,858 | | 1,660 |

**<u>Appendix Table C4</u>** Cont'd

| Experimental Conditions | Org-C, % | | TN, mg/kg | | $NH_4^+$-N, mg/kg | | $NO_3^-$-N, mg/kg | | AP, mg/kg | | AK, mg/kg | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Start | End[a] | Start | End[a] | Start | End[a] | Start | Start | End[a] | Start | End[a] | End[a] |
| Compost, Leachate irrigation | | | | | | | | | | | | |
| depth 0-5 cm | 12.87* | 8.14 | 10,549* | 14,967 | 35.4* | n.d. | 123.9* | 121.6 | 4,311* | 4,063 | 3,880* | 5,000 |
| 5-15 cm | | 8.27 | | 12,539 | | 45.6 | | 121.8 | | 4,436 | | 2,950 |
| 15-30 cm | | 7.99 | | 6,741 | | 183.3 | | 73.1 | | 4,591 | | 3,275 |
| 30-50 cm | | 7.97 | | 7,160 | | 158.0 | | 41.1 | | 4,517 | | 3,925 |
| 50-60 cm | | 8.10 | | 6,672 | | 135.5 | | 33.1 | | 4,362 | | 4,300 |
| C with *S. virginicus*, Leachate irrigation | | | | | | | | | | | | |
| depth 0-5 cm | 12.87* | 9.55 | 10,549* | 13,237 | 35.4* | 111.5 | 123.9* | 103.6 | 4,311* | 3,498 | 3,880* | 2,970 |
| 5-15 cm | | 9.17 | | 11,117 | | 161.4 | | 82.9 | | 2,962 | | 2,720 |
| 15-30 cm | | 8.61 | | 8,084 | | 179.5 | | 100.3 | | 3,767 | | 2,100 |
| 30-50 cm | | 8.82 | | 8,403 | | 293.8 | | 40.0 | | 4,048 | | 1,740 |
| 50-60 cm | | 8.73 | | 9,131 | | 290.3 | | 16.1 | | 4,169 | | 2,030 |
| C with *P. repens*, Leachate irrigation | | | | | | | | | | | | |
| depth 0-5 cm | 12.87* | 8.67 | 10,549* | 11,216 | 35.4* | 32.1 | 123.9* | 154.6 | 4,311* | 3,273 | 3,880* | 2,960 |
| 5-15 cm | | 8.72 | | 14,581 | | 166.0 | | 139.0 | | 3,099 | | 2,570 |
| 15-30 cm | | 8.75 | | 8,471 | | 275.0 | | 54.1 | | 4,011 | | 2,320 |
| 30-50 cm | | 8.68 | | 8,357 | | 205.3 | | 58.7 | | 4,185 | | 2,462 |
| 50-60 cm | | 8.66 | | 7,841 | | 148.1 | | 48.5 | | 3,923 | | 2,700 |

Note: *At total depth

[a] End of the experiment with rainwater irrigation are day 224, 388 and 472 in C, C+*S. virginicus* and C+*P. repens*, respectively

End of the experiment with leachate irrigation are day 308, 472 and 324 in C, C+*S. virginicus* and C+*P. repens*, respectively

**<u>Appendix Table C5</u>** Physical properties of cover materials in non-vegetated and vegetated column experiments without irrigation

| Experimental Conditions | pH (1:2.5) | | EC (1:2.5), dS/m | | CEC, $cmol_c/kg$ | | MC, %d.w. | | Bulk Density, $kg/m^3$ | |
|---|---|---|---|---|---|---|---|---|---|---|
| | Start | End[a] | Start | End[a] | Start | End[a] | Start | End[a] | Start | End[a] |
| Sandy Loam, No irrigation | | | | | | | | | | |
| depth 0-5 cm | 7.09* | 7.08 | 0.31* | 0.20 | 9.3* | 8.1 | 13.8* | 1.4 | 1,057* | 926 |
| 5-15 cm | | 7.24 | | 0.13 | | 9.4 | | 3.7 | | 950 |
| 15-30 cm | | 7.17 | | 0.15 | | 11.7 | | 10.0 | | 1,017 |
| 30-50 cm | | 7.15 | | 0.18 | | 8.7 | | 16.4 | | 1,127 |
| 50-60 cm | | 7.24 | | 0.18 | | 8.1 | | 14.7 | | 1,121 |
| SL with *P. repens*, No irrigation | | | | | | | | | | |
| depth 0-5 cm | 7.41* | 7.65 | 0.24* | 0.21 | 7.1* | 8.2 | 14.5* | 11.2 | 1,264* | 1,243 |
| 5-15 cm | | 7.65 | | 0.18 | | 8.0 | | 13.4 | | 1,412 |
| 15-30 cm | | 7.65 | | 0.17 | | 7.6 | | 11.1 | | 1,318 |
| 30-50 cm | | 7.54 | | 0.19 | | 6.5 | | 15.3 | | 1,497 |
| 50-60 cm | | 7.66 | | 0.22 | | 7.6 | | 12.0 | | 904 |
| Compost, No irrigation | | | | | | | | | | |
| depth 0-5 cm | 6.03* | 6.17 | 12.52* | 11.82 | 19.0* | 20.8 | 34.4* | 29.8 | 679* | 1,130 |
| 5-15 cm | | 6.17 | | 13.76 | | 20.9 | | 26.5 | | 791 |
| 15-30 cm | | 6.03 | | 11.33 | | 19.5 | | 33.7 | | 753 |
| 30-50 cm | | 6.01 | | 14.02 | | 20.5 | | 42.5 | | 678 |
| 50-60 cm | | 6.00 | | 12.80 | | 19.8 | | 43.0 | | 847 |
| C with *P. repens*, No irrigation | | | | | | | | | | |
| depth 0-5 cm | 6.03* | 6.06 | 12.52* | 13.31 | 19.0* | 21.2 | 34.4* | 17.3 | 698* | 1,243 |
| 5-15 cm | | 6.17 | | 8.49 | | 22.3 | | 22.2 | | 791 |
| 15-30 cm | | 5.88 | | 13.52 | | 20.1 | | 33.6 | | 753 |
| 30-50 cm | | 6.04 | | 11.70 | | 22.3 | | 41.7 | | 678 |
| 50-60 cm | | 6.60 | | 12.40 | | 18.5 | | 45.0 | | 847 |

Note: *At total depth

[a] End of the experiment without irrigation are day 289, 200, 200 and 198 in SL, SL+*P. repens*, C and C+*P. repens*, respectively

**Appendix Table C6** Chemical properties of cover materials in non-vegetated and vegetated column experiments without irrigation

| Experimental Conditions | Org-C, % | | TN, mg/kg | | $NH_4^+$-N, mg/kg | | $NO_3^-$-N, mg/kg | | AP, mg/kg | | AK, mg/kg | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Start | End[a] | Start | End[a] | Start | End[a] | Start | End[a] | Start | End[a] | Start | End[a] |
| Sandy Loam, No irrigation | | | | | | | | | | | | |
| depth 0-5 cm | 0.52* | 0.54 | 989* | 1,518 | 13.3* | 25.4 | 40.9* | 7.3 | 18* | 31 | 56* | 53 |
| 5-15 cm | | 0.68 | | 1,948 | | 26.2 | | n.d. | | 16 | | 56 |
| 15-30 cm | | 1.66 | | 2,275 | | 27.3 | | n.d. | | 9 | | 54 |
| 30-50 cm | | 1.30 | | 2,105 | | 24.6 | | 0.9 | | 8 | | 54 |
| 50-60 cm | | 0.53 | | 1,741 | | 17.1 | | 9.0 | | 7 | | 55 |
| SL with *P. repens*, No irrigation | | | | | | | | | | | | |
| depth 0-5 cm | 0.36* | 0.67 | 1,071* | 1,191 | 25.0* | 22.5 | 2.0* | 7.4 | 9* | 23 | 42* | 68 |
| 5-15 cm | | 0.71 | | 868 | | 19.0 | | 2.3 | | 11 | | 56 |
| 15-30 cm | | 0.60 | | 1,105 | | 26.0 | | 0.8 | | 10 | | 46 |
| 30-50 cm | | 0.72 | | 1,268 | | 28.5 | | 0.7 | | 6 | | 43 |
| 50-60 cm | | 0.72 | | 1,054 | | 23.7 | | 2.9 | | 8 | | 54 |
| Compost, No irrigation | | | | | | | | | | | | |
| depth 0-5 cm | 8.62* | 8.42 | 8,183* | 7,973 | 51.9* | 166.5 | 122.9* | 164.2 | 4,739* | 4,913 | 3,300* | 3,810 |
| 5-15 cm | | 7.67 | | 10,160 | | 224.9 | | 165.6 | | 4,951 | | 3,600 |
| 15-30 cm | | 7.01 | | 5,182 | | 183.1 | | 164.8 | | 4,353 | | 4,335 |
| 30-50 cm | | 6.61 | | 6,644 | | 210.7 | | 165.3 | | 4,822 | | 3,810 |
| 50-60 cm | | 6.93 | | 5,888 | | 191.0 | | 164.9 | | 4,568 | | 4,005 |
| C with *P. repens*, No irrigation | | | | | | | | | | | | |
| depth 0-5 cm | 8.62* | 7.55 | 8,183* | 7,447 | 51.9* | 160.7 | 122.9* | 164.0 | 4,739* | 4,398 | 3,300* | 3,405 |
| 5-15 cm | | 7.66 | | 7,930 | | 164.0 | | 166.7 | | 4,499 | | 2,865 |
| 15-30 cm | | 6.43 | | 6,265 | | 146.7 | | 164.5 | | 4,349 | | 4,305 |
| 30-50 cm | | 5.42 | | 6,127 | | 144.4 | | 165.7 | | 4,705 | | 3,990 |
| 50-60 cm | | 6.49 | | 6,258 | | 151.7 | | 165.2 | | 4,829 | | 4,230 |

Note: *At total depth

[a] End of the experiment without irrigation are day 289, 200, 200 and 198 in SL, SL+*P. repens*, C and C+*P. repens*, respectively

**<u>Appendix Table C7</u>** EPS contents (expressed as mg C/g dry soil) at the end of column experiments with and without irrigation

| | Rainwater irrigation | | | | | Leachate irrigation | | | | | No irrigation | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | SL | SL+C | C | C with *S. virginicus* | C with *P. repens* | SL | SL+C | C | C with *S. virginicus* | C with *P. repens* | SL | SL with *P. repens* | C | C with *P. repens* |
| EPS, mg/g | | | | | | | | | | | | | | |
| depth 0-5 cm | 2.7 | 9.2 | 18.7 | 14.1 | 18.6 | 3.4 | 12.5 | 14.2 | 13.4 | 14.5 | 2.0 | 1.0 | 8.6 | 10.2 |
| 5-15 cm | 2.3 | 7.9 | 10.9 | 8.8 | 15.6 | 2.3 | 6.6 | 15.0 | 12.1 | 17.9 | 2.2 | 1.5 | 8.5 | 7.5 |
| 15-30 cm | 2.1 | 6.7 | 9.7 | 7.5 | 6.5 | 1.7 | 4.4 | 11.0 | 8.2 | 9.4 | 2.5 | 1.9 | 6.5 | 7.6 |
| 30-50 cm | 1.9 | 6.9 | 12.7 | 7.6 | 6.4 | 1.4 | 5.0 | 11.1 | 8.6 | 9.9 | 4.8 | 1.9 | 8.0 | 7.3 |
| 50-60 cm | 1.6 | 6.7 | 9.7 | 7.9 | 7.8 | 1.3 | 3.9 | 11.0 | 9.6 | 9.6 | 2.9 | 1.9 | 6.7 | 7.2 |

# Appendix D

## Data of Plant Growth in Column Experiment

**Appendix Table D1** Growth of *S. virginicus* and *P. repens* in vegetated compost columns with rainwater irrigation

| Day | *S. virginicus* in compost (rainwater) | | | | | *P. repens* in compost (rainwater) | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | Number of shoots | Grass height (cm) | Number of leaves | Leaf width (cm) | Leaf length (cm) | Number of shoots | Grass height (cm) | Number of leaves | Leaf width (cm) | Leaf length (cm) |
| 0 | 7 | 18.0 | 35 | 0.5 | 8.0 | 6 | 18.0 | 14 | 0.6 | 8.5 |
| 6 | 7 | 26.0 | 35 | 0.5 | 8.0 | 6 | 29.0 | 14 | 0.6 | 8.5 |
| 20 | 5 | 35.5 | 43 | 0.6 | 9.5 | 6 | 38.0 | 12 | 0.6 | 9.5 |
| 22[a1] | 5 | 20.0 | 18 | 0.6 | 9.0 | 6 | 20.0 | 5 | 0.6 | 9.0 |
| 29 | 4 | 23.0 | 23 | 0.4 | 9.5 | 3 | 39.0 | 9 | 0.5 | 8.0 |
| 37 | 4 | 23.0 | 6 | 0.3 | 10.0 | 3 | 41.5 | 12 | 0.3 | 14.0 |
| 55 | 2 | 27.5 | 2 | 0.2 | 7.0 | 2 | 59.0 | 24 | 0.3 | 13.0 |
| 61 | 2 | 31.0 | 8 | 0.2 | 9.0 | 3 | 60.0 | 29 | 0.6 | 20.5 |
| 62[b1] | 6 | 29.0 | 83 | 0.3 | 9.0 | 6 | 60.0 | 38 | 0.4 | 10.0 |
| 83[b2] | 7 | 51.0 | 97 | 0.3 | 16.0 | 6 | 65.0 | 35 | 0.5 | 22.0 |
| 99 | 6 | 50.0 | 27 | 0.3 | 15.0 | 7 | 65.0 | 46 | 0.3 | 13.0 |
| 115 | 6 | 50.0 | 25 | 0.3 | 15.0 | 7 | 65.0 | 48 | 0.4 | 15.0 |
| 125 | 6 | 50.0 | 15 | 0.3 | 14.5 | 7 | 64.5 | 52 | 0.4 | 16.0 |
| 140 | 6 | 50.0 | 8 | 0.3 | 15.0 | 8 | 64.0 | 57 | 0.4 | 19.0 |
| 157 | 6 | 50.0 | 7 | 0.3 | 15.0 | 8 | 63.5 | 63 | 0.3 | 20.0 |
| 168 | 5 | 50.0 | 4 | 0.3 | 7.0 | 8 | 67.0 | 70 | 0.3 | 20.0 |
| 182 | 5 | 50.0 | 3 | 0.3 | 7.0 | 7 | 70.5 | 84 | 0.3 | 20.0 |
| 193 | 2 | 50.0 | 2 | 0.3 | 5.0 | 7 | 75.0 | 96 | 0.3 | 20.0 |
| 211 | 0 | 50.0 | 0 | 0.0 | 0.0 | 7 | 77.0 | 102 | 0.4 | 20.5 |
| 216[b2] | 7 | 30.0 | 74 | 0.3 | 8.0 | 7 | 77.0 | 102 | 0.4 | 20.5 |
| 230 | 5 | 30.0 | 41 | 0.3 | 8.0 | 7 | 80.0 | 100 | 0.4 | 21.0 |
| 255 | 3 | 30.0 | 18 | 0.2 | 7.0 | 7 | 82.0 | 95 | 0.4 | 21.0 |
| 270 | 1 | 30.0 | 10 | 0.2 | 7.0 | 6 | 83.0 | 82 | 0.5 | 21.0 |
| 300 | 1 | 30.0 | 5 | 0.2 | 7.0 | 6 | 85.0 | 75 | 0.5 | 21.0 |
| 324 | 1 | 30.0 | 3 | 0.2 | 7.0 | 6 | 87.0 | 73 | 0.5 | 21.0 |
| 340 | 0 | 30.0 | 0 | 0.0 | 0.0 | 6 | 89.0 | 73 | 0.5 | 21.0 |
| 358 | 0 | 30.0 | 0 | 0.0 | 0.0 | 6 | 91.0 | 71 | 0.5 | 21.5 |
| 359[a2] | 0 | 30.0 | 0 | 0.0 | 0.0 | 6 | 50.0 | 70 | 0.5 | 22.0 |
| 388 | - | - | - | - | - | 5 | 61.0 | 65 | 0.6 | 22.5 |
| 408 | - | - | - | - | - | 5 | 75.0 | 64 | 0.6 | 23.0 |
| 420 | - | - | - | - | - | 5 | 75.0 | 64 | 0.6 | 20.0 |
| 440 | - | - | - | - | - | 6 | 60.0 | 48 | 0.5 | 15.0 |
| 455 | - | - | - | - | - | 6 | 61.5 | 49 | 0.4 | 13.5 |
| 472 | - | - | - | - | - | 6 | 63.0 | 50 | 0.4 | 12.5 |

Note: [a1] cut grasses for the height of 20 cm
[a2] cut grasses (*P. repens*) for the height of 50 cm
[b1] re-cultivate grasses
[b2] re-cultivate grasses (only *S. virginicus*)

**Appendix Table D2** Growth of *S. virginicus* and *P. repens* in vegetated compost columns with leachate irrigation

| Day | *S. virginicus* in compost (leachate) | | | | | *P. repens* in compost (leachate) | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | Number of shoots | Grass height (cm) | Number of leaves | Leaf width (cm) | Leaf length (cm) | Number of shoots | Grass height (cm) | Number of leaves | Leaf width (cm) | Leaf length (cm) |
| 0 | 6 | 19.0 | 32 | 0.8 | 7.5 | 6 | 18.0 | 16 | 0.3 | 8.0 |
| 6 | 6 | 19.0 | 32 | 0.8 | 7.5 | 6 | 20.0 | 16 | 0.6 | 8.0 |
| 20 | 6 | 27.5 | 39 | 0.5 | 9.0 | 6 | 27.0 | 12 | 0.3 | 13.5 |
| 22[a1] | 6 | 20.0 | 20 | 0.5 | 9.0 | 6 | 20.0 | 6 | 0.3 | 9.5 |
| 29 | 6 | 24.5 | 33 | 0.5 | 9.0 | 5 | 26.0 | 10 | 0.4 | 15.0 |
| 37 | 6 | 28.5 | 40 | 0.5 | 9.0 | 4 | 32.0 | 10 | 0.2 | 7.0 |
| 55 | 6 | 34.0 | 50 | 0.5 | 9.5 | 3 | 45.0 | 12 | 0.3 | 6.5 |
| 61 | 6 | 39.0 | 59 | 0.5 | 9.5 | 3 | 46.5 | 12 | 0.3 | 6.5 |
| 62[b1] | 6 | 39.0 | 59 | 0.3 | 9.0 | 6 | 46.5 | 30 | 0.4 | 10.0 |
| 83 | 6 | 48.5 | 70 | 0.3 | 14.5 | 6 | 58.5 | 25 | 0.6 | 15.5 |
| 99 | 6 | 54.0 | 60 | 0.3 | 13.0 | 5 | 59.0 | 37 | 0.4 | 17.0 |
| 115 | 6 | 55.0 | 63 | 0.4 | 13.5 | 6 | 59.0 | 39 | 0.4 | 16.5 |
| 125 | 7 | 57.0 | 77 | 0.3 | 14.0 | 6 | 59.0 | 43 | 0.4 | 17.0 |
| 140 | 7 | 60.0 | 95 | 0.4 | 15.0 | 6 | 59.0 | 66 | 0.3 | 17.0 |
| 157 | 8 | 63.0 | 134 | 0.3 | 15.0 | 7 | 59.0 | 87 | 0.3 | 17.0 |
| 168 | 8 | 62.5 | 130 | 0.3 | 15.0 | 7 | 59.0 | 87 | 0.3 | 17.0 |
| 182 | 9 | 63.0 | 121 | 0.3 | 15.0 | 7 | 59.0 | 87 | 0.3 | 16.5 |
| 193 | 9 | 61.5 | 115 | 0.3 | 14.5 | 7 | 58.0 | 87 | 0.3 | 16.5 |
| 211 | 10 | 61.0 | 114 | 0.3 | 14.5 | 7 | 57.0 | 87 | 0.3 | 15.0 |
| 216 | 10 | 61.0 | 114 | 0.3 | 15.0 | 7 | 57.0 | 87 | 0.3 | 15.0 |
| 230 | 10 | 62.0 | 93 | 0.4 | 15.0 | 5 | 57.0 | 42 | 0.3 | 9.0 |
| 255 | 9 | 62.0 | 84 | 0.3 | 12.0 | 2 | 57.0 | 10 | 0.3 | 9.0 |
| 270 | 7 | 62.5 | 58 | 0.4 | 12.0 | 0 | 57.0 | 0 | 0.0 | 0.0 |
| 300 | 7 | 62.5 | 55 | 0.4 | 13.5 | 0 | 57.0 | 0 | 0.0 | 0.0 |
| 324 | 5 | 63.0 | 41 | 0.4 | 14.0 | - | - | - | - | - |
| 340 | 5 | 63.0 | 37 | 0.4 | 14.0 | - | - | - | - | - |
| 358 | 4 | 64.0 | 32 | 0.4 | 13.0 | - | - | - | - | - |
| 359[a2] | 4 | 50.0 | 30 | 0.3 | 13.0 | - | - | - | - | - |
| 388 | 2 | 50.0 | 12 | 0.2 | 5.0 | - | - | - | - | - |
| 408 | 0 | 50.0 | 0 | 0.0 | 0.0 | - | - | - | - | - |
| 420 | 0 | 50.0 | 0 | 0.0 | 0.0 | - | - | - | - | - |
| 440 | 0 | 50.0 | 0 | 0.0 | 0.0 | - | - | - | - | - |
| 455 | 0 | 50.0 | 0 | 0.0 | 0.0 | - | - | - | - | - |
| 472 | 0 | 50.0 | 0 | 0.0 | 0.0 | - | - | - | - | - |

Note: $^{a1}$ cut grasses for the height of 20 cm
$^{a2}$ cut grasses (*S. virginicus*) for the height of 50 cm
$^{b1}$ re-cultivate grasses (only *P. repens*)

**Appendix Table D3** Growth of *P. repens* in vegetated sandy loam and compost columns without irrigation

| Day | *P. repens* in sandy loam (no irrigation) | | | | | *P. repens* in compost (no irrigation) | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | Number of shoots | Grass height (cm) | Number of leaves | Leaf width (cm) | Leaf length (cm) | Number of shoots | Grass height (cm) | Number of leaves | Leaf width (cm) | Leaf length (cm) |
| 0 | 7 | 30.0 | 35 | 0.5 | 9.0 | 9 | 30.0 | 26 | 0.4 | 12.0 |
| 17 | 7 | 54.5 | 42 | 0.6 | 34.5 | 9 | 32.0 | 24 | 0.5 | 16.5 |
| 27 | 6 | 75.0 | 51 | 0.7 | 41.5 | 9 | 34.0 | 19 | 0.5 | 22.0 |
| 28 [a1] | 6 | 50.0 | 51 | 0.7 | 41.5 | 9 | 34.0 | 19 | 0.5 | 22.0 |
| 44 | 6 | 52.0 | 45 | 0.7 | 41.5 | 5 | 34.0 | 9 | 0.3 | 10.0 |
| 60 | 5 | 59.5 | 33 | 0.7 | 30.0 | 2 | 34.0 | 3 | 0.3 | 8.0 |
| 77 | 5 | 63.0 | 33 | 0.7 | 27.0 | 0 | 34.0 | 0 | 0.0 | 0.0 |
| 92 | 5 | 65.0 | 32 | 0.5 | 25.0 | 0 | 34.0 | 0 | 0.0 | 0.0 |
| 107 | 3 | 65.0 | 18 | 0.4 | 18.0 | 0 | 34.0 | 0 | 0.0 | 0.0 |
| 122 | 3 | 65.0 | 10 | 0.3 | 15.0 | 0 | 34.0 | 0 | 0.0 | 0.0 |
| 133 | 0 | 65.0 | 0 | 0.0 | 0.0 | 0 | 34.0 | 0 | 0.0 | 0.0 |
| 141 | 0 | 65.0 | 0 | 0.0 | 0.0 | 0 | 34.0 | 0 | 0.0 | 0.0 |
| 179 | 0 | 65.0 | 0 | 0.0 | 0.0 | 0 | 34.0 | 0 | 0.0 | 0.0 |
| 195 | 0 | 65.0 | 0 | 0.0 | 0.0 | 0 | 34.0 | 0 | 0.0 | 0.0 |
| 200 | 0 | 65.0 | 0 | 0.0 | 0.0 | 0 | 34.0 | 0 | 0.0 | 0.0 |

Note: [a1] cut grasses (only *P. repens* in sandy loam) for the height of 50 cm

# Appendix E

## Data of Effluents in Column Experiment

**Appendix Table E1** Characteristics of effluents in non-vegetated sandy loam column with rainwater irrigation

| Day | Sandy loam (rainwater irrigation) | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | pH | EC (dS/m) | BOD (mg/L) | COD (mg/L) | TKN (mg/L) | $NH_4^+$-N (mg/L) | $NO_2^-$-N (mg/L) | $NO_3^-$-N (mg/L) | TP (mg/L) |
| 0 | | | | | | | | | |
| 8* | | | | | | | | | |
| 16 | 7.54 | 5.00 | 1.6 | 96 | 4.5 | 0.9 | 0.003 | 0.64 | 0.15 |
| 27 | 7.56 | 4.24 | 7.6 | 96 | 5.3 | n.d. | 0.043 | 0.35 | 0.07 |
| 44 | 7.15 | 4.54 | 15.8 | 291 | 8.0 | 2.7 | 0.007 | 0.13 | 0.11 |
| 60 | 7.24 | 4.30 | 19.8 | 95 | 7.1 | n.d. | 0.003 | 0.04 | 0.09 |
| 76 | 6.09 | 3.45 | 11.3 | 156 | 6.0 | n.d. | 0.009 | 0.07 | 0.06 |
| 96 | 6.72 | 1.24 | 4.5 | 98 | 11.4 | n.d. | 0.007 | 0.11 | 0.07 |
| 116 | 7.10 | 1.02 | 14.5 | 123 | 6.7 | 2.0 | 0.006 | 0.07 | 0.05 |
| 128 | 8.13 | 0.91 | 5.3 | 80 | 8.7 | 2.7 | 0.008 | 0.06 | 0.07 |
| 147 | 6.56 | 0.86 | 8.8 | 58 | 9.4 | 2.0 | 0.009 | 0.05 | 0.07 |
| 160 | 7.22 | 0.84 | 3.3 | 76 | 4.7 | 4.0 | 0.023 | 0.03 | 0.15 |
| 180 | 7.38 | 0.91 | 3.8 | 164 | 10.7 | 4.7 | 0.014 | 0.03 | 0.11 |
| 208 | 8.20 | 0.63 | 4.5 | 89 | 12.7 | 6.7 | 0.123 | 0.07 | 0.29 |
| 224 | 8.77 | 0.63 | 4.8 | 65 | 13.4 | 6.7 | 0.128 | 0.11 | 0.10 |

Note: *Start percolation

**Appendix Table E2** Characteristics of effluents in non-vegetated sandy loam/ compost mixture column with rainwater irrigation

| Day | Sandy loam+Compost (rainwater irrigation) | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | pH | EC (dS/m) | BOD (mg/L) | COD (mg/L) | TKN (mg/L) | $NH_4^+$-N (mg/L) | $NO_2^-$-N (mg/L) | $NO_3^-$-N (mg/L) | TP (mg/L) |
| 0 | | | | | | | | | |
| 16* | | | | | | | | | |
| 36 | 7.78 | 20.4 | 25.7 | 2,954 | 250 | 94 | 0.11 | 0.69 | 3.65 |
| 48 | 7.73 | 17.2 | 14.3 | 2,514 | 267 | 100 | 0.06 | 1.01 | 3.14 |
| 67 | 7.23 | 13.4 | 17.1 | 2,255 | 267 | 114 | 0.02 | 1.36 | 2.70 |
| 80 | 7.47 | 9.8 | 50.0 | 2,127 | 238 | 114 | 0.01 | n.d. | 2.65 |
| 100 | 7.15 | 8.6 | 38.1 | 1,964 | 223 | 114 | 0.01 | n.d. | 2.26 |
| 128 | 8.61 | 6.6 | 36.3 | 1,220 | 169 | 67 | 0.39 | n.d. | 1.11 |
| 144 | 9.36 | 6.1 | 13.1 | 1,017 | 160 | 53 | 0.08 | 0.71 | 0.96 |

Note: *Start percolation

**Appendix Table E3** Characteristics of effluents in non-vegetated compost column with rainwater irrigation

| Day | Compost (rainwater irrigation) | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | pH | EC (dS/m) | BOD (mg/L) | COD (mg/L) | TKN (mg/L) | $NH_4^+$-N (mg/L) | $NO_2^-$-N (mg/L) | $NO_3^-$-N (mg/L) | TP (mg/L) |
| 0 | | | | | | | | | |
| 16* | | | | | | | | | |
| 44 | 7.00 | 60.4 | 72 | 7,963 | 461 | 187 | 1.13 | 0.24 | 14.0 |
| 60 | 7.12 | 51.6 | 97 | 6,761 | 615 | 207 | 1.08 | 0.18 | 6.6 |
| 76 | 6.73 | 47.9 | 119 | 7,524 | 695 | 254 | 0.05 | 0.47 | 9.2 |
| 96 | 7.45 | 20.0 | 78 | 8,271 | 722 | 348 | n.d. | n.d. | 11.1 |
| 116 | 8.67 | 18.9 | 188 | 8,154 | 775 | 321 | n.d. | 0.01 | 10.2 |
| 128 | 7.60 | 14.9 | 200 | 6,000 | 749 | 334 | n.d. | n.d. | 13.2 |
| 147 | 7.60 | 13.1 | 95 | 5,349 | 802 | 401 | n.d. | 0.02 | 10.7 |
| 160 | 7.81 | 11.4 | 190 | 4,636 | 707 | 361 | n.d. | 0.02 | 12.3 |
| 180 | 7.44 | 11.8 | 225 | 5,318 | 669 | 281 | 0.01 | n.d. | 9.6 |
| 208 | 8.12 | 12.8 | 80 | 5,390 | 562 | 174 | 0.26 | 0.02 | 8.2 |
| 224 | 8.48 | 9.0 | 80 | 3,153 | 508 | 134 | 0.37 | n.d. | 10.0 |

Note: *Start percolation

**Appendix Table E4** Characteristics of effluents in non-vegetated sandy loam column with leachate irrigation

| Day | Sandy loam (leachate irrigation) | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | pH | EC (dS/m) | BOD (mg/L) | COD (mg/L) | TKN (mg/L) | $NH_4^+$-N (mg/L) | $NO_2^-$-N (mg/L) | $NO_3^-$-N (mg/L) | TP (mg/L) |
| 0 | | | | | | | | | |
| 4* | | | | | | | | | |
| 12 | 6.85 | 3.0 | 9.5 | 114 | 21 | 13 | 0.010 | 0.97 | 1.59 |
| 16 | 7.14 | 2.6 | 5.3 | 83 | 21 | 11 | 0.009 | 2.72 | 0.75 |
| 20 | 6.55 | 2.4 | 7.0 | 28 | 43 | 5 | 0.018 | 17.29 | 1.45 |
| 24 | 5.84 | 2.3 | 14.9 | 28 | 8 | 3 | 0.031 | 18.72 | 1.19 |
| 28 | 6.53 | 2.3 | 6.5 | 69 | 16 | n.d. | 0.063 | 14.30 | 1.29 |
| 32 | 6.57 | 2.4 | 13.0 | 124 | 11 | n.d. | 0.019 | 2.34 | 2.33 |
| 40 | 7.02 | 2.8 | 3.0 | 79 | 7 | 3 | 0.001 | 0.04 | 0.13 |
| 48 | 6.86 | 3.3 | 6.8 | 106 | 9 | 4 | 0.013 | 0.01 | 0.17 |
| 56 | 6.69 | 3.7 | 15.5 | 132 | 9 | 4 | 0.014 | n.d. | 0.10 |
| 64 | 6.55 | 3.2 | 9.1 | 139 | 11 | 5 | 0.016 | n.d. | 0.12 |
| 72 | 6.76 | 8.6 | 15.2 | 136 | 12 | 5 | 0.037 | 0.12 | 0.26 |
| 84 | 6.51 | 8.5 | 21.4 | 250 | 14 | 5 | 0.012 | 0.05 | 0.12 |
| 92 | 6.53 | 9.0 | 16.5 | 235 | 16 | 8 | 0.013 | 0.02 | 0.17 |
| 100 | 6.87 | 10.1 | 15.0 | 204 | 25 | 13 | 0.015 | 0.03 | 0.19 |
| 111 | 6.75 | 9.4 | 14.5 | 247 | 40 | 29 | 0.005 | 0.03 | 0.10 |
| 128 | 7.04 | 8.0 | 16.5 | 341 | 53 | 42 | 0.004 | n.d. | 0.12 |
| 144 | 7.01 | 10.2 | 21.0 | 270 | 16 | 54 | 0.004 | n.d. | 0.12 |
| 160 | 5.96 | 10.9 | 8.5 | 259 | 78 | 69 | 0.012 | n.d. | 0.08 |
| 180 | 6.81 | 4.8 | 10.0 | 234 | 98 | 85 | 0.009 | 0.01 | 0.05 |
| 200 | 7.10 | 5.3 | 19.0 | 246 | 91 | 99 | 0.006 | 0.02 | 0.05 |
| 212 | 7.06 | 5.2 | 5.5 | 206 | 120 | 115 | 0.011 | 0.02 | 0.07 |
| 231 | 6.66 | 5.3 | 12.8 | 243 | 144 | 126 | 0.010 | 0.01 | 0.08 |
| 244 | 7.15 | 5.3 | 10.8 | 251 | 150 | 134 | 0.026 | 0.03 | 0.16 |
| 264 | 6.99 | 5.8 | 9.8 | 316 | 198 | 134 | 0.036 | 0.00 | 0.10 |
| 292 | 7.95 | 6.7 | 3.5 | 293 | 123 | 86 | 0.171 | 0.01 | 0.11 |
| 308 | 8.03 | 6.2 | 6.8 | 114 | 107 | 91 | 0.114 | 0.03 | 0.10 |

Note: *Start percolation

**<u>Appendix Table E5</u>** Characteristics of effluents in non-vegetated sandy loam/ compost mixture column with leachate irrigation

| Day | Sandy loam+Compost (leachate irrigation) | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | pH | EC (dS/m) | BOD (mg/L) | COD (mg/L) | TKN (mg/L) | $NH_4^+$-N (mg/L) | $NO_2^-$-N (mg/L) | $NO_3^-$-N (mg/L) | TP (mg/L) |
| 0 | | | | | | | | | |
| 27* | | | | | | | | | |
| 32 | 6.79 | 23.8 | 11.1 | 2,408 | 201 | 53 | 0.46 | 3.43 | 8.24 |
| 40 | 7.17 | 24.2 | 8.0 | 1,968 | 170 | 93 | 0.12 | 1.06 | 8.85 |
| 48 | 6.92 | 18.4 | 24.3 | 1,660 | 174 | 67 | 0.46 | 1.32 | 6.63 |
| 56 | 7.05 | 16.1 | 33.0 | 1,500 | 167 | 74 | 0.62 | 0.59 | 6.91 |
| 64 | 7.37 | 8.6 | 18.5 | 1,896 | 160 | 67 | 0.44 | 0.64 | 6.61 |
| 72 | 7.35 | 35.0 | 26.4 | 1,602 | 174 | 64 | 0.13 | 0.85 | 6.48 |
| 84 | 7.26 | 30.3 | 41.4 | 1,251 | 167 | 80 | 0.34 | 0.63 | 7.57 |
| 92 | 7.36 | 26.0 | 30.0 | 1,624 | 174 | 102 | 0.30 | 0.55 | 8.61 |
| 100 | 7.64 | 25.4 | 42.9 | 1,394 | 207 | 112 | 0.13 | 0.62 | 9.78 |
| 111 | 7.37 | 26.3 | 46.4 | 1,447 | 234 | 150 | 0.05 | 0.76 | 8.74 |
| 128 | 7.15 | 17.2 | 22.9 | 2,086 | 261 | 193 | 0.01 | n.d. | 8.26 |
| 144 | 7.16 | 26.0 | 37.5 | 1,555 | 267 | 194 | 0.02 | n.d. | 8.96 |
| 160 | 6.56 | 26.7 | 41.3 | 1,557 | 125 | 227 | 0.02 | n.d. | 4.35 |
| 180 | 7.39 | 10.3 | 23.1 | 1,538 | 383 | 254 | n.d. | n.d. | 8.52 |
| 200 | 7.91 | 10.9 | 21.4 | 1,477 | 365 | 254 | n.d. | n.d. | 6.83 |
| 212 | 7.97 | 10.6 | 18.6 | 1,257 | 359 | 261 | 0.01 | n.d. | 7.26 |
| 231 | 7.22 | 10.6 | 22.9 | 1,099 | 383 | 287 | 0.01 | n.d. | 6.09 |
| 244 | 7.63 | 10.4 | 78.1 | 1,200 | 374 | 258 | 0.04 | n.d. | 6.09 |
| 264 | 7.26 | 11.2 | 65.0 | 1,418 | 521 | 294 | 0.02 | 0.03 | 5.25 |
| 292 | 7.98 | 13.3 | 58.2 | 1,098 | 334 | 276 | 0.22 | n.d. | 3.80 |
| 308 | 8.78 | 9.7 | 42.0 | 773 | 201 | 62 | 0.11 | 0.03 | 2.85 |

Note: *Start percolation

**Appendix Table E6** Characteristics of effluents in non-vegetated compost column with leachate irrigation

| Day | Compost (leachate irrigation) | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | pH | EC (dS/m) | BOD (mg/L) | COD (mg/L) | TKN (mg/L) | $NH_4^+$-N (mg/L) | $NO_2^-$-N (mg/L) | $NO_3^-$-N (mg/L) | TP (mg/L) |
| 0 | | | | | | | | | |
| 28* | | | | | | | | | |
| 32 | 6.65 | 24.9 | 48 | 2,339 | 254 | 80 | 0.28 | 3.43 | 11.6 |
| 40 | 6.88 | 27.2 | 54 | 2,690 | 242 | 98 | 0.26 | 0.83 | 20.6 |
| 48 | 6.79 | 24.2 | 18 | 2,377 | 227 | 100 | 0.28 | 0.71 | 16.0 |
| 56 | 7.02 | 18.6 | 30 | 2,520 | 227 | 100 | 0.01 | 0.08 | 14.8 |
| 64 | 7.49 | 9.4 | 14 | 2,338 | 234 | 107 | 0.01 | 0.15 | 12.2 |
| 72 | 7.31 | 41.9 | 25 | 2,587 | 241 | 112 | n.d. | 0.83 | 12.0 |
| 84 | 7.23 | 38.1 | 41 | 2,502 | 254 | 123 | n.d. | 0.46 | 16.3 |
| 92 | 7.31 | 32.9 | 46 | 3,136 | 227 | 118 | n.d. | 0.57 | 12.6 |
| 100 | 7.64 | 31.6 | 59 | 2,573 | 261 | 112 | n.d. | 0.33 | 17.3 |
| 111 | 7.74 | 30.5 | 44 | 2,841 | 207 | 139 | 0.02 | 0.89 | 14.3 |
| 128 | 7.22 | 29.8 | 48 | 3,350 | 334 | 198 | n.d. | n.d. | 20.8 |
| 144 | 7.17 | 30.6 | 53 | 2,637 | 339 | 214 | n.d. | n.d. | 19.7 |
| 160 | 6.66 | 29.1 | 51 | 2,724 | 357 | 234 | n.d. | n.d. | 15.9 |
| 180 | 7.42 | 10.2 | 50 | 2,215 | 383 | 241 | n.d. | n.d. | 16.0 |
| 200 | 7.74 | 11.2 | 40 | 2,031 | 374 | 254 | n.d. | n.d. | 14.1 |
| 212 | 7.63 | 10.6 | 90 | 1,657 | 339 | 274 | 0.06 | n.d. | 14.6 |
| 231 | 7.30 | 10.9 | 44 | 1,735 | 437 | 287 | n.d. | n.d. | 15.6 |
| 244 | 7.70 | 10.7 | 83 | 1,582 | 414 | 330 | 0.04 | n.d. | 15.0 |
| 264 | 7.24 | 11.6 | 46 | 1,745 | 535 | 357 | n.d. | n.d. | 14.7 |
| 292 | 8.03 | 13.9 | 121 | 1,586 | 495 | 267 | 0.24 | n.d. | 17.7 |
| 308 | 8.55 | 11.6 | 115 | 1,668 | 241 | 107 | 0.23 | n.d. | 17.4 |

Note: *Start percolation

**Appendix Table E7** Characteristics of effluents in vegetated compost (*S. virginicus*) column with rainwater irrigation

| Day | Compost + *S. virginicus* (rainwater irrigation) | | | | | | |
|---|---|---|---|---|---|---|---|
| | pH | EC (dS/m) | BOD (mg/L) | COD (mg/L) | TKN (mg/L) | $NH_4^+$-N (mg/L) | TP (mg/L) |
| 0 | | | | | | | |
| 32* | | | | | | | |
| 52 | 7.06 | 8.4 | 113 | 3,305 | 351 | 111 | 25.6 |
| 72 | 7.23 | 12.4 | 138 | 4,721 | 508 | 223 | 18.7 |
| 91 | 7.17 | 11.6 | 50 | 3,345 | 441 | 258 | 17.2 |
| 108 | 7.95 | 10.9 | 67 | 3,545 | 441 | 294 | 17.7 |
| 128 | 7.35 | 11.0 | 66 | 3,247 | 455 | 250 | 14.1 |
| 147 | 8.16 | 11.1 | 95 | 3,429 | 428 | 250 | 12.4 |
| 171 | 8.24 | 9.8 | 73 | 2,595 | 428 | 205 | 11.1 |
| 200 | 8.26 | 7.7 | 195 | 1,816 | 334 | 169 | 12.5 |
| 223 | 8.17 | 6.2 | 73 | 1,557 | 308 | 178 | 16.2 |
| 247 | 8.10 | 5.4 | 123 | 1,477 | 308 | 178 | 16.5 |
| 260 | 7.90 | 4.9 | 47 | 1,231 | 361 | 214 | 18.9 |
| 280 | 8.10 | 4.6 | 33 | 937 | 241 | 143 | 17.9 |
| 296 | 7.62 | 5.0 | 43 | 1,171 | 615 | 250 | 17.9 |
| 309 | 7.68 | 4.8 | 40 | 1,171 | 374 | 348 | 17.5 |
| 330 | 7.59 | 10.2 | 54 | 1,600 | 187 | 89 | 31.4 |
| 346 | 6.98 | 10.2 | 30 | 1,200 | 241 | 125 | 15.8 |
| 368 | 6.88 | 12.8 | 4 | 1,700 | 201 | 116 | 19.7 |
| 388 | 6.93 | 8.4 | 12 | 1,700 | 227 | 143 | 23.0 |

Note: *Start percolation
$NO_2^-$-N and $NO_3^-$-N were not detected

**Appendix Table E8** Characteristics of effluents in vegetated compost (*P. repens*) column with rainwater irrigation

| Day | Compost + *P. repens* (rainwater irrigation) | | | | | | |
|---|---|---|---|---|---|---|---|
| | pH | EC (dS/m) | BOD (mg/L) | COD (mg/L) | TKN (mg/L) | $NH_4^+$-N (mg/L) | TP (mg/L) |
| 0 | | | | | | | |
| 32* | | | | | | | |
| 52 | 7.32 | 8.5 | 197 | 4,249 | 477 | 99 | 25.9 |
| 72 | 7.32 | 14.4 | 104 | 5,351 | 481 | 223 | 18.9 |
| 91 | 7.18 | 13.0 | 96 | 4,218 | 575 | 357 | 18.9 |
| 108 | 7.95 | 11.8 | 67 | 4,283 | 468 | 303 | 17.2 |
| 128 | 7.27 | 11.9 | 66 | 3,529 | 495 | 267 | 14.6 |
| 147 | 8.24 | 11.0 | 73 | 3,840 | 455 | 276 | 13.3 |
| 171 | 8.23 | 10.0 | 48 | 3,114 | 468 | 267 | 14.3 |
| 200 | 8.90 | 10.3 | 117 | 4,411 | 334 | 71 | 22.6 |
| 223 | 9.44 | 9.6 | 43 | 4,670 | 281 | 53 | 5.1 |
| 247 | 8.33 | 6.6 | 130 | 2,215 | 361 | 187 | 16.5 |
| 260 | 7.94 | 5.3 | 33 | 1,231 | 388 | 223 | 19.1 |
| 280 | 8.20 | 4.7 | 40 | 937 | 267 | 169 | 21.0 |
| 296 | 7.44 | 4.7 | 45 | 1,171 | 548 | 250 | 21.0 |
| 309 | 7.51 | 4.7 | 40 | 937 | 334 | 241 | 21.7 |
| 330 | 7.57 | 10.2 | 28 | 800 | 294 | 169 | 11.6 |
| 346 | 7.3 | 13.5 | 14 | 1,500 | 321 | 196 | 20.0 |
| 368 | 6.83 | 15.4 | 48 | 1,100 | 321 | 214 | 21.7 |
| 384 | 6.95 | 14.7 | 6 | 1,200 | 254 | 214 | 20.7 |
| 400 | 6.74 | 13.3 | 4 | 1,600 | 842 | 187 | 21.3 |
| 419 | 6.68 | 12.3 | 4 | 1,400 | 254 | 140 | 25.2 |
| 432 | 7.07 | 5.9 | 8 | 300 | 254 | 196 | 17.8 |
| 456 | 6.30 | 12.0 | 16 | 1,800 | 361 | 107 | 9.4 |
| 472 | 6.57 | 11.1 | 24 | 1,900 | 401 | 98 | 14.5 |

Note: *Start percolation
$NO_2^-$-N and $NO_3^-$-N were not detected

**Appendix Table E9** Characteristics of effluents in vegetated compost (*S. virginicus*) column with leachate irrigation

| Day | Compost + *S. virginicus* (leachate irrigation) | | | | | | |
|---|---|---|---|---|---|---|---|
| | pH | EC (dS/m) | BOD (mg/L) | COD (mg/L) | TKN (mg/L) | $NH_4^+$-N (mg/L) | TP (mg/L) |
| 0 | | | | | | | |
| 20* | | | | | | | |
| 52 | 7.10 | 16.8 | 120 | 5,164 | 521 | 214 | 18.5 |
| 72 | 7.29 | 14.7 | 116 | 4,564 | 481 | 276 | 18.9 |
| 91 | 7.80 | 14.8 | 104 | 3,636 | 588 | 339 | 16.4 |
| 108 | 8.26 | 14.7 | 203 | 4,578 | 615 | 276 | 16.0 |
| 128 | 7.60 | 14.7 | 64 | 3,671 | 602 | 348 | 13.0 |
| 147 | 8.17 | 14.8 | 57 | 4,389 | 655 | 339 | 11.1 |
| 171 | 8.16 | 14.3 | 57 | 3,632 | 588 | 357 | 10.4 |
| 200 | 8.31 | 14.2 | 40 | 3,892 | 481 | 303 | 10.2 |
| 223 | 8.10 | 13.2 | 50 | 2,595 | 562 | 383 | 12.3 |
| 247 | 8.21 | 12.6 | 73 | 2,462 | 508 | 339 | 11.4 |
| 260 | 7.88 | 11.8 | 60 | 1,969 | 682 | 508 | 13.1 |
| 280 | 8.16 | 11.7 | 30 | 2,107 | 582 | 472 | 13.3 |
| 296 | 7.89 | 11.4 | 30 | 1,639 | 670 | 553 | 13.9 |
| 309 | 7.59 | 11.1 | 33 | 1,405 | 642 | 722 | 15.0 |
| 330 | 7.56 | 12.4 | 12 | 1,400 | 615 | 437 | 10.1 |
| 346 | 7.12 | 14.7 | 18 | 1,500 | 669 | 508 | 11.0 |
| 368 | 6.93 | 17.5 | 8 | 1,500 | 455 | 374 | 21.6 |
| 384 | 7.09 | 17.5 | 4 | 1,800 | 648 | 517 | 8.4 |
| 400 | 7.44 | 15.2 | 4 | 1,800 | 656 | 517 | 6.3 |
| 419 | 7.04 | 17.2 | 12 | 1,400 | 727 | 562 | 9.2 |
| 432 | 7.42 | 17.4 | 16 | 2,100 | 669 | 570 | 7.0 |
| 456 | 6.87 | 17.6 | 34 | 2,400 | 660 | 597 | 18.3 |
| 472 | 6.96 | 17.9 | 14 | 1,900 | 763 | 642 | 16.3 |

Note: *Start percolation
$NO_2^-$-N and $NO_3^-$-N were not detected

**Appendix Table E10** Characteristics of effluents in vegetated compost (*P. repens*) column with leachate irrigation

| Day | Compost + *P. repens* (leachate irrigation) | | | | | | |
|---|---|---|---|---|---|---|---|
| | pH | EC (dS/m) | BOD (mg/L) | COD (mg/L) | TKN (mg/L) | $NH_4^+$-N (mg/L) | TP (mg/L) |
| 0 | | | | | | | |
| 16* | | | | | | | |
| 52 | 7.34 | 16.0 | 230 | 4,436 | 508 | 116 | 13.8 |
| 72 | 7.23 | 15.6 | 206 | 5,351 | 441 | 241 | 18.2 |
| 91 | 7.25 | 14.0 | 68 | 3,345 | 548 | 294 | 17.7 |
| 108 | 7.91 | 13.2 | 75 | 3,397 | 508 | 321 | 19.4 |
| 128 | 7.31 | 13.8 | 68 | 3,529 | 535 | 321 | 13.8 |
| 147 | 8.13 | 13.3 | 87 | 3,566 | 628 | 374 | 11.3 |
| 171 | 8.13 | 12.2 | 92 | 2,335 | 495 | 374 | 12.3 |
| 200 | 8.23 | 12.1 | 167 | 2,335 | 428 | 258 | 9.6 |
| 223 | 8.17 | 10.9 | 160 | 2,076 | 468 | 276 | 12.5 |
| 247 | 8.16 | 11.6 | 192 | 2,215 | 361 | 214 | 13.4 |
| 260 | 8.80 | 27.9 | 290 | 6,892 | 735 | 62 | 25.1 |
| 324 | 8.53 | 18.8 | 233 | 4,566 | 348 | 116 | 10.3 |

Note: *Start percolation
$NO_2^-$-N and $NO_3^-$-N were not detected

# Appendix F

## Data of Methanotrophic Activity Study in Batch Experiment

**Appendix Table F1** Headspace methane concentrations in batch experiment with different $NH_4^+$-N addition

| Incubation time (hr) | Sandy loam + $NH_4^+$-N (µg N/g soil) | | | | | SL/Compost mixture + $NH_4^+$-N (µg N/g soil) | | | | | Compost + $NH_4^+$-N (µg N/g soil) | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | 0 | 10 | 30 | 50 | 100 | 0 | 10 | 30 | 50 | 100 | 0 | 10 | 30 | 50 | 100 |
| 0.0 | 8.9 | 9.1 | 9.2 | 8.9 | 9.0 | 9.0 | 9.0 | 9.0 | 8.9 | 8.8 | 9.0 | 9.1 | 9.0 | 8.9 | 9.0 |
| 2.0 | - | - | - | - | - | 5.0 | 5.4 | 6.0 | 6.2 | 6.4 | 6.9 | 7.2 | 7.2 | 6.8 | 6.7 |
| 4.0 | - | - | - | - | - | 2.5 | 2.8 | 3.4 | 3.5 | 3.6 | 5.1 | 5.6 | 5.8 | 5.0 | 4.9 |
| 7.0 | 8.1 | 8.3 | 8.5 | 8.2 | 8.3 | 0.8 | 0.9 | 1.4 | 1.1 | 1.3 | 3.2 | 3.6 | 4.0 | 3.1 | 2.9 |
| 10.0 | - | - | - | - | - | 0.2 | 0.3 | 0.8 | 0.5 | 0.6 | 2.0 | 2.3 | 2.8 | 1.8 | 1.7 |
| 15.0 | - | - | - | - | - | 0.1 | 0.1 | 0.4 | 0.3 | 0.3 | 0.9 | 1.0 | 1.4 | 0.6 | 0.7 |
| 24.5 | 4.7 | 5.4 | 5.5 | 6.3 | 6.2 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |
| 49.0 | 0.6 | 0.8 | 0.9 | 2.1 | 2.6 | - | - | - | - | - | - | - | - | - | - |
| 72.5 | 0.0 | 0.0 | 0.0 | 0.3 | 0.4 | - | - | - | - | - | - | - | - | - | - |
| 96.5 | - | - | - | 0.0 | 0.0 | - | - | - | - | - | - | - | - | - | - |

Note: All data are percentage of methane in headspace

**Appendix Table F2** Headspace methane concentrations in batch experiment with different $NO_3^-$-N addition

| Incubation time (hr) | Sandy loam + $NO_3^-$-N (µg N/g soil) | | | | | SL/Compost mixture + $NO_3^-$-N (µg N/g soil) | | | | | Compost + $NO_3^-$-N (µg N/g soil) | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | 0 | 10 | 30 | 50 | 100 | 0 | 10 | 30 | 50 | 100 | 0 | 10 | 30 | 50 | 100 |
| 0.0 | 9.1 | 9.0 | 9.0 | 8.9 | 8.8 | 9.0 | 8.9 | 9.0 | 8.9 | 8.7 | 9.0 | 8.6 | 8.9 | 8.6 | 8.5 |
| 2.0 | - | - | - | - | - | 5.0 | 5.5 | 5.6 | 5.7 | 5.8 | 6.9 | 6.9 | 7.2 | 6.9 | 7.3 |
| 4.0 | - | - | - | - | - | 2.5 | 2.8 | 2.9 | 3.0 | 3.3 | 5.1 | 5.3 | 5.8 | 5.4 | 6.0 |
| 7.0 | 8.3 | 8.4 | 8.4 | 8.3 | 8.2 | 0.8 | 0.9 | 1.0 | 1.2 | 1.5 | 3.2 | 3.3 | 4.0 | 3.6 | 4.2 |
| 10.0 | - | - | - | - | - | 0.3 | 0.3 | 0.3 | 0.4 | 0.6 | 2.0 | 1.8 | 2.3 | 2.1 | 2.6 |
| 15.0 | - | - | - | - | - | 0.1 | 0.1 | 0.1 | 0.2 | 0.3 | 0.9 | 0.7 | 0.7 | 0.8 | 0.8 |
| 24.5 | 5.4 | 5.5 | 5.4 | 5.4 | 5.5 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |
| 49.0 | 0.8 | 0.7 | 0.8 | 1.1 | 1.2 | - | - | - | - | - | - | - | - | - | - |
| 72.5 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | - | - | - | - | - | - | - | - | - | - |

Note: All data are percentage of methane in headspace

**Appendix Table F3** Headspace methane concentrations in batch experiment with different TOC contents

| Incubation time (hr) | Ratio of sandy loam and compost | | | | |
|---|---|---|---|---|---|
| | SL | 3:1 | 1:1 | 1:3 | C |
| 0.0 | 8.5 | 8.6 | 8.6 | 8.9 | 8.9 |
| 7.0 | 7.9 | 2.5 | 0.9 | 0.9 | 2.9 |
| 24.5 | 5.5 | 0.0 | 0.0 | 0.0 | 0.0 |
| 49.0 | 0.8 | - | - | - | - |
| 72.5 | 0.0 | - | - | - | - |

Note: All data are percentage of methane in headspace.
: TOC contents in sandy loam, mixture (3:1), mixture (1:1), mixture (1:3) and compost are 12.4, 45.5, 70.3, 79.1 and 84.8 μg/g soil, respectively

**Appendix Table F4** Headspace methane concentrations in batch experiment with various types and depths of cover soils from column experiments (with irrigation)

| Incubation time (hr) | Sandy loam with rainwater irrigation | | | | | SL/Compost mixture with rainwater irrigation | | | | | Compost with rainwater irrigation | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | 0-5 cm | 5-15 cm | 15-30 cm | 30-50 cm | 50-60 cm | 0-5 cm | 5-15 cm | 15-30 cm | 30-50 cm | 50-60 cm | 0-5 cm | 5-15 cm | 15-30 cm | 30-50 cm | 50-60 cm |
| 0.0 | 9.2 | 9.2 | 9.2 | 9.1 | 9.1 | 9.1 | 9.4 | 9.4 | 9.4 | 9.3 | 9.2 | 9.2 | 9.2 | 9.3 | 9.3 |
| 6.0 | - | - | - | - | - | 5.4 | 5.9 | 9.3 | 9.4 | 9.3 | 3.0 | 5.4 | 9.2 | 9.3 | 9.3 |
| 12.0 | - | - | - | - | - | 2.8 | 3.1 | 9.2 | 9.3 | 9.3 | 0.8 | 3.3 | 8.9 | 9.3 | 9.2 |
| 18.7 | 8.4 | 8.6 | 8.0 | 9.0 | 9.0 | 0.8 | 0.7 | 8.1 | 9.3 | 9.3 | 0.0 | 2.0 | 7.4 | 9.3 | 9.2 |
| 26.0 | - | - | - | - | - | 0.3 | 0.3 | 3.1 | 8.5 | 9.0 | - | 0.9 | 2.4 | 9.2 | 9.2 |
| 34.0 | - | - | - | - | - | 0.1 | 0.1 | 0.8 | 2.9 | 7.8 | - | 0.4 | 0.6 | 9.1 | 9.1 |
| 41.7 | 5.6 | 4.6 | 3.4 | 7.0 | 7.8 | 0.0 | 0.0 | 0.0 | 0.2 | 5.3 | - | 0.0 | 0.0 | 9.0 | 9.1 |
| 50.0 | - | - | - | - | - | - | - | - | 0.0 | 1.6 | - | - | - | 7.7 | 9.0 |
| 60.0 | - | - | - | - | - | - | - | - | - | 0.1 | - | - | - | 3.7 | 8.7 |
| 70.0 | 0.7 | 0.3 | 0.0 | 2.9 | 5.9 | - | - | - | - | 0.0 | - | - | - | 1.4 | 8.5 |
| 78.0 | - | - | - | - | - | - | - | - | - | - | - | - | - | 0.4 | 6.2 |
| 87.0 | - | - | - | - | - | - | - | - | - | - | - | - | - | 0.1 | 1.4 |
| 96.0 | 0.0 | 0.0 | 0.0 | 0.2 | 4.5 | - | - | - | - | - | - | - | - | 0.0 | 0.0 |
| 121.3 | - | - | - | 0.0 | 3.4 | - | - | - | - | - | - | - | - | - | - |
| 145.3 | - | - | - | - | 2.3 | - | - | - | - | - | - | - | - | - | - |
| 168.0 | - | - | - | - | 1.4 | - | - | - | - | - | - | - | - | - | - |
| 190.0 | - | - | - | - | 0.6 | - | - | - | - | - | - | - | - | - | - |
| 216.7 | - | - | - | - | 0.1 | - | - | - | - | - | - | - | - | - | - |
| 237.5 | - | - | - | - | 0.0 | - | - | - | - | - | - | - | - | - | - |

**<u>Appendix Table F4</u>** Cont'd

| Incubation time (hr) | Sandy loam with leachate irrigation | | | | | SL/Compost mixture with leachate irrigation | | | | | Compost with leachate irrigation | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | 0-5 cm | 5-15 cm | 15-30 cm | 30-50 cm | 50-60 cm | 0-5 cm | 5-15 cm | 15-30 cm | 30-50 cm | 50-60 cm | 0-5 cm | 5-15 cm | 15-30 cm | 30-50 cm | 50-60 cm |
| 0.0 | 8.9 | 8.9 | 9.0 | 9.0 | 9.1 | 9.1 | 9.2 | 9.0 | 9.2 | 9.2 | 9.2 | 9.0 | 8.8 | 9.2 | 9.1 |
| 6.0 | - | - | - | - | - | 1.8 | 3.6 | 9.0 | 9.2 | 9.2 | 1.9 | 3.4 | 8.8 | 9.2 | 9.1 |
| 12.0 | - | - | - | - | - | 0.4 | 1.2 | 8.9 | 9.1 | 9.2 | 0.5 | 1.2 | 8.7 | 9.2 | 9.1 |
| 18.7 | 8.9 | 8.9 | 9.2 | 9.3 | 9.2 | 0.0 | 0.2 | 8.5 | 9.1 | 9.2 | 0.0 | 0.3 | 8.1 | 9.2 | 9.1 |
| 26.0 | - | - | - | - | - | - | 0.1 | 5.7 | 9.0 | 9.1 | - | 0.0 | 1.9 | 9.1 | 9.1 |
| 34.0 | - | - | - | - | - | - | 0.0 | 0.8 | 8.9 | 9.1 | - | 0.0 | 0.4 | 9.0 | 9.1 |
| 41.7 | 7.8 | 7.8 | 8.8 | 9.2 | 9.1 | - | 0.0 | 0.0 | 8.7 | 9.0 | - | 9.0 | 0.0 | 8.5 | 9.1 |
| 50.0 | - | - | - | - | - | - | 9.2 | - | 3.9 | 6.5 | - | 3.4 | - | 3.9 | 9.0 |
| 60.0 | - | - | - | - | - | - | 3.6 | - | 0.5 | 1.9 | - | 1.2 | - | 0.5 | 8.7 |
| 70.0 | 4.3 | 5.2 | 5.9 | 6.5 | 7.8 | - | 1.2 | - | 0.0 | 0.3 | - | 0.3 | - | 0.0 | 8.3 |
| 78.0 | - | - | - | - | - | - | 0.2 | - | - | 0.1 | - | 0.0 | - | | 4.0 |
| 87.0 | - | - | - | - | - | - | 0.1 | - | - | 0.0 | - | - | - | - | 0.8 |
| 96.0 | 1.3 | 2.7 | 2.5 | 2.3 | 4.3 | - | 0.0 | - | - | | - | - | - | - | 0.0 |
| 121.3 | 0.0 | 0.7 | 0.4 | 0.2 | 1.7 | - | - | - | - | - | - | - | - | - | - |
| 145.3 | - | 0.1 | 0.0 | 0.0 | 0.4 | - | - | - | - | - | - | - | - | - | - |
| 168.0 | - | 0.0 | - | - | 0.0 | - | - | - | - | - | - | - | - | - | - |

Note: All data are percentage of methane in headspace

**Appendix Table F5** Headspace methane concentrations in batch experiment with various depths of cover compost from vegetated column experiments (with irrigation)

| Incubation time (hr) | Compost + *S. virginicus* with rainwater irrigation | | | | | Compost + *P. repens* with rainwater irrigation | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | 0-5 cm | 5-15 cm | 15-30 cm | 30-50 cm | 50-60 cm | 0-5 cm | 5-15 cm | 15-30 cm | 30-50 cm | 50-60 cm |
| 0.0 | 8.9 | 8.9 | 8.6 | 8.8 | 9.0 | 8.8 | 8.8 | 8.9 | 8.6 | 9.2 |
| 7.4 | 3.4 | 8.0 | 8.5 | 8.8 | 8.9 | 3.2 | 7.8 | 8.8 | 8.5 | 9.1 |
| 12.0 | 1.0 | 4.2 | - | - | - | 0.8 | 4.5 | - | - | - |
| 18.0 | 0.3 | 1.0 | - | - | - | 0.1 | 0.5 | 7.8 | - | - |
| 23.1 | 0.0 | 0.1 | 8.1 | 8.7 | 8.8 | 0.0 | 0.0 | 5.9 | 8.3 | 8.9 |
| 32.0 | - | 0.0 | 6.0 | - | - | - | - | 2.0 | 5.0 | - |
| 40.0 | - | - | 1.0 | 7.5 | 8.0 | - | - | 0.4 | 1.2 | 7.6 |
| 47.4 | - | - | 0.0 | 5.6 | 5.7 | - | - | 0.0 | 0.2 | 5.7 |
| 56.0 | - | - | - | 2.3 | 2.7 | - | - | - | - | 3.8 |
| 64.0 | - | - | - | 0.3 | 0.6 | - | - | - | - | 2.3 |
| 72.0 | - | - | - | 0.0 | 0.0 | - | - | - | 0.0 | 1.4 |
| 84.0 | - | - | - | - | - | - | - | - | - | 0.5 |
| 96.0 | - | - | - | - | - | - | - | - | - | 0.1 |
| 120.0 | - | - | - | - | - | - | - | - | - | 0.0 |

**Appendix Table F5** Cont'd

| Incubation time (hr) | Compost + *S. virginicus* with leachate irrigation | | | | | Compost + *P. repens* with leachate irrigation | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | 0-5 cm | 5-15 cm | 15-30 cm | 30-50 cm | 50-60 cm | 0-5 cm | 5-15 cm | 15-30 cm | 30-50 cm | 50-60 cm |
| 0.0 | 8.9 | 8.8 | 9.0 | 9.2 | 9.0 | 8.9 | 9.0 | 9.0 | 9.0 | 9.0 |
| 7.4 | 7.5 | 7.9 | 8.7 | 9.2 | 8.9 | 8.2 | 8.3 | 9.0 | 9.0 | 9.0 |
| 12.0 | 4.5 | 5.0 | - | - | - | 6.5 | 6.8 | - | - | - |
| 18.0 | 1.3 | 1.9 | - | - | - | 2.4 | 2.7 | - | - | - |
| 23.1 | 0.1 | 0.8 | 8.3 | 9.1 | 8.9 | 1.0 | 0.9 | 8.9 | 8.9 | 9.0 |
| 32.0 | - | 0.3 | 7.2 | 8.7 | - | 0.4 | 0.4 | 8.5 | - | - |
| 40.0 | - | - | 1.5 | 7.5 | - | 0.1 | 0.1 | 7.6 | - | - |
| 47.4 | 0.0 | 0.0 | 0.0 | 5.1 | 8.5 | 0.0 | 0.0 | 5.0 | 8.6 | 8.6 |
| 56.0 | - | - | - | 2.8 | 6.8 | - | - | 2.1 | 7.5 | 8.1 |
| 64.0 | - | - | - | 0.7 | 2.3 | - | - | 0.3 | 4.8 | 7.0 |
| 72.0 | - | - | - | 0.0 | 0.5 | - | - | 0.0 | 2.1 | 4.8 |
| 84.0 | - | - | - | - | 0.0 | - | - | - | 0.4 | 1.2 |
| 96.0 | - | - | - | - | - | - | - | - | 0.0 | 0.1 |
| 120.0 | - | - | - | - | - | - | - | - | - | 0.0 |

Note: All data are percentage of methane in headspace

**Appendix Table F6** Headspace methane concentrations in batch experiment with various types and depths of cover soils from vegetated and non-vegetated column experiments (without irrigation)

| Incubation time (hr) | Sandy loam without irrigation | | | | | Sandy loam + *P. repens* without irrigation | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | 0-5 cm | 5-15 cm | 15-30 cm | 30-50 cm | 50-60 cm | 0-5 cm | 5-15 cm | 15-30 cm | 30-50 cm | 50-60 cm |
| 0.0 | 8.8 | 8.7 | 8.8 | 8.6 | 8.7 | 8.9 | 8.8 | 8.7 | 8.8 | 8.8 |
| 6.5 | 8.6 | 8.6 | 8.6 | 8.6 | 8.4 | 8.5 | 8.6 | 8.6 | 8.5 | 8.8 |
| 24.5 | 8.5 | 8.4 | 8.5 | 8.0 | 7.6 | 8.0 | 8.3 | 8.2 | 8.2 | 8.6 |
| 48.5 | 8.4 | 7.7 | 7.7 | 4.6 | 4.3 | 7.2 | 6.6 | 6.0 | 7.8 | 8.1 |
| 72.0 | 8.3 | 7.1 | 5.7 | 0.4 | 1.4 | 6.1 | 4.6 | 3.6 | 7.3 | 7.6 |
| 96.0 | 8.1 | 6.8 | 2.3 | 0.0 | 0.0 | 5.0 | 2.5 | 1.5 | 6.9 | 7.2 |
| 120.0 | 7.8 | 6.3 | 0.0 | - | - | 4.1 | 1.1 | 0.6 | 6.5 | 6.7 |
| 144.5 | 7.6 | 6.0 | - | - | - | 2.9 | 0.1 | 0.0 | 6.0 | 6.1 |
| 167.5 | 7.4 | 5.7 | - | - | - | 1.9 | 0.0 | - | 5.6 | 5.8 |
| 191.0 | 7.2 | 5.3 | - | - | - | 1.3 | - | - | 5.4 | 5.6 |
| 215.0 | 7.0 | 5.0 | - | - | - | 1.1 | - | - | 5.2 | 5.4 |
| 268.0 | 6.7 | 4.6 | - | - | - | 0.2 | - | - | - | - |
| 312.5 | 6.4 | 4.2 | - | - | - | 0.0 | - | - | 4.9 | 4.9 |
| 383.5 | 5.9 | 3.5 | - | - | - | - | - | - | 4.7 | 4.8 |
| 413.0 | 5.6 | 3.0 | - | - | - | - | - | - | 4.5 | 4.3 |
| 455.5 | 5.0 | 2.5 | - | - | - | - | - | - | 4.2 | 4.1 |

**<u>Appendix Table F6</u>** Cont'd

| Incubation time (hr) | Compost without irrigation | | | | | Compost + *P. repens* without irrigation | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | 0-5 cm | 5-15 cm | 15-30 cm | 30-50 cm | 50-60 cm | 0-5 cm | 5-15 cm | 15-30 cm | 30-50 cm | 50-60 cm |
| 0.0 | 9.0 | 8.6 | 8.7 | 8.8 | 8.8 | 9.0 | 8.9 | 9.1 | 9.0 | 8.6 |
| 4.0 | 9.0 | 8.5 | 8.6 | 8.7 | 8.7 | 8.7 | 8.7 | 9.0 | 8.9 | 8.8 |
| 23.0 | 8.8 | 8.4 | 8.5 | 8.6 | 8.5 | 8.7 | 8.7 | 8.6 | 8.8 | 8.7 |
| 46.5 | 8.7 | 8.1 | 8.2 | 8.4 | 8.3 | 8.7 | 8.7 | 8.2 | 8.4 | 8.5 |
| 70.5 | 8.4 | 7.4 | 7.5 | 8.0 | 8.2 | 8.6 | 8.6 | 7.3 | 7.7 | 8.3 |
| 95.5 | 8.1 | 6.4 | 6.4 | 7.5 | 7.9 | 8.4 | 8.5 | 6.1 | 6.6 | 7.6 |
| 119.0 | 7.8 | 5.3 | 5.5 | 6.5 | 7.7 | 8.3 | 8.2 | 5.1 | 5.5 | 7.1 |
| 158.0 | 7.0 | 3.8 | 4.0 | 4.9 | 7.1 | 7.9 | 7.9 | 3.5 | 3.9 | 5.9 |
| 191.5 | 6.8 | 2.6 | 2.8 | 3.7 | 6.9 | 7.8 | 7.4 | 2.2 | 2.5 | 4.9 |
| 220.0 | 6.5 | 1.9 | 2.2 | 2.9 | 6.6 | 7.5 | 7.1 | 1.4 | 1.7 | 4.3 |
| 238.0 | 6.3 | 1.4 | 1.7 | 2.3 | 6.5 | 7.4 | 6.8 | 1.0 | 1.3 | 3.9 |
| 306.0 | 5.7 | 0.3 | 0.5 | 0.9 | 6.1 | 7.0 | 6.3 | 0.3 | 0.4 | 2.5 |
| 361.0 | 5.3 | 0.1 | 0.2 | 0.4 | 5.8 | 6.8 | 5.8 | 0.0 | 0.2 | 1.7 |
| 409.5 | 4.9 | 0.0 | 0.0 | 0.1 | 5.5 | 6.4 | 5.3 | - | 0.0 | 1.1 |
| 461.0 | - | - | - | 0.0 | - | 6.1 | 4.8 | - | - | 0.6 |
| 499.0 | 4.5 | - | - | - | 5.2 | 5.7 | 4.5 | - | - | 0.2 |

Note: All data are percentage of methane in headspace