TABLE OF CONTENTS

Page

LIST OF TABLES

LIST OF TABLES (Continued)

LIST OF FIGURES

LIST OF FIGURES (Continued)

LIST OF FIGURES (Continued)

LIST OF ABBREVIATIONS

Anammox	=	Anaerobic ammonia oxidation
AIT	=	Asian Institute of Technology
AMX	=	Anammox Bacteria
BOD	=	Biochemical Oxygen Demand
CH_4	=	Methane
C/N	=	Carbon to Nitrogen ratio
CO_2	=	Carbon dioxide
COD	=	Chemical Oxygen Demand
CW	=	Constructed Wetland
DOC	=	Dissolved Organic carbon
GHG	=	Green House Gas
H_2	=	Hydrogen
HCO_3^-	=	Bicarbonate
HLR	=	Hydraulic Loading Rate
H_2O	=	Water
HSFCW	=	Horizontal Subsurface Flow Constructed Wetland
MC	=	Moisture Content
MSW	=	Municipal Solid Waste
N_2	=	Nitrogen
NOB	=	Nitrate Oxidizing Bacteria
N_2O	=	Nitrous Oxide
NO^-_2	=	Nitrite
NO^-_3	=	Nitrate
NH_3	=	Ammonia
NH_4-N	=	Ammonia Nitrogen
O_2	=	Oxygen
POC	=	Particulate Organic Carbon
RT	=	Retention Time
SF	=	Surface Flow

LIST OF ABBREVIATIONS (Continued)

SSF	=	Subsurface Flow
TDS	=	Total Dissolved Solids
TKN	=	Total Kjeldahl Nitrogen
TOC	=	Total Organic Carbon
TS	=	Total Solids
VOC	=	Volatile Organic Compound

GREENHOUSE GAS EMISSION FROM CONSTRUCTED WETLAND FOR TREATING LANDFILL LEACHATE IN THE TROPICS

INTRODUCTION

Background

Sustainable environmental management is recently becoming an issue of global concern. Around the world, solid waste management becomes an important issue in urban areas. Currently, the generation of wastes has gained an important consideration in modern societies as a result of changes in habits and lifestyle of consumers, along with economic development. Due to the steady increase in population, urbanization, and industrialization, municipal solid waste generation has been increasing over the last decade. For example, in Thailand, about 38,000 ton/day of refuse was collected in the year 2002 as compared to 29,000 ton/day in 1992 (Chaya and Gheewala, 2006). These generated solid wastes need to be disposed in an environmental sound manner in order to get rid of many unfaouvarable conditions. In the cities of developing countries, the main disposal practice to MSW is open dumping. Uncontrolled landfilling of waste leads to pollutant emission over a long period of time which requires appropriate emission control and treatment methods. Any dumpsites are in uncontrolled manner, creating considerable health, safety and environmental problems. (UNEP, 2005)

It is a well known fact that dumpsite or sanitary landfill creates two major environmental issues namely emission of green house gases and producing landfill leachate. Although the latter case is less vulnerable to emit the GHG, significant amount of landfill leachate is being produced. Various ways and means have been established to cope the GHG emission from the above mentioned disposal method and to treat the leachate in an environmental sound manner. Landfill leachate is waste water emanated from sanitary landfill treating a variety of municipal and industrial solid wastes. Due to anaerobic conditions and long retention time prevailing in sanitary landfills, landfill leachate normally contains high concentration of organic

matters, nutrients, pathogens and heavy metals which, if not properly collected and treated, can cause serious pollution to nearby surface and groundwater sources. The presence of heavy metals at high concentrations in landfill leachate usually causes toxic effects to microbes, making it difficult to be treated biologically. Although several physical, chemical and biological processes can be employed to treat landfill leachate, for developing countries they can be expensive in construction, operation and requiring high-skilled labor in operation. On the other hand, where land is available at low-cost, natural system, such as waste stabilization ponds and constructed wetland are attractive alternatives for landfill leachate treatment (Sawaittayothin and Polprasert, 2006). Moreover, the improvements in the design of landfills result in extending the contaminating life span of these facilities. The disposal of landfill leachates is of concern because they have the potential to degrade the environment. The treatment and disposal of landfill leachates is becoming a major environmental issue, especially with regulatory agencies and environmentalists. Constructed wetlands are increasingly being employed to treat the landfill leachate, and the use of natural systems in waste management seems to be gaining in popularity as a result of their sustainability and cost savings. At percent, there are several constructed wetland treatment facilities in operation around the world (Mulamoottil *at el.*, 1999).

During the last 20 years, there has been a world-wide increase in the use of constructed wetland to reduce nutrient concentration (especially phosphorus and nitrogen), to degrade organic compounds, and to retain metals from various sorts of waste water (Kadlec and Knight, 1996). Such waste water includes nutrient rich sewerage waters, industrial waste streams, landfill and mining leachate, etc. A major factor driving this interest is the relatively low cost of wetland construction and management compared to other alternatives. Therefore, wetlands have become important components of waste water treatment programmes in developing countries. Furthermore not only the developing countries but also the developed counties have adopted this technology to treat their waste waster, especially landfill leachate. Especially in North America there are more than 1000 CW and a comparable numbers in Europe (Mulamoottil *at el*., 1999). In general the constructed wetland and the area

covered by constructed wetland are increasing globally. The most interesting fact is that these treatment facilities are being successfully operated in many location mentioned above (Mulamoottil *at el.*, 1999).

Problem statement

Different types of constructed wetland are available for treatment of leachate and waste water, namely surface flow wetlands, subsurface flow wetlands, and hybrid systems that incorporate surface and subsurface flow wetlands. In addition to that these constructed wetland systems can also be combined with conventional treatment technologies (Luise *et al*., 2000). All these various systems have their own positive and negative aspects and the selection of a particular systems depend upon many factors, namely the capital cost, land area required, land cost, climate condition, quantity of leachate to treat, and even public acceptance (Luise *et al.,* 2000). But due to many reasons and specially the health aspect and public access problem, the subsurface CW is being taken over the other systems at percent.

Wetland environment may emit considerable amount of CH_4, CO_2, and N_2O gases formed under the anoxic condition in the sediment of inundated area (Conrad, 1989). In wetland, nutrients and organic matter are removed permanently from terrestrial and aquatic ecosystems when they are converted through microbial processes to gaseous compounds to be released into the atmosphere. Some of these gases, as mentioned at the beginning of this paragraph, can have adverse effects in the atmosphere because they act as greenhouse gas and cause global warming. Thus, there is a risk that water pollution control can turn into an atmospheric pollution problem (Liikanen *et al*., 2006). The N_2O as one of the GHG, is increasing in the atmosphere at a rate of about 0.3%, $year^{-1}$ (Mosier, 1998). It has an atmospheric lifetime of about 120 years, a global warming potential (GWP) of 296 relative to CO_2 over a 100 year time horizon, and it responsible for about 6% of anticipated warming (IPCC, 2001). Moreover the CH_4 which is another greenhouse gas increasing in the atmosphere at the rate of about 0.8% $year^{-1}$ (Mosier, 1998). Methane in the atmosphere has a life time of 8.4 years. On a 100 year time horizon, CH_4 has a global warming potential of

23 relative to CO_2, and is responsible for about 20% of anticipated warming (IPCC, 2001).

Wetland gas dynamics are also greatly affected by climatic and weather conditions, especially by temperature and moisture (Moore and Dalva, 1993). Both the rate of photosynthesis (the source of energy and carbon in ecosystem) and the heterotrophic microbial activities producing greenhouse gas increases with increasing temperature. Moisture conditions, i.e. the height of the water table, in wetland determine the location and extent of toxic and anoxic microbial processes in the soil profile. Production of CH_4, a strictly anaerobic process, is highest in wetland with high water tables (Moore and Dalva, 1993). Also wetland gas fluxes have a strong seasonal and temporal variability resulting from variation in the environmental factors regulating the microbial processes behind the gas fluxes (Liikanen *et al*., 2006).

Thus, although constructed wetland can be beneficial for waste water or landfill leachate treatment they may have an adverse environmental impact by increasing the flux of greenhouse gases to the atmosphere. In order to quantify the impact of the increasing use of this CW on the atmospheric burden of methane, and others GHG, different types of constructed wetland in different regions, ecosystems and microhabitats need to be investigated (Johansson *et al.,* 2004). It is therefore necessary to study the emission of GHG from CW for treating landfill leachate under the tropical climate condition in order to quantify the gas emitting and to get the better understanding of the different mechanisms in side the CW. Ultimately these finding may contribute to find the solutions for problems which are encounter in CW processes.

OBJECTIVES

The ultimate goal of this study is to determine the emission of greenhouse gases, such as CH_4, CO_2 and N_2O from the constructed wetland for landfill leachate treatment. The specific objectives of this research are the following:

1. To determine the composition of greenhouses gases emitting form CW

2. To evaluate the treatment efficiency of CW for treating landfill leachate

Scope of the study

1. Landfill leachate will be used as a substrate, which was collected from the Tha Raeng station, Bangkok, and Pathumthani dump site in Thailand.

2. The close flux chamber technique was employed to determine the composition of gases.

3. The horizontal subsurface flow constructed wetlands which are located in AIT campus was used to perform the experiment.

LITERATURE REVIEW

1. Introduction

Due to rapid economic and population growth, along with urbanization, it is not uncommon to see many developing countries are struggling to provide a proper waste management system; a basic municipal service taken for granted by the developed world (Vidanaarachchi, *et al*., 2006). As urbanization continues to take place, the management of solid waste is becoming a major public health and environmental concern in urban areas of many developing countries. The concern is serious, particularly in the capital cities (Ogawa, 1996). A study by Zurbrugg (1999) suggested that problems and issues of MSW management are of immediate importance in many urban areas of the developing world. The main factors affecting the waste generation are population and mean living standard of the country (Daskalopoulos *et al*., 1998). The existence of a wide variety of processes and technologies for MSW treatment, or even the various possibilities of combining them, have given rise to the appearance of a number different structures and solutions for MSW treatment (Magrinho *et al.,* 2006). Sanitary landfilling is one of the most challenging approaches in waste management practices. It is known as the final option method in the hierarchy of waste management, and is the method that has been adopted for MSW treatment. However, even with sanitary landfilling being the most common method of MSW management, there is no landfill gas energy recovery. Nevertheless, there also some common problems arising from waste disposal at landfills due to the limited land resources available and the population is kept increasing (Jin *et al*., 2005). This would make landfills as the ultimate disposal of waste seems unattractive. Additionally, the national and international agencies are aware of the detrimental impact from an environmental point of view.

In the present situation, according to the most recent technologies, the optional solution for MSW treatment is not fully established especially in developing countries. However, waste minimization, production, prevention, reuse, recycling, recovery for the organic fraction, and incineration, are attractive methods since there are

limitations in landfilling in some European countries. Nevertheless, again, the organic fraction of waste still remains in landfills, which will definitely cause problems to the environment such as; air pollution, surface and ground water pollution. This may lead to global environmental concern. Global warming and climate change from the huge amount of gases is emitted. Furthermore many technologies have been developed to mitigate the above mentioned environmental concerns, especially for the emission of the GHG.

Treating the landfill leachate by employing wetlands has become the most attractive approach all over the world during last 20-25 years (Mulamoottil *at el.*, 1999). There are many technologies available and each one of them has its own advantages and disadvantages. Wetland is one of the challenging options since low capital cost and all most zero operation and maintaining cost as well as it is a good environment for the wild life habitat (Kadlec & Knight, 1996). Wetland also can be categorized for two main groups, namely natural wetland, and Constructed Wetland. Since it is difficult to control the processes within the natural wetland the constructed wetland has been taken over the natural wetland. In addition to that the CW also can be subdivided to three groups, surface flow, subsurface flow and hybrid system (Luise, 2000). Each one has its own advantages and disadvantages and the selection of proper one to different case will be varied with many conditions.

2. Landfill Leachate

Landfill leachate refers to the liquid that seeps through a landfill site and enters the environment. This liquid may already be in the material dumped into the landfill, or it may be the result of rainwater entering the landfill, filtering through the waste material and picking up additional chemicals before leaking out into the environment. Landfill leachate that escapes from the environment is most likely to eventually mix with the groundwater near the site. The disposal of landfill generated leachates is widely recognized as matters of concern because of the potential for negative impacts to the environment. As protection of the environment is vital to the well-being of present and future generations, any improvement that could be made in

solid waste management practices will be welcomed by society at large and by all levels of government (McBean *et al.,* 1999).

2.1 Landfill Leachate Composition

Leachate water quality is quite variable from site to site, depending upon the contents of the stack and its hydrology. It is typically high in ammonium nitrogen and chemical oxygen demand (COD), with moderate quantities of volatile organics and metals (Kadlec, 1999). McBean and frank (1999) pointed out the factors that influence leachate composition include refuse type and composition, refuse density, pretreatment, placement sequence and depth, moisture infiltration, ambient temperature, landfill management practices, and age of the landfill.

Table 1 Leachate composition

Compounds	Unit	Concentration	General range
BOD_5	mg/L	4-57,700	1,000-30,000
COD	mg/L	9-89,250	1,000-50,000
TOC	mg/L	0-28,500	700-10,000
Total volatile acids (as acetic acid)	mg/L	70-27,700	-
BOD_5/COD	-	0.02-0.87	0.6-0.8
COD/TOC	-	0.4-4.8	1-4.0
Total Kjeldahl nitrogen (as N)	mg/L	7-1,970	10-500
Nitrate (as N)	mg/L	0-51	0.1-10
Ammonia (as N)	mg/L	0-1,966	-
Total phosphate	mg/L	0.2-130	0.5-50
Total alkalinity (as $CaCO_3$)	mg/L	0-20,850	500-10,000
Total hardness (as $CaCO_3$)	mg/L	0-22,800	500-10,000
Total solids	mg/L	0-59,200	3,000-50,000
Total dissolved solids	mg/L	584-44,900	1,000-20,000
Specific conductance	μmhos/cm	1,44-17,100	2,000-8,000
pH	-	3.7-8.8	5-7.5
Calcium	mg/L	60-7,200	100-3,000
Magnesium	mg/L	17-15,600	30-5000
Chromium (total)	mg/L	0.02-18	0.05-1
Cadmium	mg/L	0.03-17	0.001-0.1
Copper	mg/L	0.005-9.9	0.02-1
Lead	mg/L	0.001-2	0.1-1
Nickel	mg/L	0.02-79	0.1-1
Iron	mg/L	4-2,820	10-1,000
Zinc	mg/L	0.06-370	0.5-30

Source: Lee *et al.,* (1986).

2.2 Alternative Methods for Management of Landfill Leachate

1. Spray irrigation on adjacent grassland
2. Recirculation of leachate through the landfill
3. Disposal off site to sewer for treatment as an admixture with domestic sewage
4. Physical-chemical treatment
5. Anaerobic biological treatment
6. Aerobic biological treatment
7. Wetlands

However, the selection of any technology will depend upon basically the economical factor, and others. But if any technology is required the large amount of investment cost as well as operation and maintenance cost, such type of technology is not economically viable solution the given problem. This will be a big issue for the developing countries because they have many other top priorities other than treating leachate, waste water or simply solid waste management in a environmental sound manner. Therefore from the above list the last treatment option may be suited for such situations, i.e. wetland processes. Wetlands offer a wide spectrum of natural processes that may serve to reduce leachate contaminants. Volatile Organic Compounds (VOCs) are air-stripped from the surface of the wetland waters and biodegraded by consortia of wetland microbes. Ammonium nitrogen my also volatilize and undergo nitrification and dinitrification. The wetland carbon cycle provides the energy source for nitrate reduction. This technology requires land instead of mechanical devices to accomplish treatment. If the necessary land id available, it typically offers modest capital savings over any competitive processes. However, it typically offers a very large advantage in operation cost, because operation is simple and maintenance is very low, furthermore it behaves as an ecosystem for the wild life habitat (Kadlec, 1999).

3. Constructed wetlands as treatment systems

A constructed wetland is a shallow basin filled with some sort of substrate, usually soil or gravel, and planted with vegetation tolerant of saturated conditions. Water is introduced at one end and flows over the surface or through the substrate, and is discharged at the other end through a weir or other structure which controls the depth of the water in the wetland (Luise, 2000). During the last 20 years, there has been a world-wide increase in the use of constructed wetland to reduce nutrient concentration (especially phosphorus and nitrogen), to degrade organic compounds, and to retain metals from various sorts of waste water (Kadlec and Knight, 1996). Such wastewater includes nutrient rich sewerage waters, industrial waste streams, landfill and mining leachate, etc. Table 2 illustrates few studies done in past by employing constructed wetland all over the world.

Table 2 Constructed wetland employed as treatment system

Type of Wetland	Substrate	Source
Free water surface flow	Primary treated sewage	Koottatep and Polprasert. ,1997
Subsurface flow	Waste water	Mander *et al.*, 2003
Free water surface flow	Secondary treated waste water	Johansson *et al.*, 2004
Subsurface flow	Landfill leachate	Chiemchaisri *et al.,* 2006
Free water surface flow	Peat mining runoff	Liikanen *et al.,* 2006
Subsurface flow	Waste water	Mander *et al.*, 2006
Subsurface flow Free water surface flow	Waste water	Gui *et al.,* 2007
Free water surface flow	Landfill leachate	Sawaittayothin and Polprasert., 2007

4. Advantages of Constructed Wetlands

1. Constructed wetlands are a cost-effective and technically feasible approach to treating wastewater and runoff for several reasons:

2. Wetlands can be less expensive to build than other treatment options

3. Operation and maintenance expenses (energy and supplies) are low

4. Operation and maintenance require only periodic, rather than continuous, on-site labor

5. Wetlands are able to tolerate fluctuations in flow

6. They facilitate water reuse and recycling.

5. Limitations of Constructed Wetlands

There are limitations associated with the use of constructed wetlands:

1. They generally require larger land areas than do conventional mechanical treatment systems.

2. Wetland treatment may be economical relative to other options only where land is available and affordable.

3. Performance may be less consistent than in conventional treatment.

4. Wetland treatment efficiencies may vary ‘seasonally in response to changing environmental conditions, including rainfall and drought. While the average performance over the year may be acceptable, wetland treatment cannot be relied upon if effluent quality must meet stringent discharge standards at all times.

5. The biological components are sensitive to toxic chemicals, such as ammonia and pesticides

6. Flushes of pollutants or surges in water flow may temporarily reduce treatment effectiveness

Source: Komex Environmental Ltd, (2004).

6. Types of Constructed Wetlands

There are several types of constructed wetlands: surface flow wetlands, subsurface flow wetlands, and hybrid systems that incorporate surface and subsurface flow wetlands. Constructed wetland systems can also be combined with conventional treatment technologies. The types of constructed wetlands appropriate for domestic wastewater, agricultural wastewater, coal mine drainage, storm water runoff, and landfill leachate (Luise, 2000).

6.1 Surface Flow Wetland

A surface flow (SF) wetland consists of a shallow basin, soil or other medium to support the roots of vegetation, and a water control structure that maintains a shallow depth of water (figure 1). The water surface is above the substrate. In SF wetlands, the near surface layer is aerobic while the deeper waters and substrate are usually anaerobic. Storm water wetlands and wetlands built to treat mine drainage and agricultural runoff are usually SF wetlands. Johansson *et al*., (2004) and Gui *et al*., (2007) have used SF wetlands for their study. The advantages of SF wetlands are that their capital and operating costs are low, and that their construction, operation, and maintenance are straightforward. The main disadvantage of SF systems is that they generally require a larger land area than other systems.

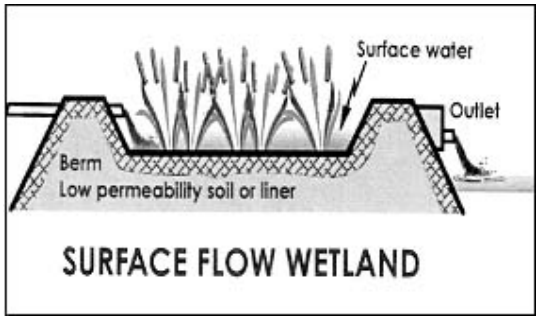

Figure 1 Surface Flow CW

Source: Komex Environmental Ltd, (2004).

6.2 Subsurface Flow Wetland

A subsurface flow (SSF) wetland consists of a sealed basin with a porous substrate of rock or gravel. The water level is designed to remain below the top of the substrate. SSF systems are called by several names, including vegetated submerged bed, root zone method, microbial rock reed filter, and plant-rock filter systems.

The advantages cited for SSF wetlands are greater cold tolerance, minimization of pest, an odor problems, possibly, greater assimilation potential per unit of land area than in SF systems. It has been claimed that the porous medium provides greater surface area for treatment contact than is found in SF wetlands, so that the treatment responses should be faster for SSF wetlands which can, therefore, be smaller than a SF system designed for the same volume of wastewater. Since the water surface is not exposed, public access problems are minimal. The disadvantages of SSF wetlands are that they are more expensive to construct, on a unit basis, than SF wetlands. Because of cost, SSF wetlands are often used for small flows. Chiemchaisri *et al*., (2006) and Gui *et al*., (2007) have employed SSF for 112 L/d and 500 L/d volume to treat. SSF wetlands may be more difficult to regulate than SF wetlands, and maintenance and repair costs are generally higher than for SF wetlands.

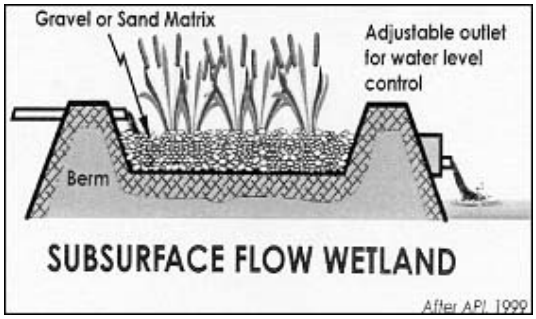

Figure 2 Subsurface Flow CW

Source: Komex Environmental Ltd, (2004).

7. Treatment Processes in Constructed Wetland

When water percolates through solid waste that is undergoing decomposition, both biological materials and chemical constituents are leached into solution. The composition of the leachate with respect to the type of pollutants and the content varies with the age of the landfill, the character of the disposed wastes and the degree of dilution with surface and groundwater. The components, which are normally considered to be treated and pollution, are, Organic substance, Nitrogen (primarily in ammonium iron), and heavy metals. Major influential components in treatment processes of CW include substratum, microorganisms and aquatic plants (Reed *et al.,* 1995). Substratum, such as soil, sand and gravel, serves as the supporting media for the plant growth and the attachment of microbial biofilm in the CW. The microorganisms are typically responsible for degradation of organic content in the waste water or leachate (Koottatep and Polprasert, 1997). Many researchers found (Koottatep and Polprasert, 1997; Mander *et al*., 2003; Neto *et al.*, 2003; Davison *et al.,* 2006; Reinhardt *et al.,* 2006) that the nitrification and dinitrification are the main processes of the nitrogen removal in the CW. In addition to that the increased input of nutrients will increase the productivity of the ecosystem and the increased supply of organic matter can then increase the decomposition processes (Nykanen *et al.*, 1998). This is in turn to increase the production of green house gases, which are by or end products of microbial decomposition processes. Increased Carbon (C) loading has been found to enhance CH_4 emission (Tanner *et al.,* 1997).

8. Nitrogen Removal Processes in CW.

The following block diagram can be used to visualize the nitrogen transformation in CW for waste water or leachate treatment. Investigations of nitrogen (N) removal performance and its treatment mechanisms in constructed wetlands have been done by Gersberg *et al*., (1983, 1986), Breen, (1990), Tanner *et al.,* (1995), Laber *et al*., (1996), Koottatep and Polprasert, (1997) and Sawaittayothin and Polprasert, (2007). These studies showed that N removal efficiencies of the constructed wetlands are in the range of 20-90%, depending on waste water

characteristics, wetland configurations, feeding methods, and floe patterns. Further Hammer and Knight, (1994) reported that 52 CW treatment plants located in the USA had N removal efficiencies of 30-60%.

The below processes can be named as follows. 1- NH_3 volatilization. 2- Nitrification. 3- Dinitrification. 4- Nitrogen fixation. 5- Plant and microbial uptake. 6- Ammonification. 7- Nitrate ammonification. 8- Adsorption. 9- Ionic exchange. In addition to that above mentioned processes another process for N conversion has been found in early 90s, is called Anammox process (Mulder *et al*., 1995). The processes 2, 3 and anammox will be detailed in the following section due to the importance of these to this study. Moreover the rest of processes will not be covered here since they are beyond the scope of this study.

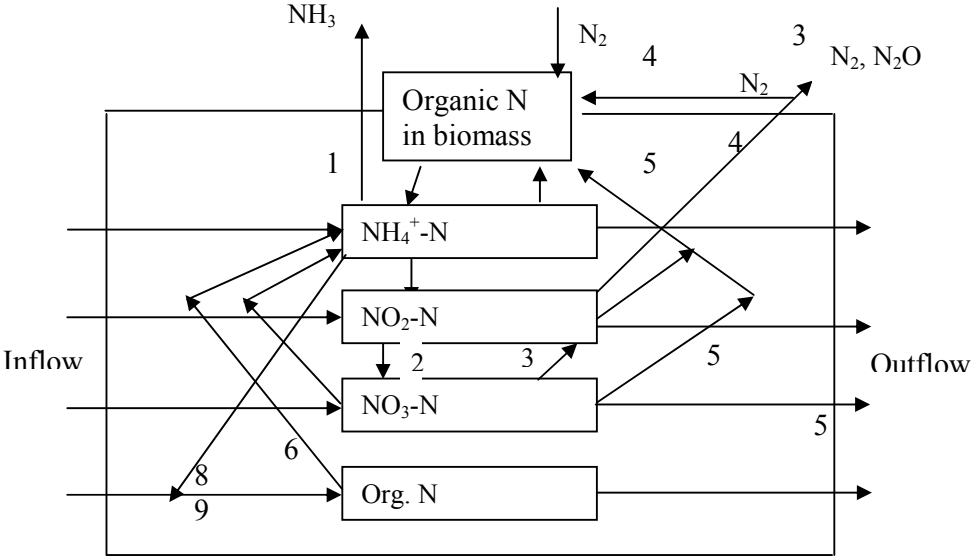

Figure 3 Possible microbial N conversions in CW.
Source: Vymazal (1999)

8.1 Nitrification

Nitrification involves the two-step conversion of ammonium to nitrite and nitrite to nitrate. It realized by autotrophic aerobic microorganisms which are

nitrosomonas species and nitrobacter species. The process for the ammonium oxidizing bacteria is

$$NH_4^+ + 3/2\ O_2 \xrightarrow[\text{Nitrosomonas}]{} NO_2^- + 2H+ + H_2O + \text{energy} \quad (1)$$

$$NO_2^- + 1/2\ O_2 \xrightarrow[\text{Nitrobacter}]{} NO_3^- + \text{energy} \quad (2)$$

The combination of Eq. (1) and Eq. (2) is presented in Eq. (3)

$$NH_4^+ + 2O_2 \longrightarrow NO_3^- + 2H^+ + H_2O + \text{energy} \quad (3)$$

Along with obtaining energy, some of ammonium ion is assimilated into cell tissue. The biomass synthesis reaction can be represented as follows:

$$4CO_2 + HCO_3^- + NH_4^+ + H_2O \longrightarrow C_5H_7O_2N + 5O_2 \quad (4)$$

The overall oxidation and synthesis reaction can be represented as follows:

$$NH_4^+ + 1.83O_2 + 1.98HCO_3^- \longrightarrow 0.021C_5H_7O_2N + 0.98NO_3^- + 1.041H_2O + 1.88H_2CO_3 \quad (5)$$

8.2 Denitrification

Biological denitrification occurs naturally when certain bacteria use nitrate as terminal electron acceptor in their respiratory process, in the absence of oxygen. Denitrification consists of a sequence of enzymatic reaction leading to the evolution of nitrogen gas. The process involves the formation of a number of nitrogen intermediates and can be summarized as follows.

Dinitrification bacteria

$$NO_3^- \longrightarrow NO_2\text{-} \longrightarrow NO \longrightarrow N_2O \longrightarrow N_2 \quad (6)$$

Or

$$NO_3^- + 6H^+ + 5e^- \longrightarrow 1/2N_2 + 3H_2O \quad (7)$$

Elemental nitrogen is the end product of this process. But intermediate accumulation of nitrite, nitric oxide and nitrous oxide may take place under certain conditions (Korom, 1992). Further Gersberg *et al*., (1983, 1986), and Harberl and Perfler, (1991) reported that the biological nitrification/ denitrification process is the major pathway for ammonia removal in the both the free surface and subsurface wetland systems.

8.3 Anammox process

Partial nitrification/Anammox is a new method for nitrogen removal from wastewater. It targets wastewater streams (or gases) high in ammonium (>0.2 g/l) and low in organic carbon (C:N ratio lower than 0.15). The two processes proceed as follows:

$$2NH_4^+ + 1.5O_2 \longrightarrow NH_4^+ + NO_2^- + H_2O + 2H^+ \quad (8)$$

$$NH_4^+ + NO_2^- \longrightarrow N_2 + 2H_2O \quad (9)$$

$$2NH_4^+ + 1.5O_2 \longrightarrow N_2 + 3H_2O + 2H^+ \quad (10)$$

Eq. (8) is called the partial nitrification, and Eq. (9) is anammox, and the Eq. (10) is called the total reaction. The produced acid is balanced by the counter-ion of ammonium, usually bicarbonate or sulfide).

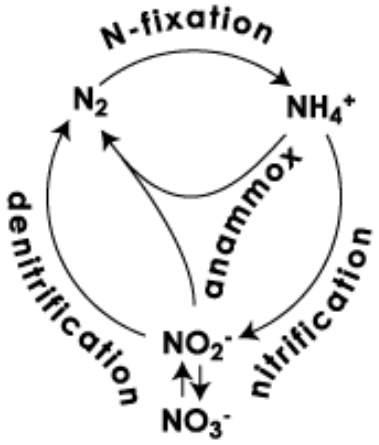

Figure 4 The biological nitrogen cycle
Source: Marc (2006).

The above described three processes are important in terms of GHG emission from the CW for the leachate treatment. Even though the N_2 is not considered as GHG, during the processes of which N_2 is formed the intermediate N compounds can be responsible for the GHG, Specially N_2O gas. In addition to that, plant uptake is another major pathway for removing N from CW. Koottatep and Polprasert, (1997) and Sawaittayothin and Polprasert, (2007) reported that plant uptake were the main responsible mechanisms for removing N from CW in tropics. The correspondent values were 43- 88% respectively.

9. Carbon removal processes in CW

The following simplified block diagram can be used to understand the basic carbon transformations which are being occurred in CW.

Where:

⟶ = Physical/ Chemical processes

⟹ = Bacterial/ Plant processes

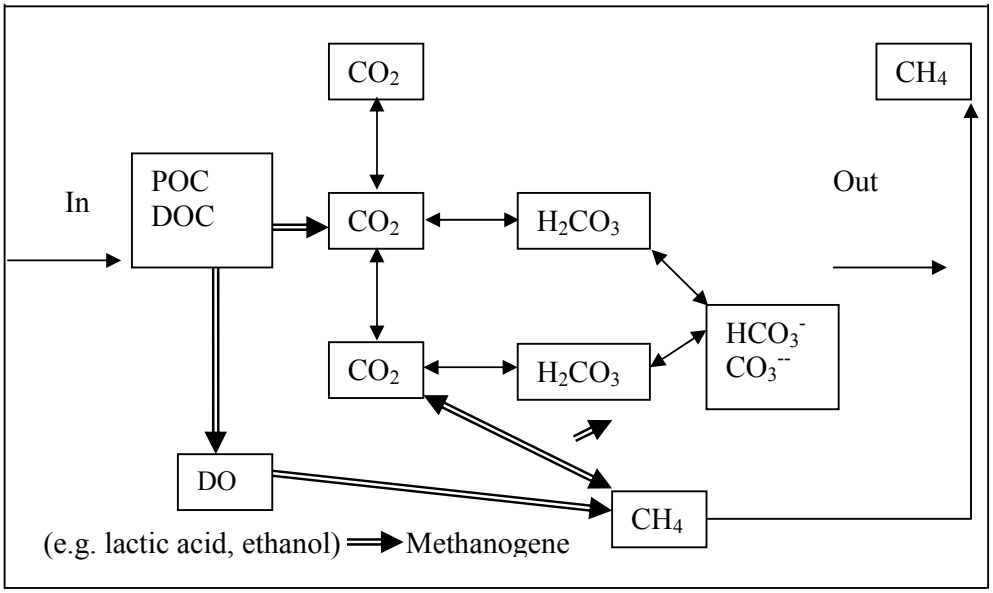

Figure 5 Carbon transformation in CW.

Source: Kadlec and Knight (1996)

From the below transformation it can be noted that due to the bacterial actions two kind of GHG are released to the environment from the CW, namely CH_4 and CO_2.

$$CHON \xrightarrow{\text{Methanogens}} CH_4 + CO_2 + \text{Cell} \qquad (11)$$

Apart from that, when it is considered the N transformation along with this C transformation CW can be a source of green house gas emission to atmosphere which is in turn will be affected to the global warming process (Johansson *et al*., 2004). Moreover, the major natural CH_4 contributor to the atmosphere is the natural wetland systems which emit the 120 Tg/yr of CH_4 (Neue, 1993).

10. Determination of Tracer gases Emission from CW

Gas emission from constructed wetland has been measured by two procedures basically, for example: a closed flux chamber method and the helium-Oxygen (He-O) method. The method that is a popular method in determination wetland gas emission is the flux chamber method over the He-O methods by many researchers (Mander *et al*., 2003; Johansson *et al.,* 2004; Mander *et al*., 2005; Liinkanen *et al.,* 2006; Gui *et al.,* 2006). Moreover some researchers have been employed both techniques to measure the gas emission from CW (Mander *et al*., 2003).

10.1 Closed Flux Chamber

A close flux chamber or static chamber is the determination of gas emission by measuring the changes of gas concentration with time inside the closed chamber. Gas from wetland can diffuse into the chamber until a pressure inside the chamber is high enough to resist the inflow gas which then gas diffusion is paused. Difference from the open chamber, air from atmosphere can not flow into this chamber. The advantages of this method are: small quantities of gas emission can be determined; the equipment is convenient to move or install on the CW without energy requirement; there is no the interference/contamination of air in the atmosphere; and gas in chamber is thorough mixed due to a long sampling time. The disadvantages of the close flux method are: an inside pressure is fast developed if the gas emission rate is very high; there was highly affected by temperature of environment; there is a contamination from air when the connection of chamber and cover soil is not well performed.

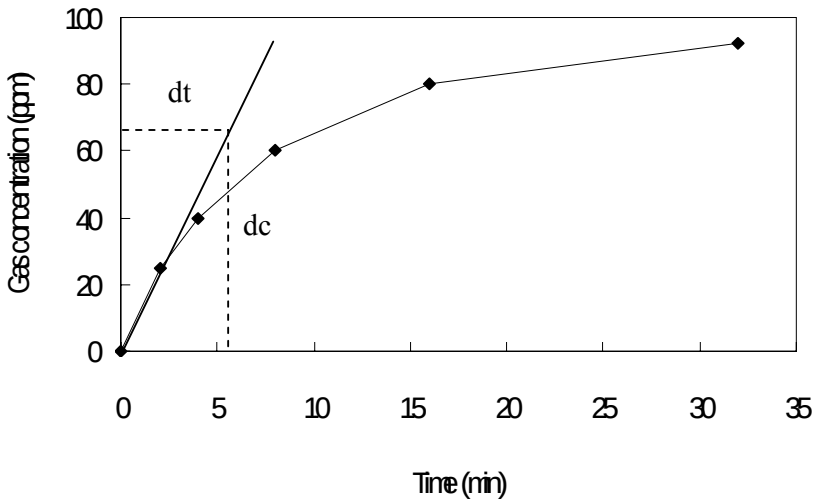

Figure 6 Concentration of methane developed inside the chamber.

Source: Maurice and Lagerkvist (1998)

$$F = \frac{\rho V \Delta C}{A \Delta t} \qquad (12)$$

F = flux of gas emission per area and time, $g/m^2/s$

ρ = gas density, kg/m^3

V = Chamber volume, m^3

A = Chamber cross section area, m^2

ΔC = Differences of gas concentration during measurement, %

Δt = Gas sampling time, s

Table 3 Summary of methane emission rate measured by a close flux chamber method.

Place	CH_4 ($g/m^2/d$) Average	Max	Chamber Size	Landfill/ Wetland	Area (ha)
Hokhuvud, Swenden	0.013 -7.68	18.43	Square chamber with 27.5 cm size	Landfill	1.6
Schoten, Belgium	-0.005 - 0.914	-	Round chamber with 15 cm dia., 60 cm height	Landfill	0.5
Skellingsted, Denmark*	<0.192-9.6	72.57	Round chamber with 60 cm diameter and 20 cm height	Landfill	-
Nashua Four Hills, USA	44.93	1494.9	Square chamber with 60 cm side	Landfill	35.5
UK, several sites*	0.8217	5.184	-	Landfill	-
Martin Farm, UK*	21.8-39.9	-	-	Landfill	-
Lulea, Swenden*	0-2.01	5.33	-	Landfill	-
Schoten, Belgium*	0.007-0.92	-	Round chamber with 15cm diameter and 60cm height	Landfill	
Malmo, Swenden	2.24	5.76	-	Landfill	-
Helsingborg, Swenden	0.256	0.96	-	Landfill	-
Mander., Teiter, Estonia	.00636	-	Round chamber with50 cm dia.,50cm height	Wetland	750m^2
Anu et al., Finland	014-0.4	-	Square chamber with 60cm*60cm	Wetland	2.4
Johansson et al., Sweden	141	1739	0.87*0.47*0.47 m chamber	Wetland	0.6
Gui et al., Japan	0.48	1.44	Round cell with 56cm diameter, 88 cm height	Wetland	1.3 m^2 (Lab S.)

Source: Boecke *et al.* (1996); Borjesson and Svensson (1997); Mosher *et al.* (1966); adapted from Christophersen *et al.* (2001); Maurice *et al.* (1995) cited in Chiemchaisri *et al*., 2004.

11. ORP distribution in soil and its relationship with gas emission

Oxidation reduction potential (ORP) can be divided into three levels (Kralova *et al*., 1992; Patrick *et al*., 1993). An ORP > 200 mV represents a totally aerobic status; an ORP in the -100-200 mV range is indicative of a mix of anaerobic and aerobic status; an ORP < -100 mV represents a totally anaerobic status. Gui *et al.*, (2007) have employed these ORP measurements for their study and have incorporated the obtained ORP values with greenhouse gas emissions of their study.

MATERIALS AND METHOD

Introduction

As mentioned in previous section, various kinds of constructed wetland are being employed. The selection of any kind of wetland depends upon the treatment degree, land available, financial aspects etc. Anyhow, each mode of operation always has its own advantages and limitations. However, this research had been dealing with horizontal subsurface flow constructed wetland. Actually in this project there were two HSCW and both were operated simultaneously. Additionally, the required leachate was collected from Tha Raeng station, Bangkok, and Pathumthani in Thailand.

The experiment was conducted in the pilot scale. Operating conditions were varied such as the mix leachate i.e. fresh leachate and stabilized leachate, same hydraulic loading rate (HLR); in this case (HLR), 28 mmd^{-1} was used, and hydraulic retention time (HRT) was 10 days, with (system B) and without (system A) leachate recirculation. Basically this research was divided for two runs. Only fresh leachate was used for feeding to the both systems during first run whereas fresh and stabilized leachate were mixed with 1:1 ratio for the second run to feed to the systems in order to increase the N content.

GHG emissions were analyzed by using the gas chromatography. A landfill leachate quality which was used to treat was also investigated.

Materials

1. Pilot scale horizontal subsurface constructed wetland operation

1.1 Configuration of HSCW

The schematic diagram of subsurface horizontal flow constructed wetland system which was used in this study is shown in figure 8. Four concrete ponds of 1 m wide and 3 m long and 1 m in depth were used. The inlet and outlet zones were filled with 30-60 mm gravel up to the 0.8 m and 1-2 mm sand was filled in plantation zone. The operating water depth was maintained at a depth of 0.6 m from the bottom level. The leachate was fed into the system by a centrifugal pump through an inlet pipe (10 mm in size) with valve control. The waster water (leachate) flew downwards was moved through treatment (plantation) zone and was discharged from the outlet zone through an out let pipe (50 mm). Cattail (*Typha augustifolia*) was used as an emergent in the system at initial planting density of 40 rhizomes per m^2.

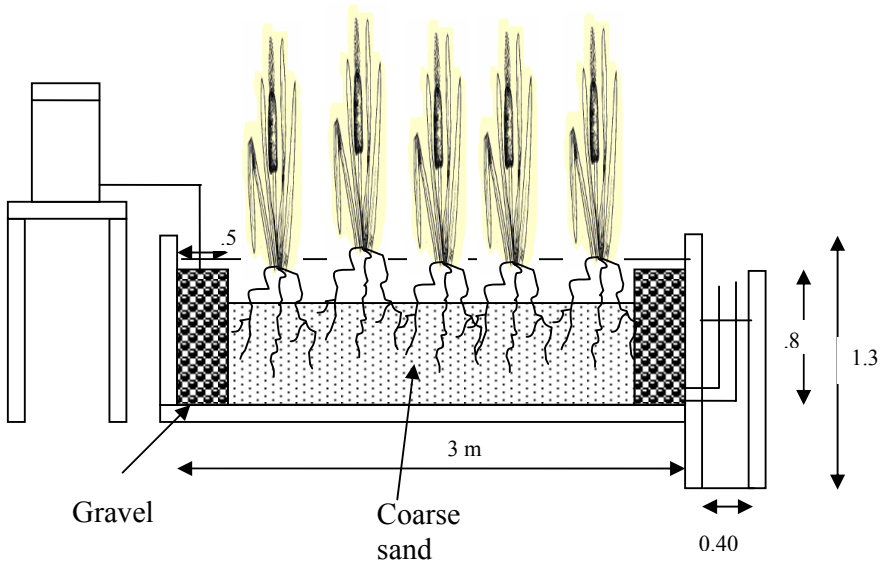

Figure 7 Schematic diagram of HSCW

2.2 Equipment for Gas Emission Measurement

A close flux chamber composes of 2 parts (Fig. 9) a chamber is made of acrylic plate with 5.0-mm thickness; 300-mm diameter, and 300-mm height. It is covered acrylic plate with 19-mm thickness that having a gas sampling port and a port of temperature measurement. A base of chamber also is made of stainless with 300-mm diameter and 125-mm height. Outside of top base side has a trench for supporting the chamber. The stainless steel part was inserted in to the soil one day before the gas measurements to minimize the disturbances. During the measurement, special care was taken to make sure that there are not any gas leakages. Total area covering soil surface of a chamber is 0.071 m^2. To select the proper dimensions of the close flux chamber various literatures were reviewed. (Refer the table 3).

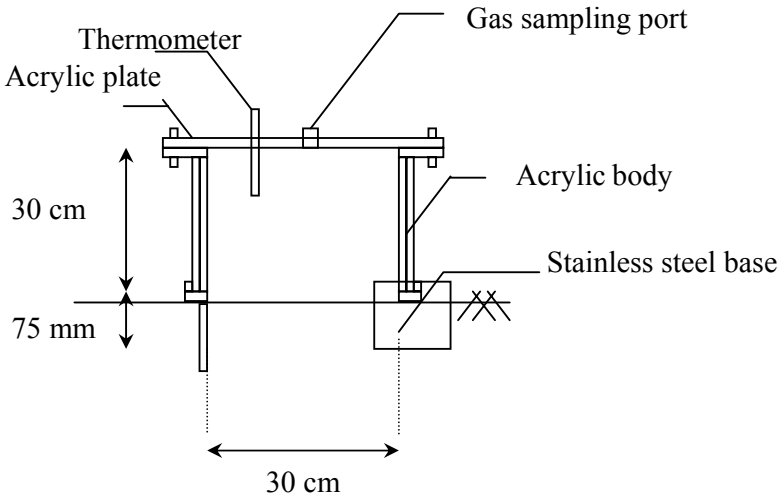

Figure 8 Schematic of closed-flux chamber

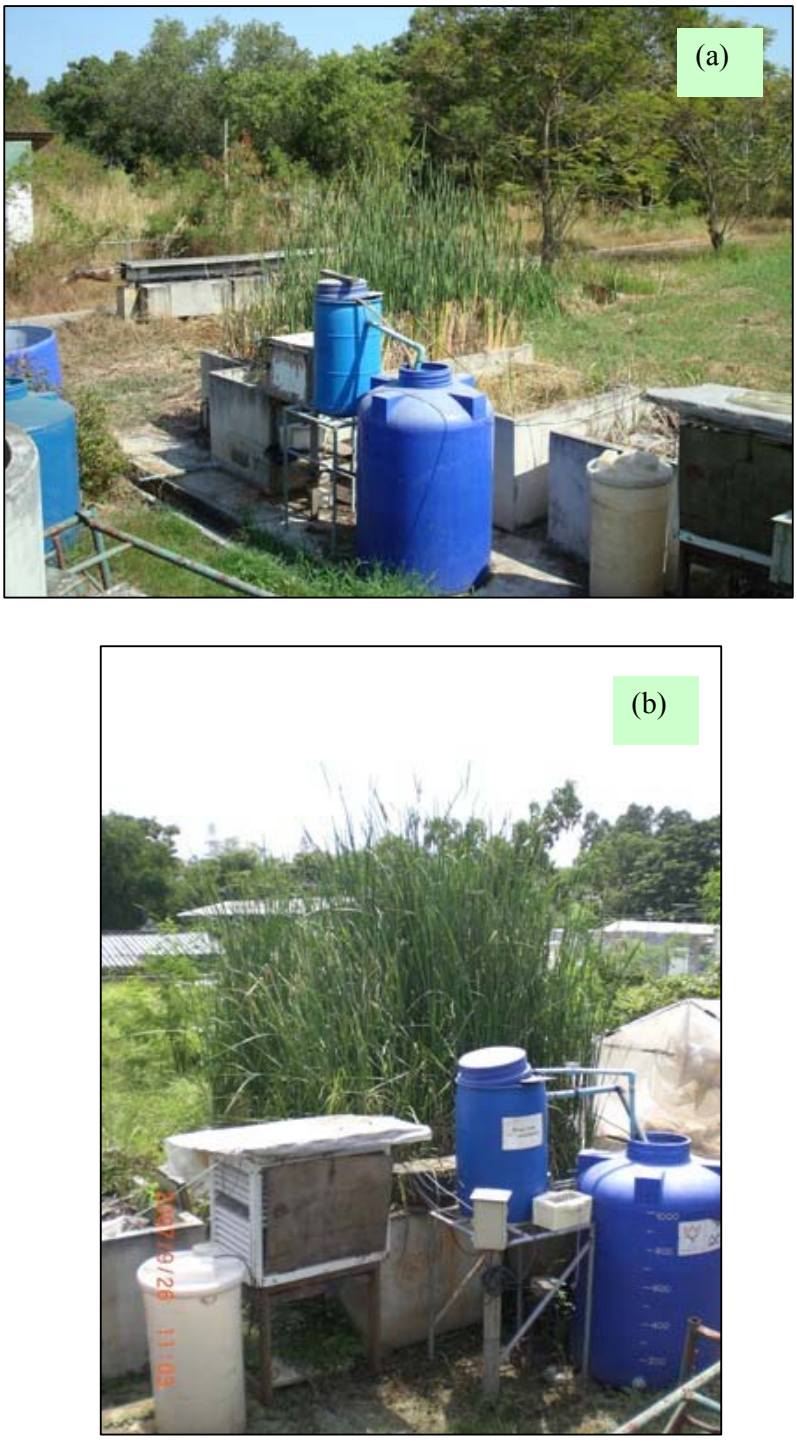

Figure 9 Experimental set up used in this study; (a): System A; (b) System B

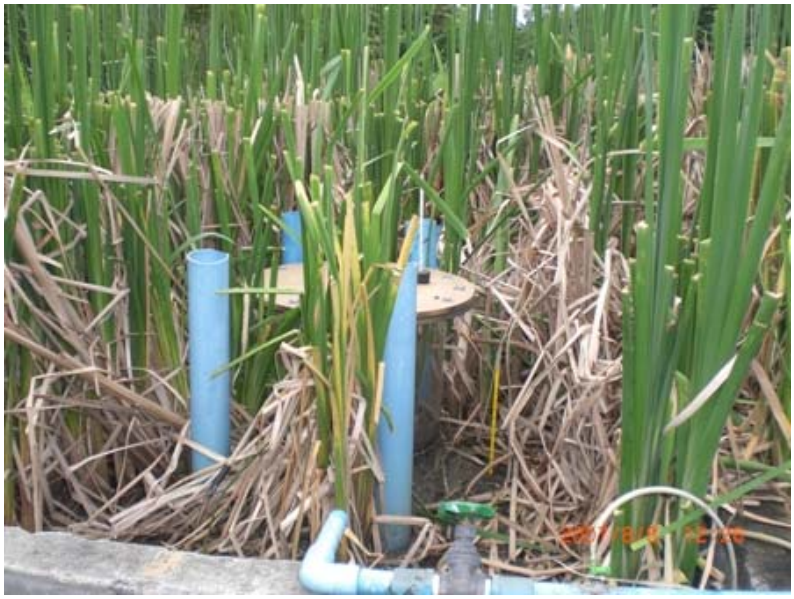

Figure 10 Close flux chamber in operation

Table 4 Characteristics of landfill leachate used in this study

Parameter	Value			
	Fresh leachate		Stabilized leachate	Mixed leachate/ **Run II**
	Before dilution	After dilution/ **Run I**	Before dilution	
pH	4.22-4.31	4.5-6.8	8.01-8.09	4.33-5.33
Temperature/(^{o}C)	27-29	27-30	26-28	27-30
COD/(mg/l)	52500-68571	2650-5350	1053-1816	3221-7040
BOD_5/(mg/l)	28200-47200	1365-2985	150-330	1380-3652
BOD_5/COD	0.7-0.85	0.6-0.8	0.1-0.4	0.45-0.6
TOC/ (mg/l)	18750-22857	N/A	330-551	1151-2385
TKN/(mg/l)	336-672	55-105	149-525	118-198
NH_3-N/(mg/l)	409-515	45-78	194-427	85-157

Methods

1. Procedures for System Operation

1.1 System operation

As shown in figure 7, two pilot scale subsurface horizontal constructed wetlands with 10 days of hydraulic retention time (HRT) and 28 mm/d of hydraulic loading rate which was equivalent to 112 l/d were constructed at the Asian Institute of Technology (AIT) campus in Pathumthani province in Thailand. Four concrete ponds of 1 m wide and 3 m long and 1 m in depth were used. The inlet and outlet zones were filled with 30-60 mm gravel up to the 0.8 m and 1-2 mm sand was filled in plantation zone. The operating water depth was maintained at a depth of 0.6 m from the bottom level. The leachate was fed into the system by a submersible pump through an inlet pipe (10 mm in size) with valve control. The waster water (leachate) flew downwards was moved through treatment (plantation) zone and was discharged from the outlet zone through an out let pipe (50 mm). Cattail (*Typha augustifolia*) was used as an emergent in the system at initial planting density of 40 rhizomes per m^2.

Basically experiment was conducted in two runs and each run all both CWs were functioned. During the first run only fresh leachate was fed to both systems. The system A was operated without leachate recirculating whereas in system B, inlet was diluted by 50% effluent leachate recirculating. Parameters were taken until CW reached to steady state condition.

The second run was operated as previously discussed, but the characteristics of substrate were altered. The same HRT and HLR were unchanged and recirculation percentage too. The characteristics of leachate fed to the systems can be figure out in table 4. It was supposed to find out the changes of gas emission when the type of leachate altered. Furthermore stabilized leachate was mixed to elevate the N content in 2 run.

3.2 Method for Gas Emission Measurement

After installation a closed-flux chamber on a final cover soil, a gas sample was collected into a 5-ml vial by a gas-tight syringe from a closed-flux chamber by time interval (every 15 minutes) up to 360 minutes. Then, gas component in a vial was identified through a gas chromatograph (GC 6890). Investigating an appropriate time for gas sampling to be performed, this measurement was conducted on random selection of about three locations in wetland. Then, plotting methane, carbon dioxide and nitrous oxide concentration with time, as discussed in pervious chapter, identify an appropriate time of gas sampling and this information was applied in the subsequent experiments. In addition, temperature of soil/air/inside the chamber was also measured during gas collection. Further complete weather report was taken from AIT campus.

Closed flux chamber operated by allowing the soil gas to accumulate in the chamber and by withdrawing samples at timed intervals. The samples were later analyzed for the change of gas concentration, and the gas flux was found according to:

$$F = \frac{\rho V \Delta C}{A \Delta t}$$

Where F = Flux of gas, ($g/m^2.s$); ρ = Density of the gas, (kg/m^3); V = Volume of the Chamber, (m^3); A = Surface that are enclosed by the Chamber, (m^2); ΔC = Change in concentration of the gas, (%); Δt = Time interval over which the samples are taken (s).

Employing above close flux chamber the gas emission was measured in all four ponds of CW. The. In other words gas emission was measured along the CW and chambers was placed at three points in one ponds, i.e., close to inlet area, middle of the CW and close to out let area.

3.3 Conditions of Gas Chromatograph

1) Gas chromatograph (Agilent 6890) with thermal conductivity (TCD) was installed with 8 ft*1/8" O.d., SS column (Heyesep Q, 80/100 Packed). Temperatures of injector, detector and column were 120, 160 and 35 ^{o}C, respectively. Helium gas is a carrier gas with a flow rate of 30 ml/min. This GC was used for measuring nitrous oxide. The sample volume was 0.3 ml.

2) Gas chromatograph (Agilent 6890) with thermal conductivity (TCD) has been installed with stainless steel column (Alltech-CRT). Temperatures of injector, detector and column were 120, 160 and 30 ^{o}C, respectively. Helium gas was a carrier gas with a flow rate of 65 ml/min. This GC was used for measuring methane, carbon dioxide, oxygen and nitrogen gas. The sample volume was 0.3 ml.

3.4 Gas and leachate sampling

1) Gas: a gas was withdrawn from a chamber by gas tight-syringe – 5 ml and injected into a sealed-serum tube- 5 ml.

2) Leachate sampling was down at inlet, middle and out let zones in both wetlands at weekly basis.

3.5 Oxidation reduction potential measurement in soil

Portable ORP meter (HANNA Co. Ltd. Romania) was used to measure soil ORP under the stable condition of both wetlands. ORP measurements were taken at inlet, middle and outlet which were the exact gas emission points.

3.6 ORP measurements

Under the stable condition of wetlands ORP measurements were taken using portable ORP meter. Along the wetland which was represented inlet, middle

and outlet points and every 15 cm from the wetland surface, at the each above mentioned points, measurements were taken.

4. Analysis parameter

Table 5 Analysis method of samples

Parameter	Unit	Analytical method/ instrument	Frequency	Remarks
Gas				
CH_4	%	Gas chromatograph GC 6890	Weekly	(Alltech-CRT)
CO_2	%	Gas chromatograph GC 6890	Weekly	
N_2O	%	Gas chromatograph GC 6890	Weekly	Heyesep Q, 80/100
Leachate				
BOD_5	mg/l	Azide modification method	Weekly	APHA (1989), Standard Methods for the Examination of Waste Water, 6th Edition.
COD	mg/l	Dichromate reflux method	Weekly	
TKN	mg/l	Macro Kjeldahl method	Fortnight	
NH_3-N	mg/l	Distillation method	Fortnight	
pH		Potable pH meter	Weekly	
ORP	mV	Portable ORP meter	do	HANNA Co.

RESULTS AND DISCUSSION

1. Performance of pollutant removal

Table 9 shows the influent and effluent qualities from the experiment systems treating young landfill leachate at hydraulic loading rate of 28mmd^{-1}. In both systems under the given conditions and under the steady state it was found that the removal efficiency in terms of COD, BOD and TKN were 98, 97 and 40 % respectively.

Table 6 Characteristics of leachate in wetlands under steady state condition

Items	pH	COD /(mg/ l)	BOD/(mg/ l)	TKN/(mg/ l)
Influent A	4.5- 6.6	3200-5350	1665-2985	65- 105
Effluent A	6.9- 7.8	80- 128	28- 55	34- 63
Influent B_1	4.8- 6.8	2560-4350	1365-2385	55- 105
Influent B_2	6.9- 7.3	80- 128	32- 48	34- 58
Effluent B	6.9-8.1	80- 118	34- 48	31- 62

Where: B_1: Raw leachate and B_2: Re-circulated leachate to the system B

These high pollutant removal efficiency rates indicate that there was ample adsorption capacity and plant biomass growth. Further it showed that plant uptake and biological degradation of organic substances by attached growth microorganisms under aerobic, facultative and anaerobic soil conditions in the top, middle and bottom zones respectively. This was proved by conducting ORP analysis In terms of nitrogen removal the average removal efficiency was 40% under the given condition. Unlike organic substance, TKN removal took place gradually along the treatment unit. Organic nitrogen can be transformed by ammonification and nitrification reactions to oxidized forms (NO_2^- and NO_3^-) and subsequently removed by either denitrification or plant uptake. The removal efficiencies obtained here are well agreed with the values obtained by Chiemchaisri *et al*., (2006).

2. Gas emission measurements

2.1 Optimum Sampling Time

The objective of this experiment was to investigate an appropriate time for determination of gas emission rate through a closed-flux chamber. In general, gas concentration in the chamber relates directly to the methane emission rate (MER), which results in variation of optimum sampling time of inside-gas. In this experiment, the result showed that methane and carbon dioxide concentration had been slightly increasing and reaching its maximum concentration within 1-2 hours after installation of chamber on the topsoil of wetland. The rate of gas emission cloud be obtained by finding a slope of linear graph. It can summarize that an appropriate time for gas sampling by a method of closed-flux chamber should be about 2 hours for this study. This time period was used for subsequent gas samplings. The time period obtained here was differed with other researches. Liikanen *et al.,* (2006) has done the gas sampling within 24-60 minutes after installing the chamber.

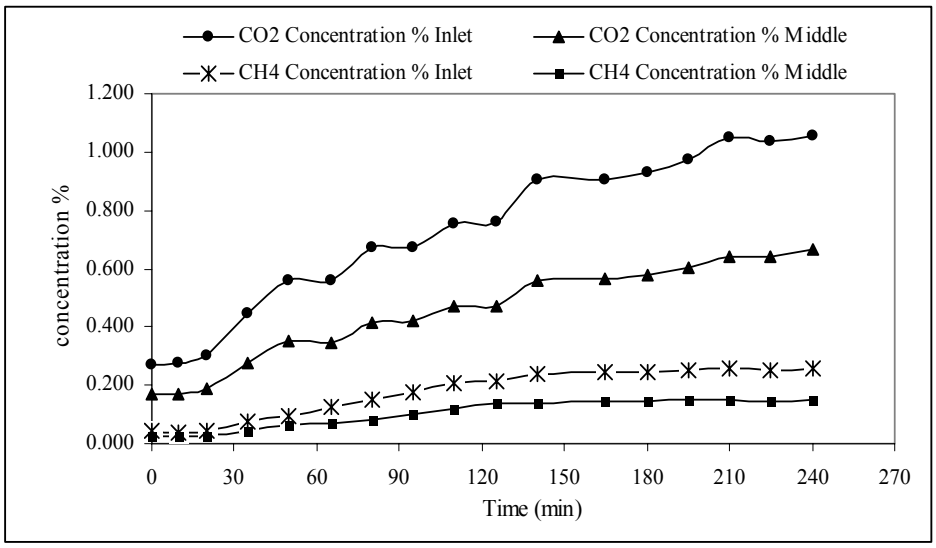

Figure 11 CH_4 & CO_2 concentration change with time inside the chamber

2.2 Effects of temperature on gas emission rate measurement

A measurement of wetland temperature was conducted at a cover soil (about 10-cm of depth) and an ambient air (at about 1-m of height from topsoil surface) by using a thermometers. It was found that an air temperature was higher than a soil temperature from about 5 to 6 degrees (Fig. 12). Both of temperatures were increasing during 11:45 to 14:15 and the maximums were found at 14:00. For soil temperature, the ranges of soil temperature were of about 28-29 ^{o}C, while an air temperature were of about 29 –34 ^{o}C. Ranges of temperature in soil and outside air at experimental site during the experiment (25 June 07) is presented in Table 5. The range of soil temperature was 27.5-33.5 ^{o}C , while the range of atmosphere temperature was 29-44.5 ^{o}C.

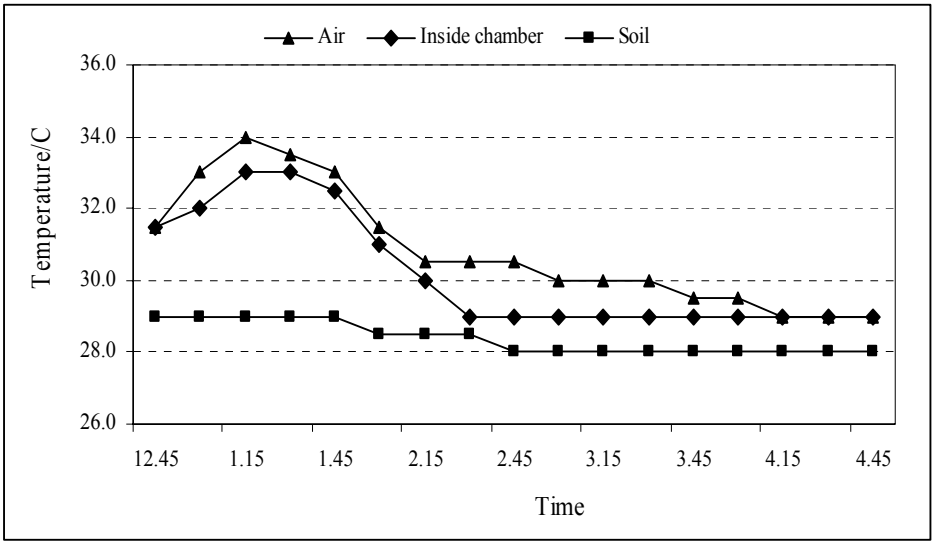

Figure 12 Temperature variations during sampling

Measurement of temperature inside a chamber was also done during measurement of landfill emission rate by a closed-flux chamber (1-2 h). Moderate fluctuation of temperature was found in a chamber and it was slightly higher than a soil temperature (1-degree average) after 2.30 pm and 3-degree average in the rest time. In the same manner it was found that there was a insignificant difference of an air temperature compared to the chamber temperature (about 1-2 degrees, Fig. 12). Borjesson and Svensson (1997) also reported that temperature in a close flux chamber

was slightly increase insignificantly by less than 1 ^{o}C difference. It suggests that an air temperature did not much affect a chamber temperature, or in the other words, an ambient temperature did not influence measurement of methane emission by a close flux chamber.

Table 7 Temperature in air and soil during fresh leachate experimental run

Date	Air Temperature/(^{0}C)			Soil Temperature/(^{0}C)		
	Maximum	Minimum	Average	Maximum	Minimum	Average
25/06/07	34.0	29.0	31.5	29.0	28.0	28.5
4/7/2007	39.5	34.0	36.8	31.0	28.0	29.5
5/7/2007	34.0	32.0	33.0	29.5	28.0	28.8
13/7/2007	40.0	36.0	38.0	32.0	29.5	30.8
19/7/2007	43.0	34.0	38.5	31.5	28.0	29.8
26/7/2007	42.0	35.0	38.5	30.0	29.0	29.5
3/8/2007	36.5	31.0	33.8	29.5	28.0	28.8
8/8/2007	30.0	27.5	28.8	28.0	27.0	27.5
16/8/2007	40.5	38.0	39.3	31.5	31.0	31.3
22/8/2007	44.5	32.5	38.5	33.5	29.0	31.3
29/8/2007	37.5	31.5	34.5	31.0	28.0	29.5
5/9/2007	40.0	35.0	37.5	31.0	28.0	29.5
12/9/2007	43.0	35.0	39.0	31.5	29.0	30.3
26/9/2007	41.0	32.0	36.5	31.5	29.0	30.3
3/10/2007	36.0	32.0	34.0	31.0	28.5	29.8
12/10/2007	33.0	29.0	31.0	28.0	27.5	27.8
Average	38.4	32.7		30.6	28.5	

3. Measurements of greenhouse gas emissions from wetland- Fresh leachate

3.1 Greenhouse gas flux pattern along the flow path

After finding out it was supposed to find out the greenhouse has emission variation throughout the wetlands. To find these basically 3 points were selected which represented the flow path of each wetland. Inlet zone which was just ahead the inflow point, middle and out let zone which was just behind the out flow were selected as 3 points and these places were used for subsequent gas measurements

throughout experimental run. Figure 13 illustrates the greenhouse gas emission pattern along the wetland for the particular week of a month.

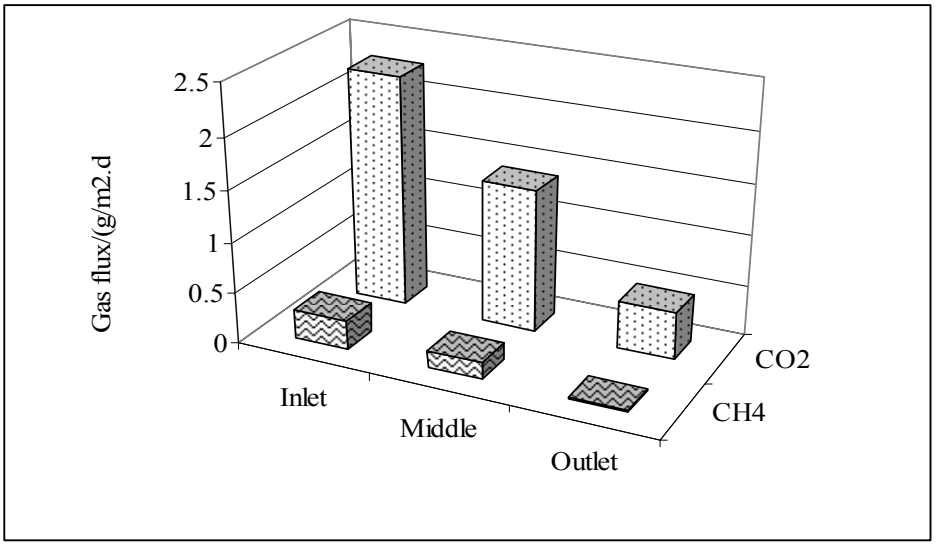

Figure 13 Gas flux profile along the wetland in a particular month

From the above figure 13 clearly shows that the greenhouse gas flux profile changes with the distance from inlet. In this particular week the CH_4 emission rate at the inlet was 0.285 $g/m^2.d$, middle 0.171 $g/m^2.d$ and in outlet zone it was 0.019 $g/m^2.d$. The correspondent CO_2 gas emission rate was 2.281, 1.399 and 0.466 $g/m^2.d$. It can be found that the maximum emission rate was occurred in inlet zone whereas the minimum was in outlet zone. Teiter and Mander, (2005) also reported that most intensive gas flux were observed in chambers installed above the inflow pipes of wetland in their study. This pattern was noticed whole experimental time period although the values significantly different. But many time occasions the emission of CH_4 at outlet zone was zero. Although it is considered as a zero emission there might be very small emission which can not be detected via GC which was used for this investigation. This type of emission pattern can be justified well because leachate was purified along the wetland due to its processes. At the inlet zone there was high strength leachate which was what fed to the system and in outlet the strength of leachate was reduced. Therefore it is reasonable to anticipate this kind of variation.

Furthermore Gui *et al*., 2006 and Johansson *et al*., 2004 also have found the same gas emission pattern from their studies.

3.2 Greenhouse gas emission from different place in wetland

After investigating the gas flux pattern it was supposed to quantify each greenhouse gases emissions form wetland. Gas emission measurements were carried out until both wetlands reached steady state condition. Gas measurements were commenced at June and after five months later both wetland reached steady state condition. Figure 14 shows CH_4 emission rate at inlet in both system A and B and figure 15 shows the correspondent CO_2 emission rate. From the figure 14 it can be noted that the CH_4 emission rate was ranged 0.0790 $g/m^2.d$ – 0.7122 $g/m^2.d$ in system A and 0.0190 $g/m^2.d$ – 0.5222 $g/m^2.d$ in system B.

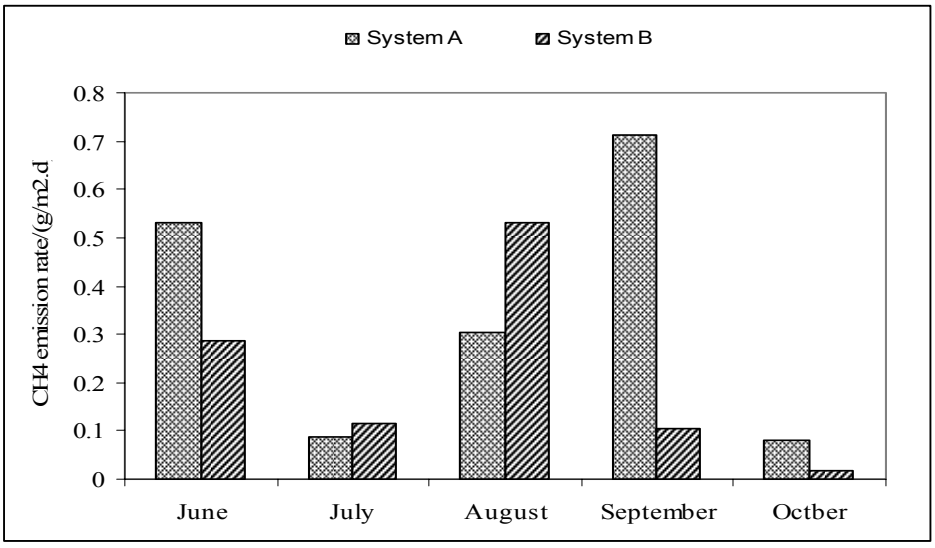

Figure 14 Emission rate of CH_4 from inlet from both systems

From figure 14 it shows that the maximum CH_4 emission of 0.7122 $g/m^2.d$ had been in September and lowest 0.0190 $g/m^2.d$ had occurred in October. As discussed in literature review part many factors affect for gas emission, among that environmental factors plays a vital role. From the observation it was noticed that

elevated air temperature was prevailed in September and this might be affected for elevated gas emission. Liikanen *et al*. (2006) also concluded that air temperature and CH_4 emission had a positive relationship. Furthermore in October relatively low air temperature was observed during our sampling dates. This might be the reason for lower CH_4 emission to emit in both systems in October. Elevated air temperature can lead to elevate soil temperature and this could accelerate the bacteria activity in the soil matrix in wetland which in turns may lead to generate more and more CH_4 by methanogens in wetland. In addition to the elevated temperature in September new leachate run was added. Although during our study all necessary steps were taken to control the inflow COD concentration below 5000 mg/l but at the new leachate run it was difficult to control it at the very first turn. Therefore this higher concentration may lead to elevated CH_4 emission too.

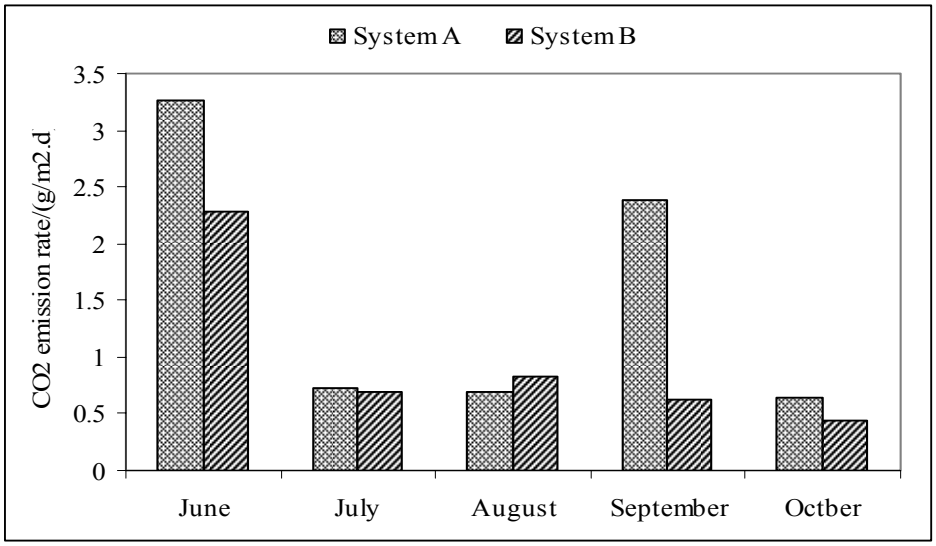

Figure 15 Emission rate of CO_2 from inlet from both systems

Figure 15 shows the CO_2 emission rate at inlet of both wetland systems. From the graph it can be noted clearly that higher CO_2 emission rate in June and September and lower gas emission in other months. Maximum gas emission was 3.265 $g/m^2.d$ and minimum correspondent value was 0.648 $g/m^2.d$ in system A. On

the other hand maximum gas emission for system B was recorded as 2.228 $g/m^2.d$ while minimum was 0.440 $g/m^2.d$. Further this graph illustrate the emission of system A is greater than system B in most of the time and much greater emission than CH_4 correspondent values. As it was explained in pervious paragraph the wormer air temperature was recorded in October and high leachate concentration was applied to the systems in June, therefore elevated CO_2 emission too observed in these two months. Teiter and Mander, (2005) also reported that in wormer months CO_2 gas emission form wetland was higher in their study.

During the study period it was observed that the greater variation of greenhouse gas emission occurred in both wetlands, but the emission of CH_4 was diminished at the outlet zone but the emission of CO_2 was not so. In the middle of wetland A the CH_4 emission was ranged 0 $g/m^2.d$ – 0.085 $g/m^2.d$, whereas in system B it was ranged 0 $g/m^2.d$- 0.061 $g/m^2.d$. In July and October the emission of CH_4 was not detected in system A and this was occurred in system B in October. This could happen because relatively low temperature of average 31^0C (Appendix table A4) prevailed in October and steady state condition at which the maximum treatment efficiency occurred in both systems.

On the other hand in some experimental days it was noticed that the water table was lowered by significant length (about 5-10 cm) than it was supposed to be. In this time period it was clearly noticed that, although the same concentration of leachate was fed to the systems, remarkable declination of gas emission in all points. Especially CH_4 emission showed much sharp declination than CO_2 emission. This might lead to the zero emission of CH_4 at middle section in both systems irrespective of leachate concentration and temperature prevailed in site. Teiter and Mander, (2005) concluded this occurrence in other words. They reported the water table increase in the horizontal subsurface constructed wetland systems may not significantly influence the efficiency of leachate purification, although it will increase CH_4 emission by a few magnitudes. Therefore our gas emission results and patterns are in line with these researches.

Figure B1 shows the CH_4 emission at middle, CO_2 emission from middle and outlet zones in both systems in Appendix B. Emission of CH_4 throughout both wetlands showed significant diminishing trend, i.e more than 94% of the total CH_4 emission was generated in the first 3 m of the wetland. This data clearly fit with data obtained by Gui *et. al*., (2007). They reported that approximate 90% of total CH_4 was generated had been emitted within 3m of the same type of wetland.

Table 8 CH_4 emission within first 3 m along the system A

Month	Total CH_4/(g/m^2.d)	CH_4 emission within first 3 m /(g/m^2.d)	%
June	0.5493	0.5408	98
July	0.0886	0.0886	100
August	0.3471	0.3257	94
September	0.7983	0.7556	95
October	0.0790	0.0790	100

Table 9 CH_4 emission within first 3 m along the system B

Month	Total CH_4/(g/m^2.d)	CH_4 emission within first 3 m /(g/m^2.d)	%
June	0.2992	0.2922	98
July	0.1257	0.1198	95
August	0.5940	0.5631	95
September	0.1045	0.1045	100
October	0.0190	0.0190	100

This kind of CH_4 emission is possible because most of the organic substances were removed within the first 1-2 m from the inlet point. Leachate analysis proved this, therefore after middle point there were lowered organic substances to be treated. As a result the emission of CH_4 can be expected to be declined and even zero emission. Chiemchaisri *et al*., (2006) also had investigated leachate treatment efficiency from the same wetland under same conditions and obtained same patterns.

4. Diurnal variation

During experiment time period, diurnal variation was also measured in order to check the greenhouse gases emission during night time. Gas measurement was done continually during 24 hr, while every 3 hr was time interval for gas measurements. Middle point was selected to carry out the experiment because it can be considered as a moderate representative for both inlet and out let zones.

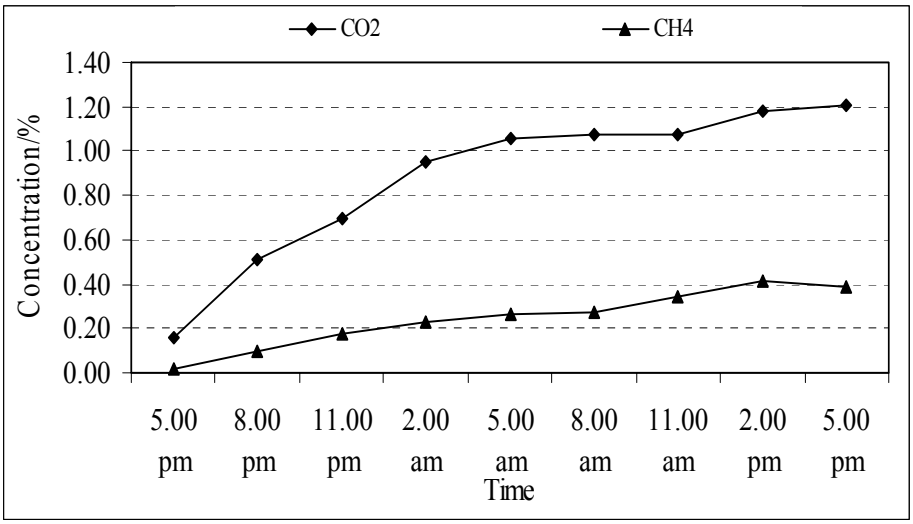

Figure 16 Diurnal variation of CH_4 & CO_2 at middle of system A

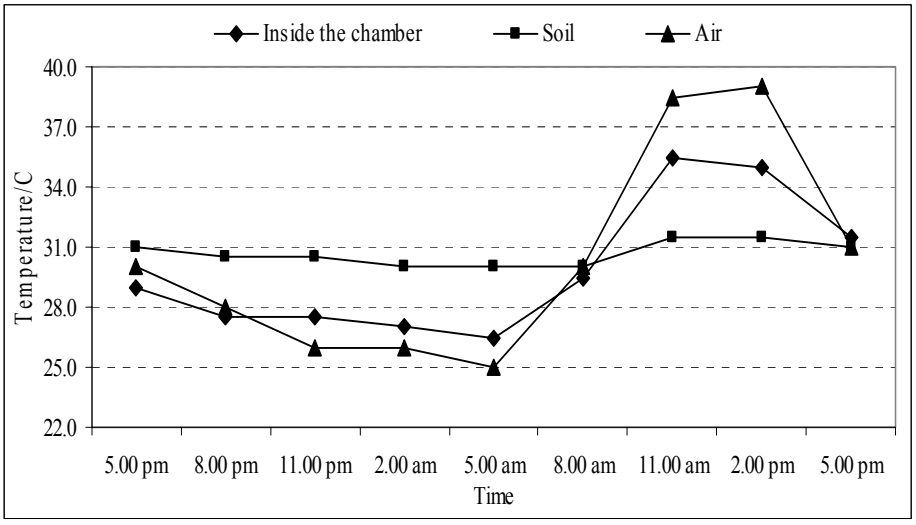

Figure 17 Temperature variation during sampling at middle of system A

From the results obtained it was found that the both greenhouse gases emission were increased during night time. Especially CO_2 emission showed a significant increment and it can be averaged 32%-80% while CH_4 emission in a day time it was increased just over 10%-20% in night time. Further it was observed when all three temperatures were more or less equally the gas emission lowered. Figure 16 and figure 17 indicated that at 8.00 pm this was happened. To increase the CO_2 emission in night time the photosynthesis bacteria in soil matrix of wetland could be the possible reason. During day time they can perform photosynthesis so that they consume more CO_2 and produce O_2 whereas in night time they may reverse the process, i.e. respiration process. Bacteria can consume O_2 and produce CO_2. As a result of these process in night time there might have a tendency to increase the emission of CO_2.

In the case of CH_4 increment in night time the following reason could be affected. The soil matrix of wetland can be divided basically three zones according to the soil oxidation reduction potential. This is explained in coming paragraph under the ORP section in detail. First strata of wetland depth can be totally aerobic, then next strata can be facultative and deeper strata can be totally anaerobic zones. CH_4 is

produced in deeper zones and it can undergo biological degradation process (Gui *et al.*, 2007) in the other two zones. Therefore in night time there can be lower temperature (see figure 17) so that aerobic bacteria might be affected and degradation process can be lowered. As a result conversion of CH_4 to CO_2 via these bacteria could be minimized, because aerobic or facultative bacteria can be more sensitive for temperature alternation than anaerobic bacteria. Other figures which are represented gas emission in system B and correspondent temperature variation are in Annex B.

5. Soil oxidation reduction potential (ORP)

To get some understand about the way of soil matrix behaves for the gas emission, the ORP distribution inside the wetlands was assessed after it reached a stable condition in October. Figure 18 shows the spatial distribution of ORP inside the wetland A and B.

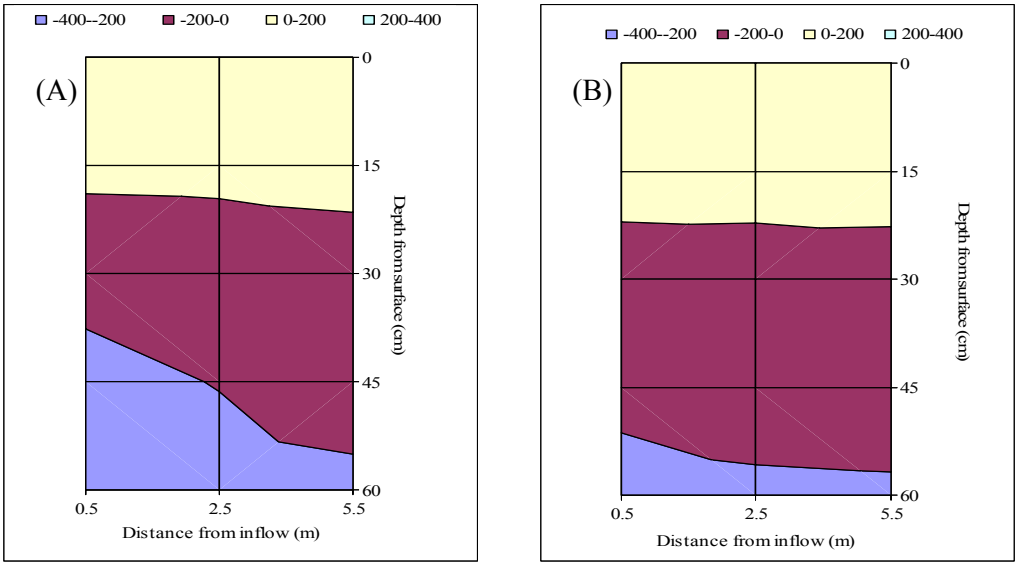

Figure 18 (A) ORP distribution in system A; (B) ORP distribution in system B.

ORP can be divided into three levels (Kralova *et al.*, 1992; Patrick *et al.*, 1993). An ORP > 200 mV represents a totally aerobic status; an ORP in the -100-200 mV range is indicative of a mix of anaerobic and aerobic status; an ORP < -100 mV

represents a totally anaerobic status. As shown in figure 18, the < -100 mV areas were mainly located bottom in the both wetlands. Further the depth of < -100 mV areas were reduced along the wetland. This can occur because along the wetland since leachate flow was treated due to different processes. No totally aerobic areas were located in any wetland. Even at the surface of both wetlands a mix of anaerobic and aerobic status were present. CH_4 emission showed a clear relationship to distribution of the ORP< -100 mV group. Approximately 95% of the total CH_4 emission was generated in the first 3 m of the wetland. In system B the ORP values of depth between 0- 30 cm from surface was greater than system A. Thus low CH_4 emission was recorded in system B than A. On the other hand it can be seen that the system A had larger totally anaerobic area than system B. This could result to generate much more CH_4 in system A than B. These both reasons ultimately could affect to lower the CH_4 emission in system B although other parameters were the more or less same.

6. Evaluation of wetland for treating mixed landfill leachate

To increase the N content and to investigate the behavior of wetland under this condition it was proposed to mix stabilized leachate with fresh leachate in the proportion of 1:1. The other important suggestion was to investigate the leachate qualities, in other words to evaluate leachate treatment performance while carrying out GHG emission. The main controlling leachate parameter was the COD of influent and effort was taken to keep it around 5000 mg/L. Diurnal variation was also carried out in this run. Table 10 shows the fresh and stabilized landfill leachate characteristics which were used to treat from the constructed wetland.

Table 10 Characteristics of fresh and stabilized leachate

Items	pH	COD	BOD	TKN	NH_3-N
		mg/ L	mg/ L	mg/ L	mg/ L
Fresh leachate	4.22- 4.31	52500-68571	28200-47200	336-672	409-515
Old leachate	8.01-8.09	1053-1816	150-330	149-525	194-427

7. Organic pollutant removal efficiencies in the system

Both wetland systems were taken 9 weeks to attain the steady state condition. But to make sure that the wetland systems became stable condition more 3 weeks experiments were carried out. Constructed wetland can be checked whether the systems achieved stable condition by conducting experiment more than three times than its hydraulic retention time (HRT) until to get the relative constant effluent BOD_5 or COD concentration (Sawaittayothin and Polprasert, (2007). Figure 23 illustrates the organic removal efficiency in terms of COD in system A.

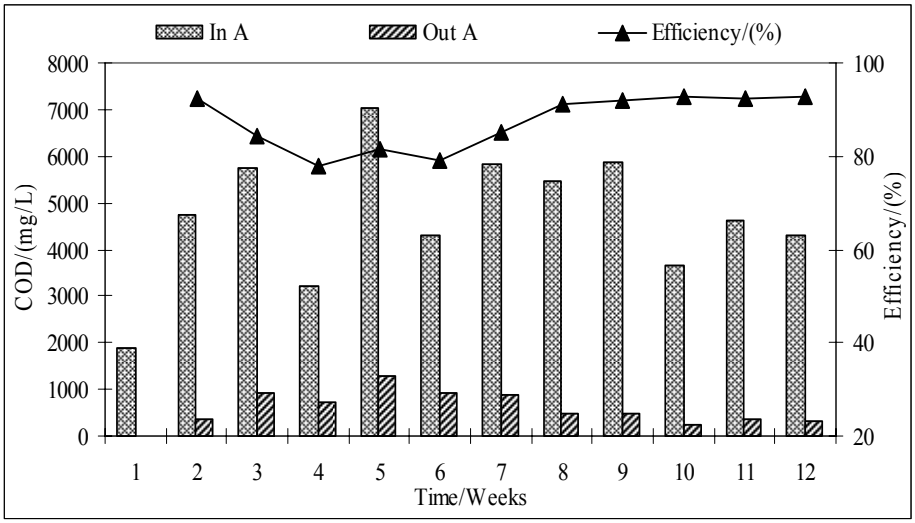

Figure 19 Organic pollutant removal efficiency in terms of COD of system A

Figure 19 clearly shows that the wetland system A had performed well in terms of organic pollutant removal. At the stable condition performance efficiency was 93%. At the beginning of experiment the efficiency was around 80% and when time went it had attained 93% removal efficiency. The possible reason for such high initial treatment efficiency may be the fact that short time duration between pervious run and this run. This run started after experiment run I finished and it was terminated at the stable condition as well. All physical parameters were the same for both runs although the quality of leachate changed significantly for the mixed leachate. This reason could be affected to shorten the time for attaining stable condition for the system. The average line indicates the value 5000 mg/L which was the intended COD value to feed the system. The lowest and highest values of COD influent were 1875mg/l and 7040 mg/l and other most of data were well inside the 18% of average COD value. This much of accuracy was taken by diluting and mixing landfill leachate both fresh and stabilized according to the mass balance and considering continuity.

These high rates of efficiency indicate that there was ample adsorption capacity and plant biomass growth. Sawaittayothin and Chongrak., (2007) reported that the mechanisms responsible for BOD_5 and COD reduction can be probably bacterial degradation in which oxygen photosynthetically produced by the cattail leaves are transferred to the root zones for the bacteria growing in the SFCW beds to biodegrade the organic compounds. Further Stottmeister *et al*., (2003) reported that plant uptake and biological degradation of organic substances by attached growth microorganisms under aerobic, facultative and anaerobic conditions in the top (rhizosphere), middle and bottom zones respectively as major treatment mechanisms in the wetland system to attain high organic removal efficiency. In this study, the oxidation reduction potential (ORP) values also investigated and it was found that our data fitted well with above mentioned statement. Figure 20 shows the organic pollutant removal efficiency in terms of BOD_5 in system A.

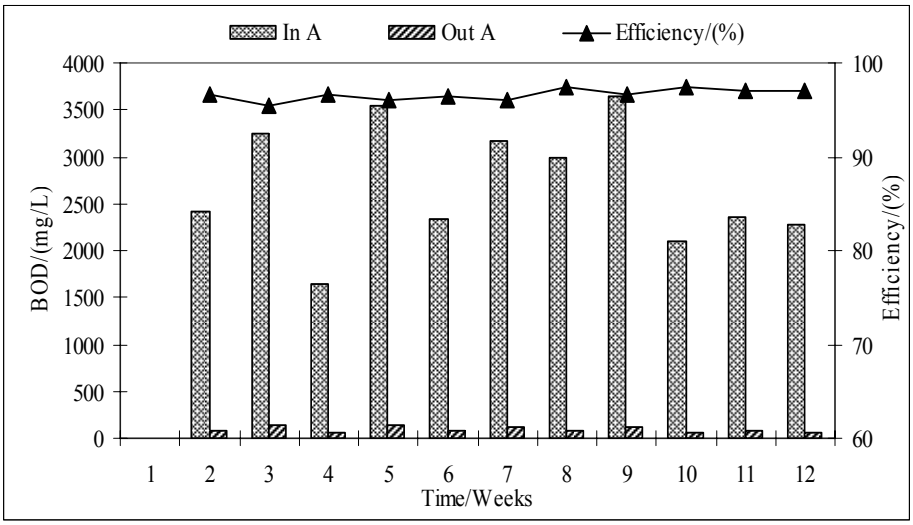

Figure 20 Organic pollutant removal efficiency in terms of BOD_5 of system A

High efficiency rate was recorded in terms of BOD_5 as well in system A and at the steady state condition the final efficiency has reached up to 97%. Further it showed that system had been reached to stable condition efficiency at the early stage and kept the efficiency quite steady rather than COD. In other words, COD efficiency rate showed significant variation through out the run. In contrast BOD_5 efficiency showed almost flat variation through out the experimental run. One possible reason for this might be the fact that the system had attained stable condition during run I and microorganisms have grown well in the system to cope up with incoming influent. In other words they need not adjustment time period since they already familiarized to system. The efficiencies obtained in this study are in line with those reported in the literature by Chiemchaisri *et al.*, (2006) with the 1-2 % declination. This difference may be the fact that in our study influent was a mixture of both young and stabilized leachate so their might have some hardly biodegradable substance especially in stabilized leachate. This could lead for slight drop of removal efficiency with respect to fresh leachate under same conditions.

The same trend was obtained in system B where leachate recirculation done. Steady state COD removal efficiency was slightly increased by just 1% than system A

and BOD_5 removal efficiency was reported as 97%. In B, plant growth was more uniform through out the wetland, in contrast in system A there was some died plant close to inlet zone. This might be due to high organic and N loading to the system A than system B. Because in system A mixed leachate was fed at a rate of 77ml/min, whereas in system B this amount of leachate loading was fed to the system with recirculate leachate, i.e. the concentration of incoming leachate was diluted by 50% by treated water in system B. Figure 21 and figure 22 illustrate the removal efficiencies in terms of COD and BOD_5 in system B.

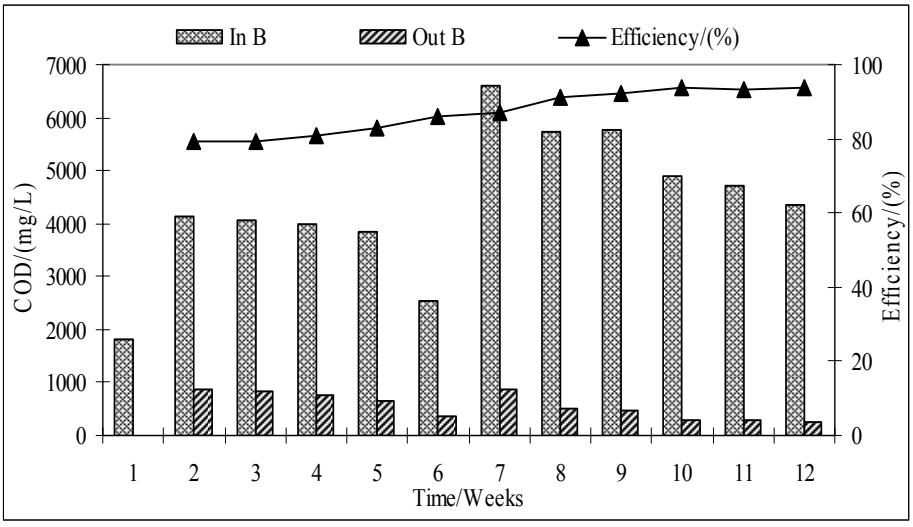

Figure 21 Organic pollutant removal efficiency in terms of COD of system B

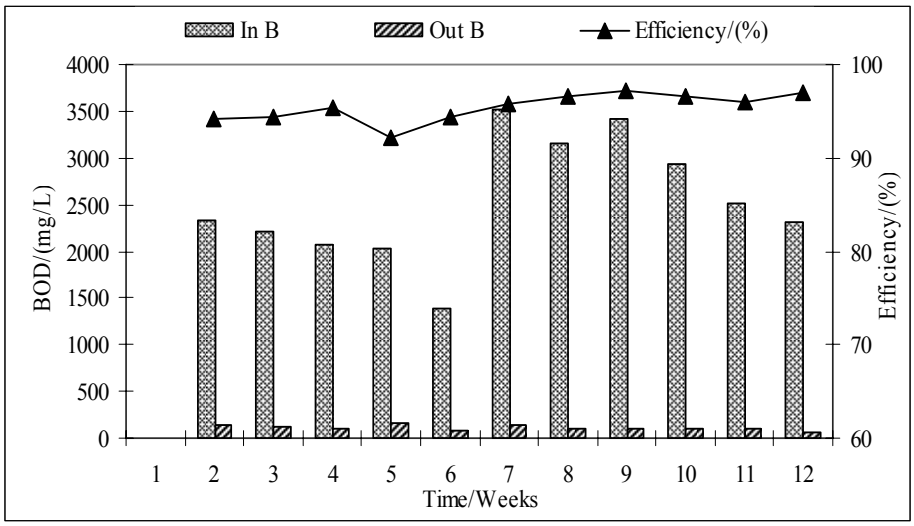

Figure 22 Organic pollutant removal efficiency in terms of BOD_5 of system B

In order to find out the efficiency profile along the flow one sample point was selected which represented the middle of the wetland system. Experiment data revealed a clear trend that in both systems, with in first 2 m the treatment efficiency rate passed the 75% mark. This was common for the both COD and BOD_5 but nitrogen removal occurred gradually along the wetland. Chiemchaisri et al., (2006) also reported this occurrence in their study. Other researchers mentioned that during their study of investigating emission of greenhouse gases for treating landfill leachate, with in first 2-3 m the gas emission was more than 80% of total gas generation. This may be also because of high organic removal efficiency rate with in the first 2-3 m in subsurface horizontal constructed wetland system (Gui *et al.,* 2007). Reddy and Burgoon (1996) reported that during their study it had been noticed the higher organic removal rates close to inflow of CWs and they have explained the occurrence may be due to fact that physical setting than microbial breakdown. Figure 23 shows it in graphically.

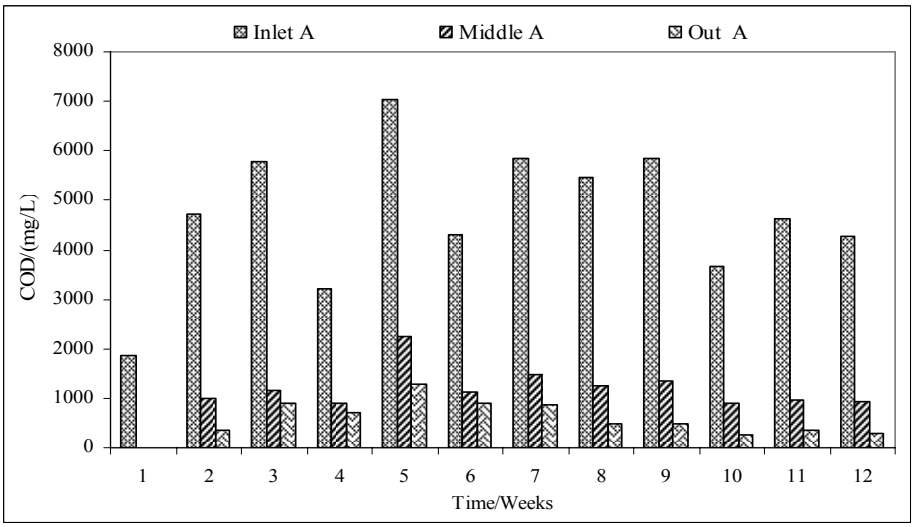

Figure 23 Organic pollutant removal profile along wetland in terms of COD of system A

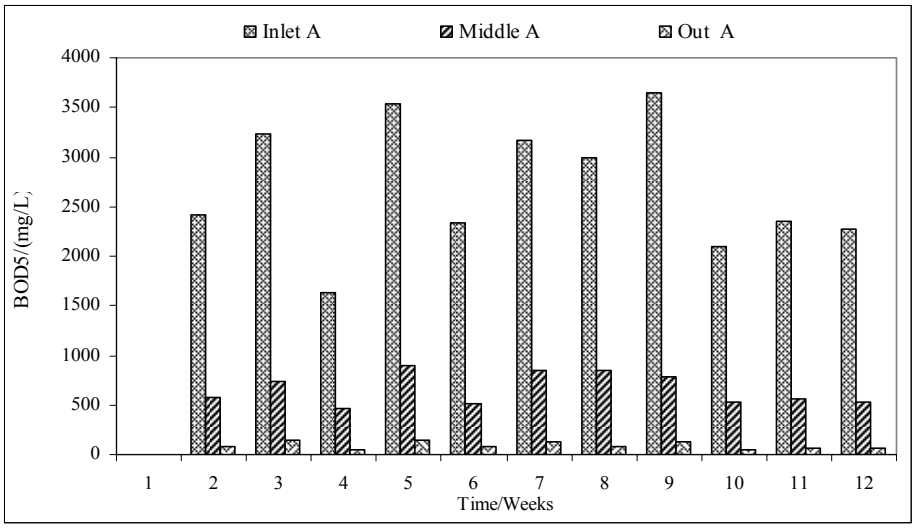

Figure 24 Organic pollutant removal profile along wetland in terms of BOD_5 of system A

For the elevated removal rate with in first 2-3 m the following reasons could be affected. Suspended solid in leachate are deposited in inlet zone causing high

removal efficiency (71-88 %) in CW (Chiemchaisri *et al*., 2006). And these deposited suspended solids clog the system, and can block the pores and decrease the hydraulic conductivity. Soil microorganisms are surrounded by polysaccharides containing structures (glycocalyx) of bacterial origin. The microorganisms and bacterial glycocalyx together form a highly organized matrix (biofilm), where most of the degradation and transformations processes occur (Mulamoottil *et al*., 1999). Therefore the removal trends obtained in our study are quite match with these explanations. Appendix figures B3 illustrate correspondent data for the system B.

8. Nitrogen removal efficiency in the system

In the case of nitrogen removal, TKN removals were ranged between 47-59 % in system A. When comparing organic pollutant removal efficiencies which were always over 94% in both systems of, this TKN removal efficiency can be considered as moderate rate of efficiency. But at the stable condition TKN removal efficiency was 50% in system A and 55% in system B. Higher efficiency had been achieved at higher loading rate in generally. Under the 10 days HRT time and 28mm/d HLR the obtained TKN removal efficiency are well accepted in our study. Chiemchaisri et al., (2006) obtained 46% TKN removal efficiency under the 28mm/d HLR in same wetland system. Hammer and Knight (1994) reported that 52 constructed wetland in the USA had N removal efficiencies of 30-60%. Further, Koottatep and Polprasert. (1997) concluded through their study in same experiment site, the N removal efficiency was 43%. Figure 25 shows TKN removal efficiency in graphically.

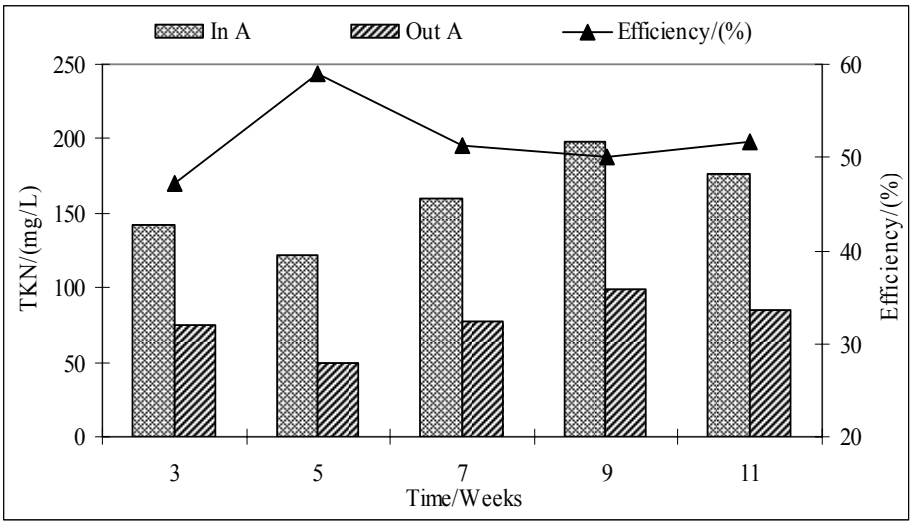

Figure 25 Nitrogen removal efficiency in wetland in terms of TKN of system A

Unlike organic substances, TKN removal took place gradually along the treatment unit. Organic nitrogen can be transformed by ammonification and nitrification reactions to oxidized forms (NO_2^- and NO_3^-) and subsequently removed by either denitrification or plant uptake. Further Vymazal (1999) reported that the mechanisms involved in nitrogen removal in constructed wetland are manifold and include volatilization, ammonification, nitrification /denitrification, plant uptake and matrix adsorption. Although such processes can be involved, many other physical factors will govern these processes. Temperature, pH, HRT is the few factors among them. Laber *et al.,* (1996) reported that nitrification and denitrification were more significant for the N removal (72%) from constructed wetland than other processes, whereas Koottatep and Polprasert. (1997) reported that plant up take was the main (43%) N removal pathway for their study. Any way in our study it is well fair to assume that plant up take was the main N removal pathway because some dead plants were observed near to inlet zone in both systems. This could be possibly caused by excessive NH_3-N loading. And the pH had quite lower values inlet area (4.23- 5.33) and this is not a favorable condition for the nitrification and denitrification. The optimum pH for the above processes is in between 7.0-8.5 Vymazal (1999). Figure 30 shows the NH_3-N removal efficiency for the system A.

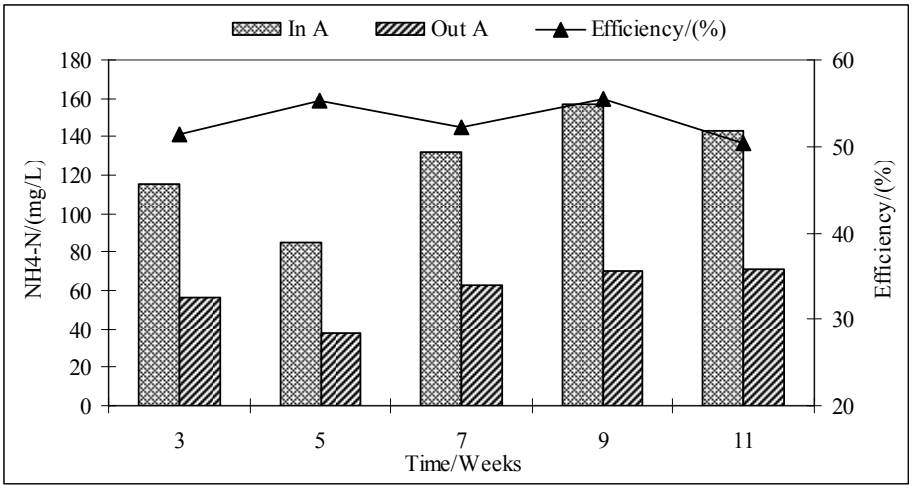

Figure 26 Nitrogen removal efficiency in wetland in terms of NH_3-N of system A

NH_3-N removal was averaged in between 50-55% in system A. Inflow concentration was varied in between 85- 157 mg/L. And the ratio of NH_3-N /TKN was in between 60-83%, for many cases it was close to 78%. To get moderate NH_3-N and even TKN the following reason could be affected. Nitrification and denitrification are highly sensitive for pH and temperature. Although temperature was suitable for processes in our case pH values were not so especially inlet area. Therefore nitrification and denitrification processes could be impeded resulting untreated leachate in terms of N content might pass to the middle and out let zones in wetland. Tjasa *et al.,* (1997) obtained 95% removal efficiency for NH_3-N in his study while maintaining favorable pH condition such as 7.4- 9.0 and temperature around 7.5^0C.

In system B where leachate recirculation was done, the N treatment efficiency was slightly high than system A. TKN removal efficiency was ranged in between 48-57 %. At the stable condition it was 55% and the correspondent value for system A was 52%. This slightly high removal efficiency might be fact that in system B, 50% effluent recirculation was done. This could enhance the nitrification/denitrification reactions. Laber *et al.,* (1996) concluded that higher N removal efficiency could be obtained through effluent recirculation and he got the 72% removal efficiency through

80% leachate recirculation. Figure 27 and 28 show NH_3-N removal efficiency and TKN removal in system B.

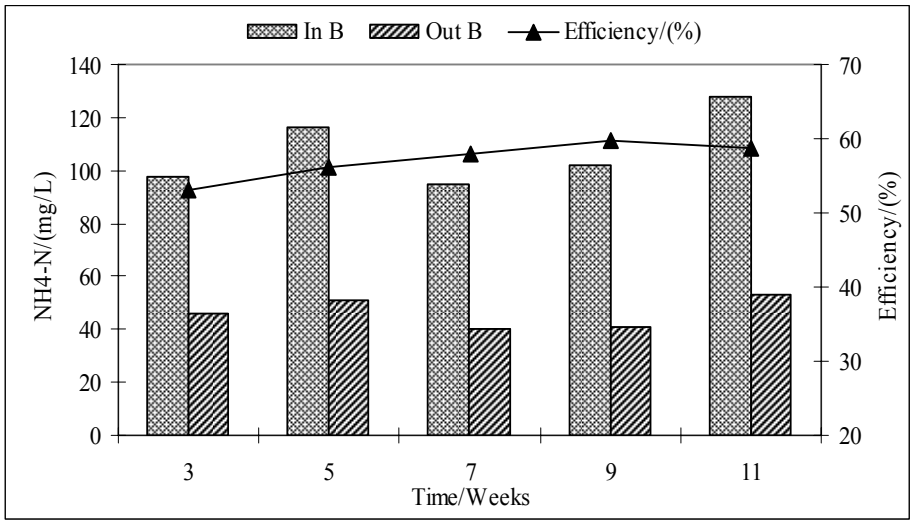

Figure 27 Nitrogen removal efficiency in wetland in terms of NH_3-N of system B

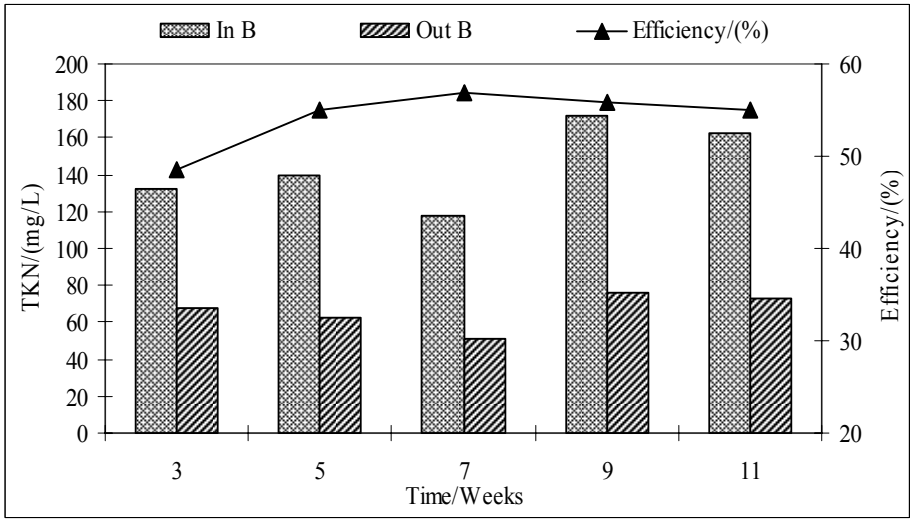

Figure 28 Nitrogen removal efficiency in wetland in terms of TKN of system B

As mentioned in previous section N removal took place along the wetland system. In this run N concentration was increased than previous run and it was averaged in between 122-198 mg/L in system A and 118-172 mg/L in system B respectively, in terms of TKN. In inlet zones of both wetland systems, there was not favorable condition for the nitrification/ denitrification process. Because of lowered pH condition could cause to impede this process, as a result of this treatment efficiency might be low in inlet zones. Further leachate flows towards the out let, it undergoes treatment through wetland due to many processes and pH of waste water obviously goes up. This could cause to create a favorable condition for nitrification/denitrification processes, which in turns can lead to keep alive treatment performance along the wetland. Therefore this process might be the reason for taking place of N removal gradually along the wetland. Chiemchaisri *et al.,* (2006) reported same occurrence during their study in same wetland system. Figure 29 shows this occurrence in graphically.

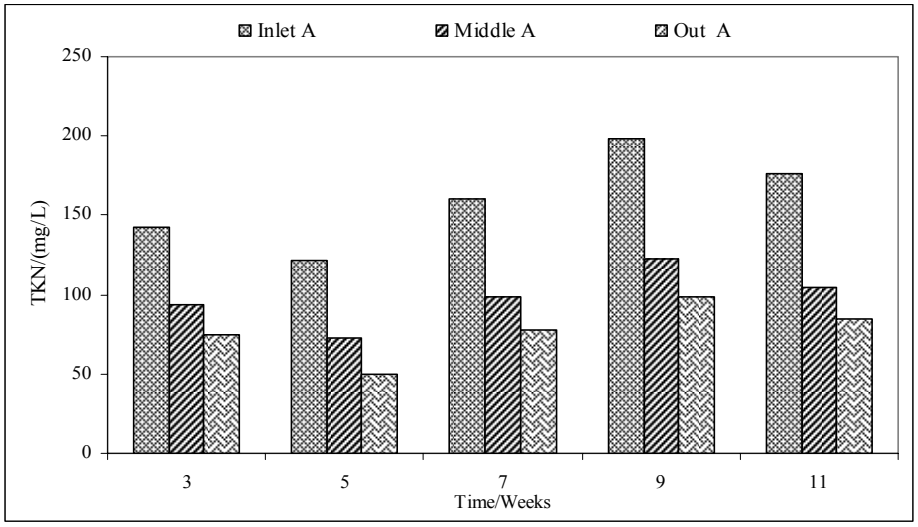

Figure 29 Nitrogen removal profile along wetland in terms of TKN of system A

Figure 30 shows NH_3-N removal profile along the wetland system A. The NH_3-N concentration was varied in between 85-157 mg/L at inlet in system A and correspondent value for system B was 95- 128 mg/L. At middle zone the efficiency

reached averagely 39% and end up in outlet zone around 52%. This shows significant difference with organic pollutant removal rate along wetland. In that case around 75% removal efficiency reached in middle zone in both systems. Correspondent graphs for system B are included in Appendix B.

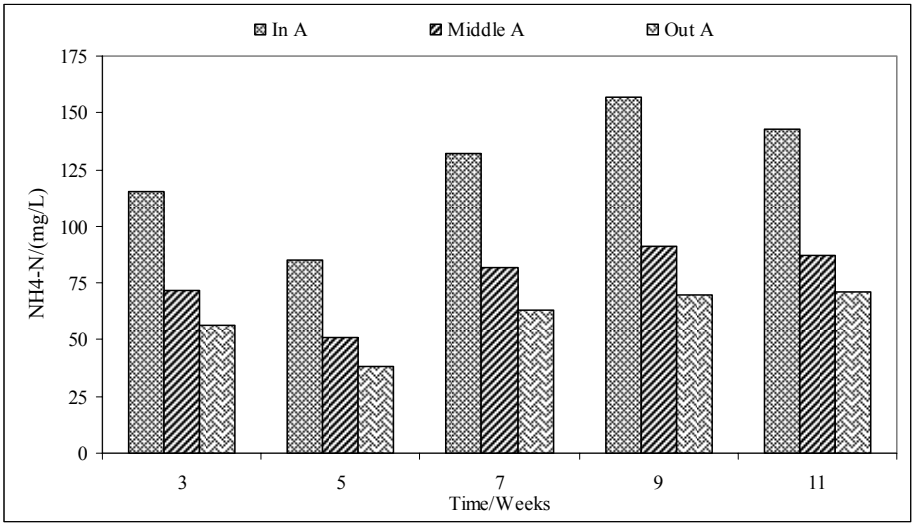

Figure 30 NH_3-N removal profile along the wetland system A

9. Variation of pH on treatment performance

Figure 31 presents the pH variation throughout the experiment period in system A. It shows clearly inlet pH was varied around 5. This is mainly because in fresh leachate the pH value was around 4.0- 4.5. Further it needed to feed inflow by which COD value around 5000 mg/L. This low value of pH was directly affected to impede nitrification/denitrification processes in inlet zone, so that only plant uptake might be responsible for removing N from waste water. This is evidenced having moderate N removal efficiency from wetland. But in middle zone pH value was raised up to neutral in many cases. It was ranged in between 6.54- 7.01. In outlet zone this pH value further increased and was ranges in between 6.72- 7.31. This may affect for the above mentioned N removal processes in both middle and outlet zones which was

evidenced by gradual removal on N from wetland. Vymazal (1999) reported that the optimum pH range for denitrification lies in between 7-8.

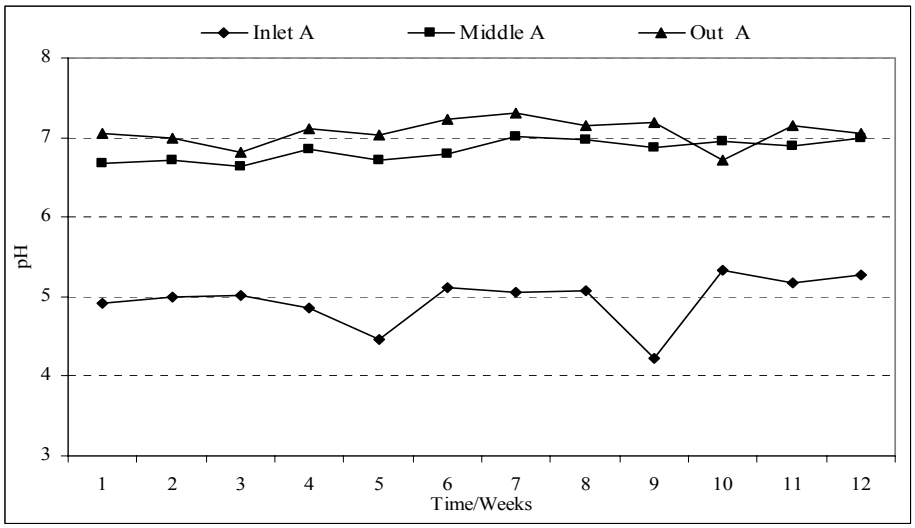

Figure 31 pH variation throughout the experiment period in system A

In system B there is no significant pH variation over the system A. But in middle and outlet areas it shows slightly increment than system A. From the treatment performance also it was noted that in system B slightly higher treatment performance over system A. Therefore this obtained pH values are reasonable.

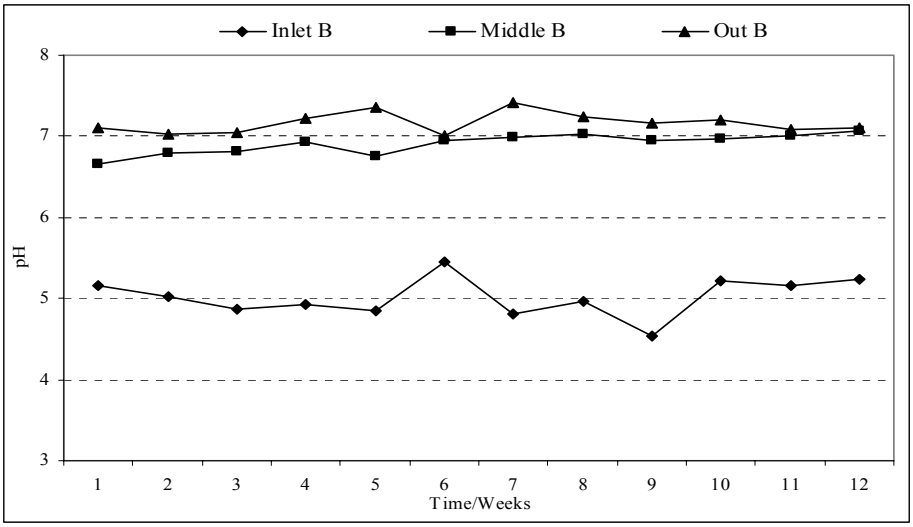

Figure 32 pH variation throughout the experiment period in system B

10. Greenhouse gas emission from different place in wetland- Mixed leachate

10.1 Methane flux rate

The average methane flux from wetland system A ranged from 0.0 to 0.5322 g CH_4-C $m^{-2}.d^{-1}$. (Appendix table A7). The zero emission was recorded at out let area and elevated CH_4 emission was noticed in inlet area. Inlet itself the CH_4 emission was ranged from 0.0380 to 0.5322 g CH_4-C $m^{-2}.d^{-1}$, whereas in middle section it was ranged from 0.0285 to 0.1711 g CH_4-C $m^{-2}.d^{-1}$. Figure 19 shows the variation of CH_4 flux rate in system A throughout the experimental period.

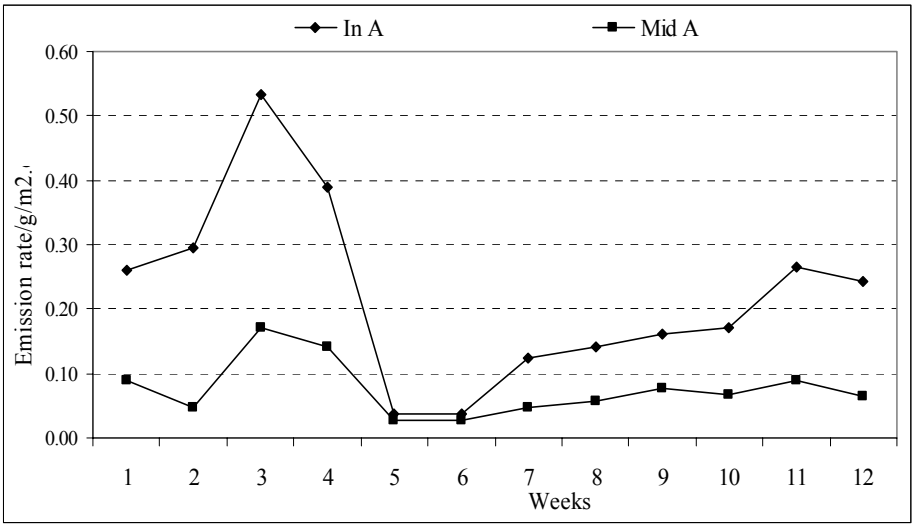

Figure 33 Emission rate of CH_4 in system A

From the figure 33 it can be clearly noticed that some peaks and valleys during experiment period. In other words the CH_4 emission rate was extremely remarkable. Teiter and Mander., (2005) reported that CH_4 emission from subsurface constructed wetland for treating waste water showed extremely remarkable variation through study period. A greater CH_4 emission variation was noticed especially first few weeks of experiment run such as first week to five week. Thereafter the degree of variation was lowered. The possible reasons for this may be the wetland has been reached to stable condition and relative constant inflow organic loading (Appendix table A8). Under the stable condition wetland microorganisms and plant could be well familiarized to the system and any variation of them might be minimized. Further environmental factors such as temperature, rainfall, ET were relatively constant in later part of study period. For the high peak of week 3, it was noticed very high water table, about 10 cm was increased than it was supposed to be. Along with this fact in week 3 the inflow had around 6000 mg/l of COD to the system. Therefore elevated concentration of inflow and high water table could lead to have such a CH_4 peak in inlet A. This was evidenced by having a peak in middle A also. Water table has a negative relationship with CH_4 emission rate Johansson *et al.,* (2004), Liikanen *et al*., (2005), Teiter and Mander., (2005), Gui *et al.,* (2007). This was clearly evidenced

during our study especially in week 5 and 6. In week the inflow concentration was the highest in study period but the lowest CH_4 emission rate was observed at the same time because water table had gone down about 20 cm than intended level. This definitely was affected for very lower gas emission during weeks of 5 and 6.

Further the degree of variation in inlet zone showed higher than middle zone and no CH_4 emission in outlet zone in both systems. This could be the fact that in inlet zone very high organic pollutant was prevailed than middle and outlet zones. At the middle and outlet zones relatively treated leachate had and over the time the changes were minor than inlet. So that degree of variation of CH_4 emission could be low. On the other hand temperature had a greater impact on methane emission. Mander *et al.,* (2003) has found that temperature as an important environmental factor influencing the CH_4 emission from CW. But this temperature factor didn't impact for CH_4 emission in our studies because in the tropics relative constant soil temperature can be prevailed throughout the year. In our study period the soil temperature was changed by just 2-3 ^{0}C around 29^{0}C. But in cold climate conditions this factor can play a vital role for emitting CH_4. Even though it is stated so, there was slightly increment of emission of CH_4 in elevated temperature. In contrast, elevated temperature can cause higher ET which in turns may impact to lower CH_4 emission because it might leave no organic pollutant carrier to undergo treatment in wetland systems. In tropics high ET can be common and this could be another hidden or unaccounted fact to alter the CH_4 emission in tropics. During the weeks 10-11 the calculated ET was averaged 15mm/d. This is relatively very high ET compared to other studies done on the same topics. But this is possible since pan evaporation in this region is over 7-10 mm/d in many times in a year (Weather report –AIT). Figure 20 shows the CH_4 flux rate in system B where 50% effluent was recirculated with fresh inflow.

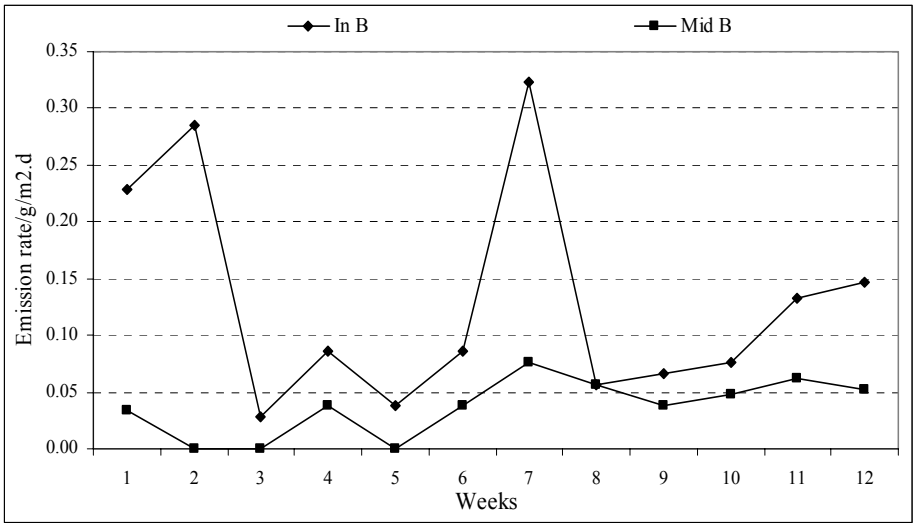

Figure 34 Emission rate of CH_4 in system B

The emission flux rate of CH_4 was range from 0.00 to 0.3231 g CH_4-C $m^{-2}.d^{-1}$. (Appendix table A7) in system B. In this system also no methane emission was noticed in out let zone. Inlet itself the CH_4 flux rate was ranged from 0.0285 to 0. 3231 g CH_4-C $m^{-2}.d^{-1}$. This value showed approximately 25 - 40% reduction compared to the system A. This reduction could be reasonable since this system was received approximately 60% of organic loading compared to the system A. From the figure 36, it was noticed that in week of 2nd, 3rd and 5 th the emission of CH_4 in middle section was zero. In week of 3rd, 5th the emission in inlet zone was remarkably reduced also. Therefore the same trend has been occurred. In contrast in 2nd week higher emission in inlet and lower emission in middle was recorded. The inflow concentration in terms of COD for this all weeks was more or less the same (Appendix table A8). But the possible reason was that some days during these weeks except 2nd week, blocking the inflow pipe to the system. Therefore the amount of leachate was fed to the system had been lowered which in turns may create two unfavorable condition for methane emission. First reducing the organic pollutant to be treated and then lower the water table. As previously discussed high ET was prevailed during our study period and because of this a negative impact for the CH_4 emission could occur in system B. The peak of 7th week was due to higher inflow concentration

during study period (Appendix table A8). After the 8th week onwards the degree of variation was reduced in both inlet and middle, this might be the facts that the system was reaching stable condition and well controlled physical parameters to the system. During this time period there was no any precipitation to the site relative dry weather was prevailed (Weather report –AIT). At the final week of experiment run the CH_4 flux rate had been reached to the value of 0.1500 g CH_4-C $m^{-2}.d^{-1}$ whereas in middle it was 0.0500 g CH_4-C $m^{-2}.d^{-1}$. All graphs illustrating CH_4 flux rate can be seen in Appendix figures B5 and B7.

10.2 Carbon dioxide flux rate

The CO_2 flux rate in system A was ranged from 0.4147 to 2.2291 g CO_2-C $m^{-2}.d^{-1}$ whereas former value was in outlet and latter figure was correspondent to the inlet zone. Inlet it self CO_2 flux rate was ranged from 0.3888 to 2.2291 g CO_2-C $m^{-2}.d^{-1}$ while in middle it was ranged from 0.2333 to 0.6480 g CO_2-C $m^{-2}.d^{-1}$. Out let zone this was ranged from 0.1296 to 0.4147 g CO_2-C $m^{-2}.d^{-1}$. Not like methane CO_2 emission was observed in all zones and during whole experiment time period. This is possible because it was measured gas emission in soil surface of CW and the generation of both gases was under the surface. Especially to generate CH_4 anaerobic condition should be prevailed, on the other hand generation of CO_2 was under aerobic condition. It was clearly noticed that under the given condition anaerobic zone was below the aerobic zone so that all generated CH_4 may not emit in wetland surface instead, it can degrade biologically in aerobic zone (Gui *et al.,* 2007). Therefore final CO_2 measurement could be the total of CO_2 generated I aerobic zone plus degradation of CH_4 in that zone. This was evidenced by all the time the emission rate of CO_2 was higher than CH_4 was in both systems and all zones. This might be the reason for zero emission of CH_4 in out let zone where less organic pollutant concentration was available. Figure 21 shows the CO_2 flux rate in system A.

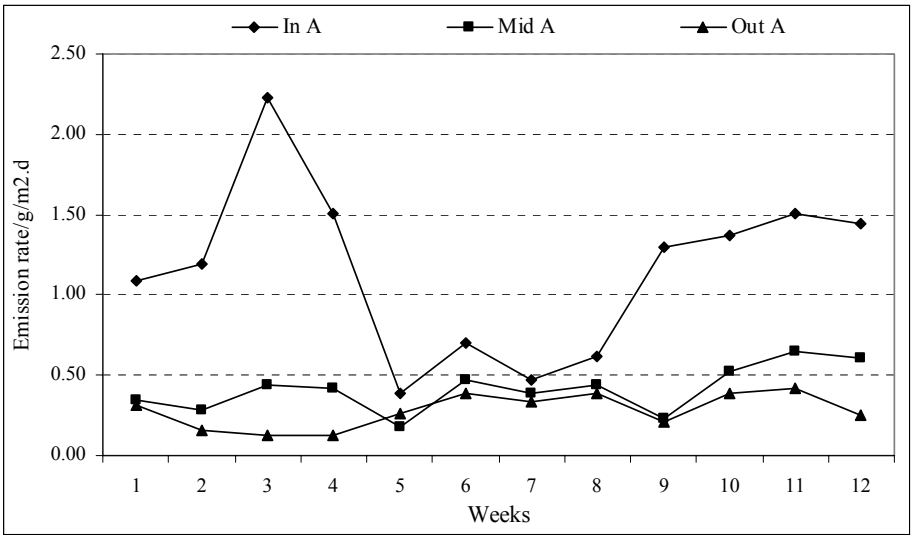

Figure 35 Flux rate of CO_2 in system A

From the figure 35 greater variation of CO_2 can be seen especially in inlet zone whereas in other two zones the degree of variation was less. But after 9th week onwards even in inlet area the degree of variation had been flattered. But in generally the degree of variation of CO_2 was noticed less than CH_4 was in our study. These results are with the agreement of the previous studies of Liikanen et al., (2006), Teiter and Mander, (2005). The flux rate was more or less flattered in both middle and outlet zones compared to inlet zone. In contrast inlet emission has shown greater variation with time. In 3rd week peak emission rate was recorded, and this may be the fact that highest inflow concentration was occurred then. And this week clogging was noticed in inlet zone. Further due to this water table went up in inlet vicinity so that higher emission could be observed. When system reached to the stable condition CO_2 flux rates were also reached to 1.500 g CO_2-C $m^{-2}.d^{-1}$, 0.600 g CO_2-C $m^{-2}.d^{-1}$ and 0.300 g CO_2-C $m^{-2}.d^{-1}$ in inlet, middle and outlet zones respectively.

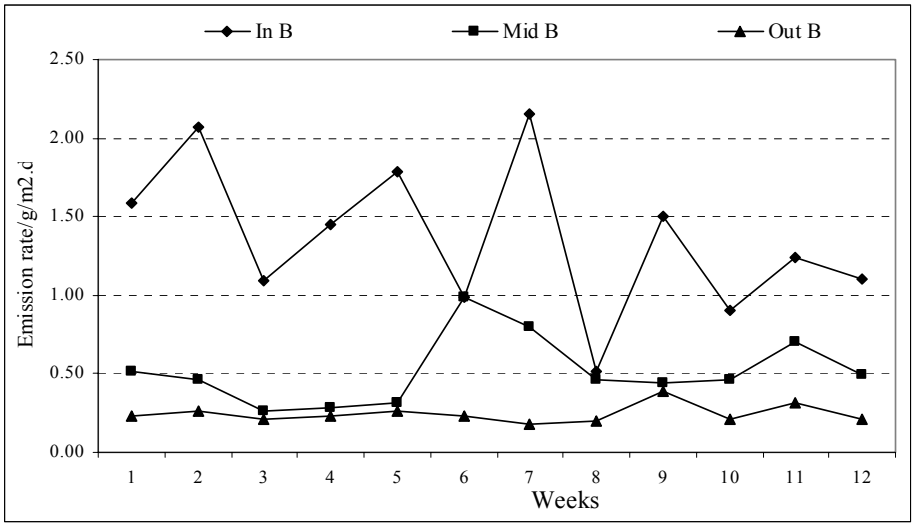

Figure 36 Flux rate of CO_2 in system B

The CO_2 flux rate in system B was ranged from 0.1814 to 2.1514 g CO_2-C $m^{-2}.d^{-1}$ whereas former value was in outlet and latter figure was correspondent to the inlet zone. Inlet it self CO_2 flux rate was ranged from 0.5184 to 2.1514 g CO_2-C $m^{-2}.d^{-1}$ while in middle it was ranged from 0.2592 to 0.8554 g CO_2-C $m^{-2}.d^{-1}$. Out let zone this was ranged from 0.1814 to 0.3888 g CO_2-C $m^{-2}.d^{-1}$. As discussed in CH_4 emission in system B, higher concentration on inflow and increment of water table may cause to higher mission in 2nd, 7th weeks. Degree of variation was significant in inlet zone CO_2 emission in this case. Like in system A both middle and outlet zones showed flatter variation of gas emission. When system reached to the stable condition CO_2 flux rates were also reached nearly to 1.100 g CO_2-C $m^{-2}.d^{-1}$, 0.510 g CO_2-C $m^{-2}.d^{-1}$ and 0.250 g CO_2-C $m^{-2}.d^{-1}$ in inlet, middle and outlet zones respectively.

11. Variation gas flux and total organic carbon

It is well common to see that the higher organic carbon loading rate is resulted for elevated CH_4 and CO_2 flux rate. Mander et al., (2003); Liikanen et al., (2006) have found that increased C loading was resulted for higher CH_4 emission. In this study also it was found that most of experiment week higher C loading caused to higher CH_4 and CO_2 emission, but in some weeks the relationship was negative. Interestingly

it was found that at that time the water table was lowered about 5-15 cm than it was supposed to be. Therefore the effect of lowering water table has been dominated over the effect of higher C loading. The gas flux is resulted of both this parameters and the final outcome was affected both the parameters. Further in our study it was clearly found that change the water table had greater influence than increment of C loading. Figure 37 and figure 38 show the variation of CH_4 and CO_2 gas flux over the organic carbon loading in system A.

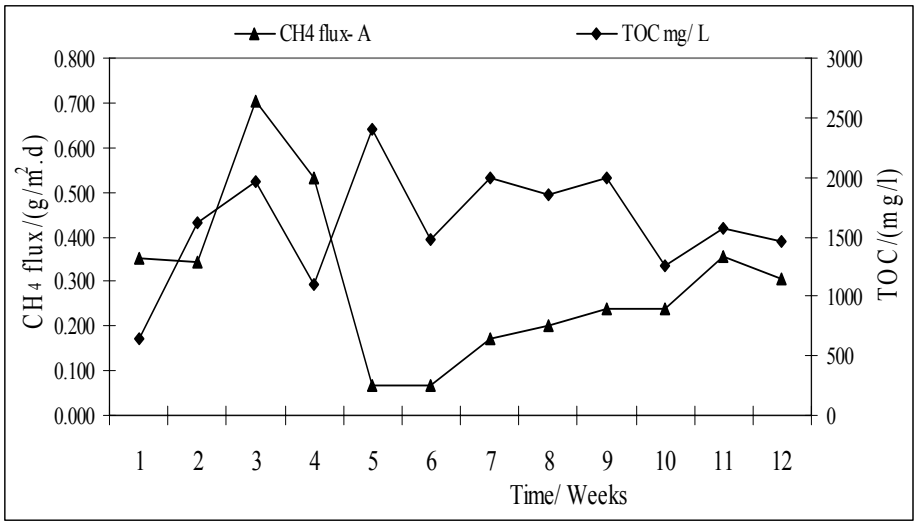

Figure 37 CH_4 flux variation over the TOC in system A

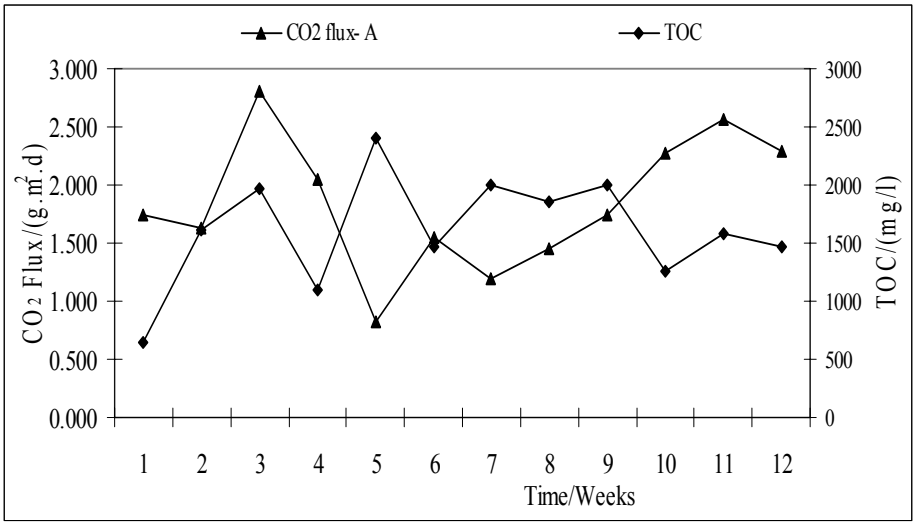

Figure 38 CO_2 flux variation over the TOC in system A

12. Comparison of GHG emission from past studies

The table 11 illustrates the details about GHG emission rate, plant type, and substrate and wetland type from some past studies. Interestingly all researches were from developed countries other than this study.

Table 11 Comparison of GHG emission of past studies

Wetland type	Substrate	Gas flux/(mg/m^2.d)			Plant cover	Reference
		CH_4	CO_2	N_2O		
Subsurface flow	Wastewater	0.04-2090	N/A	0.1-59	*Typha latifolia*	Mander et al., 2003
Free water surface flow	Secondary treated waste water	375-1739	N/A	N/A	*Typha latifolia*	Johansson et al., 2004
Free water surface flow	Peat mining runoff	140-400	7270-13600	0.340-0.450	*Sphagnum angustifolium*	Liikanen et al., 2006
Subsurface flow	Wastewater	0.04-2093	6.1-1050	0.02-62.4	*Typha latifolia*	Mander et al., 2006
Subsurface flow Free water surface flow	Wastewater	20.8-104.3	N/A	8.1-40.5		Gui et al., 2007
Subsurface flow	Landfill leachate	0-712	26-3266	N/D	*Typha augustifolia*	This study

13. Water balance in constructed wetland

A water budget of leachate inflow (In), the SSF outflow (Out), precipitation (P), and evapo-transpiration (ET) was computed at steady state condition at three days time intervals. Precipitation and other data were obtained from directly weather report of Asian Institute of Technology (AIT) where pilot scale treatment systems were located. Further ET was computed as the residual of the other water budget components for three days budget period;

$$ET = In + P - Out \quad (13)$$

Where units are volumetric (m^3) and changes of storage within the system were assumed to be negligible. The volumetric components can be expressed in linear units (m) by dividing the volume by the surface area of bed (4 m^2).

Table 12 Flow measurement data for water budget

Date	Inflow/ (m^3)	Out flow/(m^3)	Precipitation*/ (mm)	Pan Evaporation*/ (mm)	ET/(m^3)
16/01/2008	0.112	0.051	0	8.8	0.061
17/01/2008	0.112	0.048	0	9.4	0.064
18/01/2008	0.112	0.056	0	9.2	0.056
Total	0.336	0.155	0	27.4	0.181

***=** Data from weather report- AIT

A total inflow volume of 0.336 m^3 of leachate was applied to the system A during 3-day monitoring period from January 16 to January 18. The volume of treated effluent that was discharged from the constructed wetland outflow during this period was 0.155 m^3, and the loss of water is attributed to evapotranspiration (ET). Total precipitation during the period was 0 mm, further this month was another warm

month (weather repot data- AIT, 2008). The ET from wetland system A was estimated through equation 13 to be 45.25 mm (0.181 m^3). Daily mean ET was 10mm/d.

The daily ET measured in this study (10mm/d) is comparable to pan-evaporation rates for this area (weather repot data- AIT, 2008). During this experiment period time there was not any precipitation to the site and very hot condition was prevailed. High rates of ET during this sample collection period coincided with dry weather. During this period ET caused a 53% decrease in inflow relative to outflow. This is a considerable amount of water budget component and the possible reasons for having such a huge ET can be follows.

(1) A constant supply of available water (leachate),
(2) Relatively high leachate temperatures, averagely 30^0C in most of time,
(3) Interception of rainfall and uptake by cattails, especially in the SSF beds,

Where the cattails grew to a density of about 35 plants/m^2 and a height of nearly 3 m. Details about plant structures and relevant data are detailed the following section under the topic of plant structure. Further high rate of ET also is attributed to an oasis effect (Brutsaert, 1982), where evaporation is enhanced when a wet area is surrounded by a dry soil area.

Furthermore high ET can be affected for lowering GHG emission from the wetlands although high strength of leachate was fed to the system because approximately 50% of inflow is caused to ET. Therefore only another 50 % is available for the treatment. On the other hand if ET is caused less than this amount it will be in turns caused to elevate GHG emission. This will be discussed in detail under the section of gas emission from wetland in run II. Finally it can be emphasized that ET plays a vital role in wetland system especially in tropics were elevated temperatures are prevailed more than 6 months per year.

14. Plant characteristics

Table 13 illustrates the characteristics of wetland plant in both systems under the stable condition. From the data it is clear that more matured plants are in middle and out let areas in both systems. In system A, average length of leave in inlet area was 160 cm and in middle it was 186 cm and out let area it went up to 214 cm. This trend can be seen in no of leaves per plant in system A where it began from 8 and went up to 11 in outlet area. The same clear trend can be seen in system B also. Furthermore in system B the values were lager than correspondent data in system A. This occurrence clearly was noticed in systems especially at the later part of the experiment. As previously discussed in inlet area some dead plants were observed and plant density was also remarkably reduced where as in area towards from middle to outlet dense plants were noticed. But the in system B the no of dead plant in inlet was reduced comparing to the system A. The possible reason for this might be the reduced organic loading to the system B. Figure 39 shows the plant density in both systems in graphically.

Table 13 Characteristics of wetland plant in both systems at steady state condition

System	Position	Height of leave/(cm)			Total leaves	Average height*/(cm)
		Lengthiest	Modest	Shortest		
A	Inlet	190±10 (4±1)[a]	158±8 (2±1)	100±5 (2±2)	8±4	160
	Middle	223±8 (5±1)	178±8 (4±1)	133±8 (3±1)	12±3	186
	Out	238±13 (7±1)	193±8 (2±1)	153±8 (2±2)	11±4	214
B	Inlet	200±5 (5±1)	170±5 (2±1)	117±10 (1±1)	8±3	182
	Middle	212±8 (8±1)	170±5 (1±1)	100±5 (1±1)	10±3	197
	Out	275±5 (7±1)	182±8 (3±1)	103±8 (2±1)	12±3	223

[a] = ( ) no of leaves, *= value obtained; (height of leaves*no of leaves/total leaves)

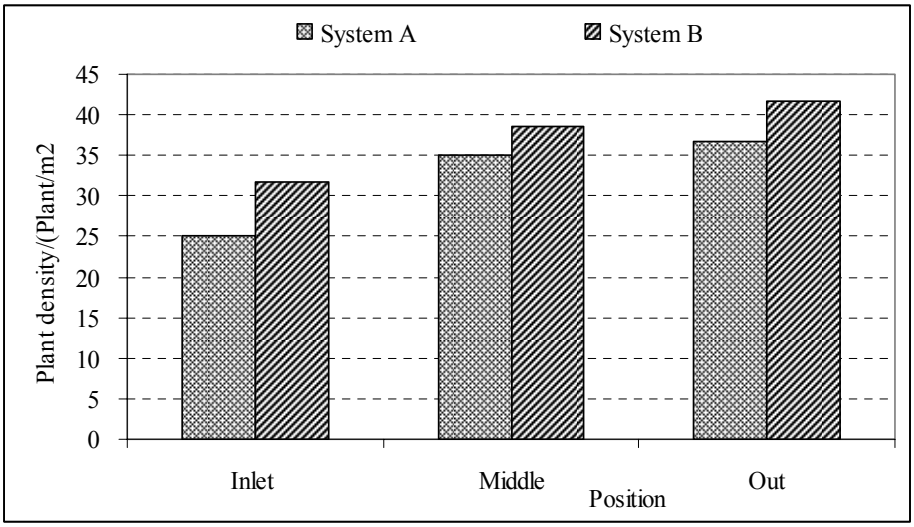

Figure 39 Plant density variation in both systems

From the figure 39, it clearly indicates that higher plant density towards the outlet area in both systems. Higher plant density was observed in all area in system B compared to system A. The highest plant density was recorded as 42 plant/m^2 in out let in system B where as lowest was 25 plant/m^2 in inlet of system A. To account this it was assumed that equal no of plants were removed to keep the gas chamber for gas sampling in all positions. As previously discussed in system A higher organic loading was provided, so that it may create some unfavorable condition for plant growth due to some pollutant such as elevated NH_3-N content especially inlet area (De Feo *et al.,* 2005). Even high organic pollutant such as COD can stress the wetland plant which in turn my lead to lower the plant growth. In middle section 35- 39 plant/m^2 were recorded in system A and B respectively. From the pollutant removal profile, it was noticed that most of pollutant were removed within first 2 m of wetland. Therefore in middle section and on wards excessive pollutant could be lowered and more favorable conditions for plant growth were available. This may lead to grow plants healthy and dense in these areas than inlets.

15. Root structure

To get some understanding about root structures and patterns, some wetland plants were uprooted and investigated physically under the stable condition. Some plants were uprooted in middle section of wetland to get a fair understanding. Figure 38 illustrates the schematic diagram of plant and root structure.

Cattail (*Typha augustifolia*) was used as an emergent plant in this study. It was noticed that the root structure had following features. The root structure was generally long (20-30 cm), sparsely branched, and grow deep into the soil about 20-30 cm. The dense small roots where the diameter was ranged 0.2-0.4 cm were developed around the shoot. The density of such small roots was approximately 3-4 roots/ cm^2 and length was ranged 15-20 cm. Koncalova, (1990) reported that this root structures are common for *Typha augustifolia* in their study also and these develop generally where the soil is anaerobic and apparently serve primarily to anchor the plants.

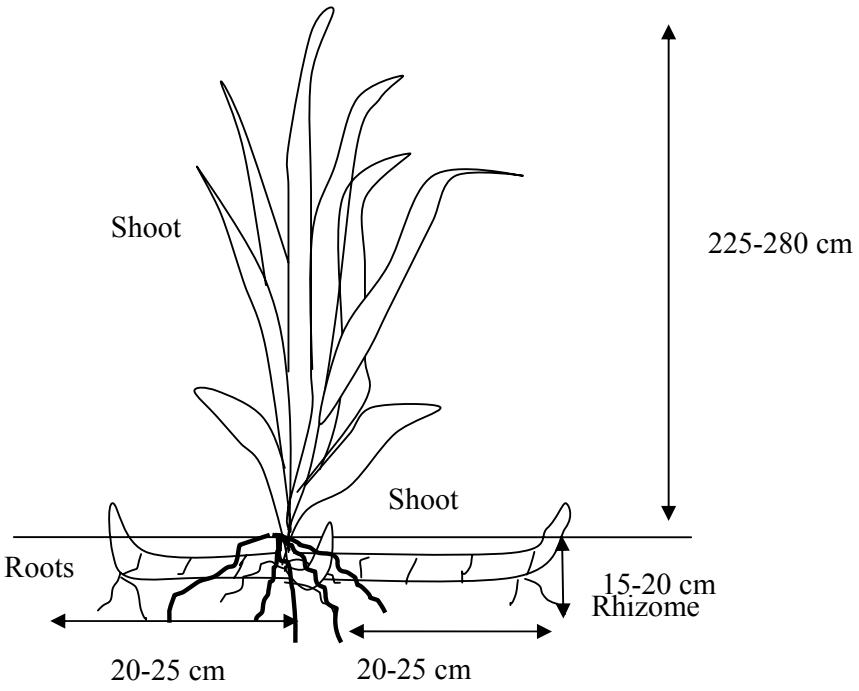

Figure 40 Plant structure of wetland plant

16. Plant growth

To understand the plant growth over the time, randomly plant height was measured. Before feeding leachate to the systems all plants were cut height about 60 cm from the surface and when it was about 100 cm (after 2 weeks) leachate was fed. The plant height was around 175 cm after one month of treatment began and plants were further grown up to 220 cm during next one month time. The average final height was 250 cm at stable conditions. In system B this figures especially in experiment went on were 10-20 cm increased.

17. Carbon balance within the system

To investigate the portion of organic carbon removed as greenhouse gases from the system, the Total Organic Carbon (TOC) was measured random samples which were represented inlet, middle and outlet samples in both systems throughout experiment study. Using that TOC data with correspondent COD values, the liner relationship was drawn (R^2=0.94). Thereafter the required TOC values were derived with the help of liner relationship. Figure 39 shows the liner relationship of COD and TOC in graphically.

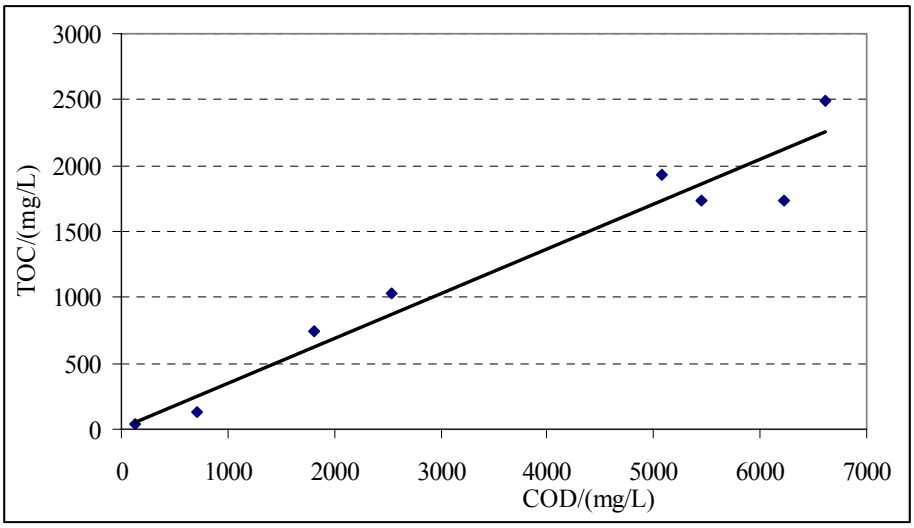

Figure 41 Linear relationship of COD and TOC

From the table 14, the organic C removed as greenhouse gas from the system A was ranged from 0.7 to 4.2% from inlet organic carbon whereas in system B this was ranged 1.2 to 4.8 %. At the steady state condition the values were 3.4 % and 3.3 % respectively. Organic carbon leaving the systems was around 3.6% and 5.8 % respectively. From this it can be concluded that approximately 93% from system A and 92% from B of organic C had been accumulated in wetland. To calculate these following assumptions were made. 1). Amount of leachate out flow is 50% from inflow. (This was based on water budget measurement done). 2). Total volume of inflow was 112 L/d and no any disturbance were occurred in all the time (This was not exactly happened, in some days inflow was blocked). 3). Wetland bed was divided into three equal parts and these were used to calculate total gas emission from that area.

Nevertheless none of above mentioned assumptions were occurred during experiment period and it was very difficult to control them all the time. But for the reasonable accuracy the given values are acceptable. Further under these conditions the total C emitted from system A and B was 5.4 g/d and 3.5 g/d respectively. This was a reasonable figure since system B was fed approximate 60% of concentration with compare to system A. Table 13 and table 14 shows the characteristics of organic carbon in systems and their fate.

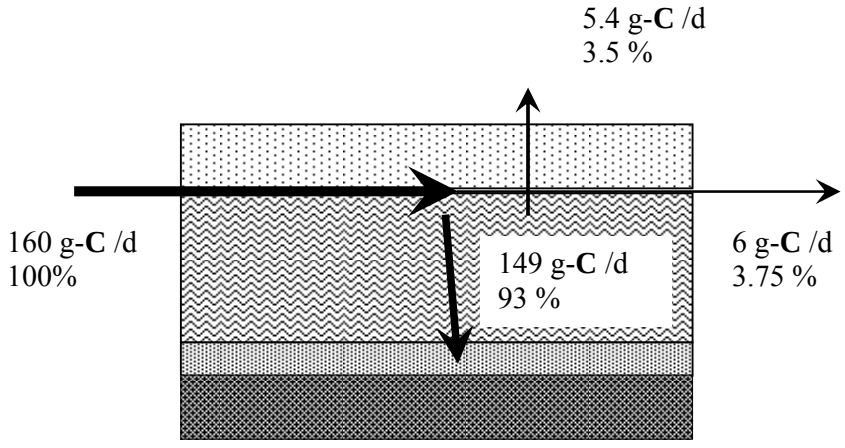

Figure 42 Carbon balance in system A under the steady state condition

Table 14 Characteristics of organic carbon balance in system A

	COD(X)/ (mg/L)		TOC(Y)/ (mg/L)		Leachate volume/ (L/d)		Organic C loading/(g/d)		CH_4-C flux/(g/m^2.d)			CO_2-C flux/(g/m^2.d)					
Week	In	Out	In	Out	In	Out	In	Out	In	Middle	Total CH_4-C/(g/d)	In	Middle	Out	Total CO_2-C /(g/d)	Total C removed /(g/d)	Organic C rem. from gas/(%)
1	1875		640		112	56	72		0.261	0.090	0.703	1.089	0.350	0.311	3.499	4.202	5.9
2	4736	366	1617	125	112	56	181	7	0.295	0.048	0.684	1.192	0.285	0.156	3.266	3.950	2.2
3	5768	908	1969	310	112	56	221	17	0.532	0.171	1.407	2.229	0.441	0.130	5.599	7.005	3.2
4	3221	715	1100	244	112	56	123	14	0.390	0.143	1.064	1.503	0.415	0.130	4.095	5.160	4.2
5	7040	1296	2403	442	112	56	269	25	0.038	0.029	0.133	0.389	0.181	0.259	1.659	1.792	0.7
6	4312	905	1472	309	112	56	165	17	0.038	0.029	0.133	0.700	0.467	0.389	3.110	3.243	2.0
7	5838	872	1993	298	112	56	223	17	0.124	0.048	0.342	0.467	0.389	0.337	2.385	2.727	1.2
8	5449	491	1860	168	112	56	208	9	0.143	0.057	0.399	0.622	0.441	0.389	2.903	3.302	1.6
9	5860	472	2001	161	112	56	224	9	0.162	0.076	0.475	1.296	0.233	0.207	3.473	3.948	1.8
10	3675	260	1255	89	112	56	141	5	0.171	0.067	0.475	1.374	0.518	0.389	4.562	5.037	3.6
11	4612	345	1575	118	112	56	176	7	0.266	0.090	0.713	1.503	0.648	0.415	5.132	5.845	3.3
12	4285	302	1463	103	112	56	164	6	0.242	0.064	0.612	1.439	0.608	0.251	4.596	5.208	3.2

Table 15 Characteristics of organic carbon balance in system B

	COD(X)/ (mg/L)		TOC(Y)/ (mg/L)		Leachate volume/ (L/d)		Organic C loading/(g/d)		CH_4-C flux/(g/m^2.d)		Total CH_4-C/(g/d)	CO_2-C flux/(g/m^2.d)			Total CO_2-C /(g/d)	Total C removed /(g/d)	Organic C rem. from gas/(%)
Week	In	Out	In	Out	In	Out	In	Out	In	Middle		In	Middle	Out			
1	1805		616		56	56	35		0.228	0.033	0.392	1.581	0.518	0.233	3.499	3.891	11.3
2	4124	855	1408	292	56	56	95	16	0.285	0.000	0.428	2.074	0.467	0.259	4.199	4.627	4.9
3	4050	831	1383	284	56	56	93	16	0.029	0.000	0.043	1.089	0.259	0.207	2.333	2.376	2.5
4	3985	765	1360	261	56	56	91	15	0.086	0.038	0.185	1.452	0.285	0.233	2.955	3.140	3.5
5	3840	654	1311	223	56	56	86	13	0.038	0.000	0.057	1.788	0.311	0.259	3.538	3.595	4.2
6	2534	355	865	121	56	56	55	7	0.086	0.038	0.185	0.985	0.985	0.233	3.305	3.490	6.3
7	6616	856	2259	292	56	56	143	16	0.323	0.076	0.599	2.151	0.804	0.181	4.704	5.303	3.7
8	5720	498	1953	170	56	56	119	10	0.057	0.057	0.171	0.518	0.467	0.194	1.769	1.940	1.6
9	5752	460	1964	157	56	56	119	9	0.067	0.038	0.157	1.503	0.441	0.389	3.499	3.656	3.1
10	4913	295	1677	101	56	56	100	6	0.076	0.048	0.185	0.907	0.467	0.207	2.372	2.557	2.6
11	4715	307	1610	105	56	56	96	6	0.133	0.062	0.292	1.244	0.700	0.311	3.383	3.675	3.8
12	4358	262	1488	89	56	56	88	5	0.147	0.052	0.299	1.104	0.492	0.210	2.711	3.010	3.4

CONCLUSION AND RECOMMENDATION

Conclusion

The study on greenhouse gas emission from horizontal subsurface constructed wetland for treating landfill leachate in the tropics can be concluded as follows.

1. Using close-flux chamber technique, CH_4 and CO_2 emission from constructed wetland were found in the range between ND to 0.732 g CH_4-C $m^{-2}.d^{-1}$and 0.096- 3.266 g CO_2-C $m^{-2}.d^{-1}$respectively. The emission of both gases was higher during the warmer months. Water table showed a negative relationship for the both gas emission whereas elevated temperature had a positive relationship. But water table increment or declination showed significant impact than elevated temperature provided that all other parameters were the same.

2. Higher emission was noted in inlet zone and it was decreasing along the flow path. The degree of variation of CH_4 was higher than CO_2. The emission in non-re-circulating constructed wetland was higher than the system with re-circulation of treated water. Diurnal variation showed that the emissions of CH_4 and CO_2 increased during night time. The increase was 10-20% for CH_4 and 30-80% for CO_2. N_2O emission was not detected at ppm level.

3. The constructed wetland operated at hydraulic loading rate of 28 mm/d and HRT of 10 days had BOD, COD and TKN removal efficiencies of 97%, 98% and 40% during steady state condition. During experiment run II, pollutant loading was increased in terms of COD and then the removal efficiencies were altered than in first run. The correspondent values were 97%, 93% and 52% in system A and 97%, 94%, 55% in system B respectively. Further stable condition was attained relatively shorter time than run I. Under the given condition 50% leachate re-circulation didn't give significant better removal efficiency than non re-circulation.

4. Both aerobic and anaerobic conditions prevailed in most underlying bed area and it affected the greenhouse gas emission from the system. No total aerobic

area was found in both runs. The ORP value was always well below the +200 mV. This could be one of reason for zero emission of N_2O.

5. Water budget measurements showed the effect of ET was remarkable. Although the measurement was done for short time period, reasonable value for ET was derived. The mean calculated ET was around 10mm/d and most of time dry weather conditions were prevailed. No significant precipitation was recorded during sampling. Under these conditions outflow accounted averagely 50-60% inflow.

6. Organic carbon balance showed only 3-4 % of influent organic carbon was removed form the systems via greenhouse gas emission. More than 92-93 % of influent organic C has been accumulated in wetland, while only 3-4% removed with outflow.

Recommendation for Future Work

1. Since water table shows significant negative relationship for the both greenhouse gas emission, water table should be considered as very important parameter and quantify its effect for gas emission while keeping pollutant efficiency at higher level.

2. Water budget analysis should be carried out at reasonable time interval such as biweekly, and then more reliable data can be developed.

3. N_2O was not detected in this study, probably due to lowered pH value of fresh leachate. To investigate this is true or not few months old leachate need to be used to feed to wetland or else purposely pH should be raised to investigate N_2O occurrence.

4. It is advisable to carry out experiment at least one year time period to find out the seasonal variation.

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APPENDICES

Appendix A

Table

Appendix Table A1 Temperature variation on sampling during Run II - System A

Date	Position	Time	Temperature/(^{0}C)			Remarks
			Air	Chamber	Soil	
19/11/2007	Inlet	11.00	32.0	32.0	27.0	
		11.30	33.5	33.0	27.0	
		12.00	32.5	32.0	27.0	
		12.30	30.0	31.0	27.0	Rain starts
		1.00	28.5	29.0	26.5	Heavy rain
	Middle	11.00	32.0	31.5	28.0	
		11.30	33.5	31.5	28.0	
		12.00	32.5	31.5	28.0	
		12.30	30.0	30.5	28.0	
		1.00	28.5	29.0	28.0	
	Out	11.00	32.0	31.0	27.5	
		11.30	33.5	30.5	27.5	
		12.00	32.5	30.0	27.5	
		12.30	30.0	29.5	27.0	
		1.00	28.5	28.5	27.0	
26/11/2007	Inlet	12.00	33.0	33.0	25.0	
		12.30	34.0	33.0	25.0	
		1.00	35.0	33.5	25.0	
		1.30	35.5	34.0	25.0	
		2.00	35.5	34.0	25.0	
	Middle	12.00	33.0	32.5	26.0	
		12.30	34.0	34.0	26.0	
		1.00	35.0	33.5	26.0	
		1.30	35.5	33.0	26.0	
		2.00	35.5	32.0	26.0	
	Out	12.00	33.0	33.0	26.0	
		12.30	34.0	35.0	26.0	
		1.00	35.0	35.0	26.0	
		1.30	35.5	35.0	26.0	
		2.00	35.5	35.0	26.0	
29/11/2007	Inlet	10.00	30.5	30.0	24.0	
		10.30	32.0	31.0	24.0	
		11.00	33.0	31.5	24.0	
		11.30	33.0	31.5	24.0	
		12.00	34.5	31.0	24.0	
	Middle	10.00	30.5	30.0	25.0	
		10.30	32.0	31.0	25.0	
		11.00	33.0	31.0	25.0	
		11.30	33.0	31.5	25.0	
		12.00	34.5	30.0	25.0	
	Out	10.00	30.5	29.0	26.0	
		10.30	32.0	31.0	26.0	
		11.00	33.0	31.0	26.0	
		11.30	33.0	31.0	26.0	
		12.00	34.5	31.0	26.0	

Appendix Table A1 (Continued)

Date	Position	Time	Temperature/(^{0}C)			Remarks
			Air	Chamber	Soil	
3/12/2007	Inlet	11.45	33.0	33.0	24.0	
		12.15	34.5	33.5	24.0	
		12.45	35.5	34.0	24.0	
		1.15	36.0	34.0	24.0	
		1.45	36.0	34.5	24.0	
	Middle	11.45	33.0	31.0	25.0	
		12.15	34.5	33.5	25.0	
		12.45	35.5	33.5	25.0	
		1.15	36.0	33.0	25.0	
		1.45	36.0	33.5	25.0	
	Out	11.45	33.0	31.0	25.0	
		12.15	34.5	34.0	25.0	
		12.45	35.5	34.0	25.0	
		1.15	36.0	34.0	25.0	
		1.45	36.0	34.5	25.0	
10/12/2007	Inlet	11.40	35.0	35.0	27.5	
		12.10	36.0	35.0	27.5	
		12.40	36.0	35.0	28.0	
		1.10	37.5	36.0	28.0	
		1.40	37.5	36.0	28.0	
	Middle	11.40	35.0	34.0	28.0	
		12.10	36.0	34.0	28.0	
		12.40	36.0	33.5	28.0	
		1.10	37.5	34.0	28.0	
		1.40	37.5	34.0	28.0	
	Out	11.40	35.0	34.0	27.5	
		12.10	36.0	33.0	27.5	
		12.40	36.0	33.0	27.5	
		1.10	37.5	34.0	27.5	
		1.40	37.5	34.0	27.5	
17/12/2007	Inlet	12.00	36.5	36.5	29.0	
		12.30	41.0	40.0	29.0	
		1.00	42.0	41.0	29.0	
		1.30	43.5	42.0	29.5	
		2.00	44.0	43.0	29.5	
	Middle	12.00	36.5	34.0	30.0	
		12.30	41.0	35.0	30.0	
		1.00	42.0	35.0	30.0	
		1.30	43.5	35.5	30.0	
		2.00	44.0	35.5	30.0	
	Out	12.00	36.5	35.0	30.0	
		12.30	41.0	36.5	30.0	
		1.00	42.0	37.0	30.0	
		1.30	43.5	3.5	30.0	
		2.00	44.0	38.0	30.0	

Appendix Table A1 (Continued)

Date	Position	Time	Temperature/(^{0}C)			Remarks
			Air	Chamber	Soil	
27/12/2007	Inlet	11.30	37.0	33.5	25.5	
		12.00	38.0	34.5	25.5	
		12.30	38.5	36.5	25.5	
		1.00	38.5	37.5	25.5	
		1.30	39.5	37.5	25.5	
	Middle	11.30	37.0	32.0	26.5	
		12.00	38.0	33.5	26.5	
		12.30	38.5	33.5	26.5	
		1.00	38.5	34.0	26.5	
		1.30	39.5	34.0	26.5	
	Out	11.30	37.0	32.0	26.5	
		12.00	38.0	33.5	26.5	
		12.30	38.5	33.5	26.5	
		1.00	38.5	35.0	26.5	
		1.30	39.5	35.0	26.5	
8/1/2008	Inlet	11.30	37.0	33.0	25.0	New Leachate
		12.00	38.0	34.0	25.0	
		12.30	38.0	37.0	25.0	
		1.00	38.0	37.0	25.0	
		1.30	39.0	37.0	25.0	
	Middle	11.30	37.0	31.0	26.0	
		12.00	38.0	33.0	26.0	
		12.30	38.0	33.0	26.0	
		1.00	38.0	32.5	26.0	
		1.30	39.0	32.0	26.0	
	Out	11.30	37.0	32.0	26.0	
		12.00	38.0	33.0	26.5	
		12.30	38.0	33.0	26.5	
		1.00	38.0	34.0	26.5	
		1.30	39.0	34.0	26.5	
14/1/2008	Inlet	1.00	38.0	35.0	27.0	
		1.30	38.5	37.0	27.0	
		2.00	37.0	38.0	27.5	
		2.30	36.5	38.0	27.5	
		3.00	36.0	38.0	27.5	
	Middle	1.00	38.0	35.0	28.0	
		1.30	38.5	34.0	28.0	
		2.00	37.0	33.5	28.0	
		2.30	36.5	33.5	28.0	
		3.00	36.0	33.0	28.0	
	Out	1.00	38.0	34.0	28.0	
		1.30	38.5	34.0	28.0	
		2.00	37.0	34.0	28.0	
		2.30	36.5	34.0	28.0	
		3.00	36.0	33.0	28.0	

Appendix Table A1 (Continued)

Date	Position	Time	Temperature/(^{0}C)			Remarks
			Air	Chamber	Soil	
21/01/2008	Inlet	11.40	35.0	34.0	27.5	
		12.10	36.0	34.0	27.5	
		12.40	36.0	34.0	28.0	
		1.10	37.5	35.0	28.0	
		1.40	37.5	35.0	28.0	
	Middle	11.40	35.0	33.0	28.0	
		12.10	36.0	33.0	28.0	
		12.40	36.0	32.5	28.0	
		1.10	37.5	33.5	28.0	
		1.40	37.5	34.0	28.0	
	Out	11.40	35.0	33.0	27.5	
		12.10	36.0	32.0	27.5	
		12.40	36.0	33.0	27.5	
		1.10	37.5	34.0	27.5	
		1.40	37.5	34.5	27.5	
28/01/2008	Inlet	12.00	35.0	35.0	27.5	
		12.30	36.0	35.0	27.5	
		1.00	36.0	35.0	28.0	
		1.30	37.5	36.0	28.0	
		2.00	37.5	36.0	28.0	
	Middle	12.00	35.0	34.0	28.0	
		12.30	36.0	34.0	28.0	
		1.00	36.0	33.5	28.0	
		1.30	37.5	34.0	28.0	
		2.00	37.5	34.0	28.0	
	Out	12.00	35.0	34.0	27.5	
		12.30	36.0	33.0	27.5	
		1.00	36.0	33.0	27.5	
		1.30	37.5	34.0	27.5	
		2.00	37.5	34.0	27.5	

Appendix Table A2 Temperature variation on sampling during Run II - System B

Date	Position	Time	Temperature/(^{0}C)			Remarks
			Air	Chamber	Soil	
22/11/2007	Inlet	11.00	32.0	32.0	26.0	
		11.30	33.0	32.0	26.0	
		12.00	34.5	33.0	26.0	
		12.30	35.5	34.0	26.0	
		1.00	35.0	34.0	26.0	
	Middle	11.00	32.0	32.0	26.5	
		11.30	33.0	33.0	26.5	
		12.00	34.5	33.5	26.5	
		12.30	35.5	34.0	26.5	
		1.00	35.0	34.0	26.5	
	Out	11.00	32.0	32.0	26.5	
		11.30	33.0	33.0	26.5	
		12.00	34.5	33.0	26.5	
		12.30	35.5	33.0	26.5	
		1.00	35.0	34.0	26.5	
29/11/2007	Inlet	12.15	30.0	30.0	24.0	
		12.45	32.0	31.0	24.0	
		1.15	33.0	31.5	24.0	
		1.45	33.0	31.5	24.0	
		2.15	32.5	31.0	24.0	
	Middle	12.15	30.0	30.0	24.0	
		12.45	32.0	31.0	24.0	
		1.15	33.0	31.0	24.0	
		1.45	33.0	31.5	24.0	
		2.15	32.5	30.0	24.0	
	Out	12.15	30.0	29.0	24.0	
		12.45	32.0	31.0	24.0	
		1.15	33.0	31.0	24.0	
		1.45	33.0	31.0	24.0	
		2.15	32.5	31.0	24.0	
30/11/2007	Inlet	12.15	31.0	30.0	24.0	
		12.45	32.0	31.0	24.0	
		1.15	33.0	31.5	24.0	
		1.45	33.0	31.5	24.0	
		2.15	32.5	31.0	24.0	
	Middle	12.15	31.0	30.0	25.0	
		12.45	32.0	31.0	25.0	
		1.15	33.0	31.0	25.0	
		1.45	33.0	31.5	25.0	
		2.15	32.5	30.0	25.0	
	Out	12.15	31.0	29.0	25.5	
		12.45	32.0	31.0	25.5	
		1.15	33.0	31.0	25.5	
		1.45	33.0	31.0	25.5	
		2.15	32.5	31.0	25.5	

Appendix Table A2_ (Continued)

Date	Position	Time	Temperature/(^{0}C)			Remarks
			Air	Chamber	Soil	
6/12/2007	Inlet	11.20	34.0	34.0	26.0	
		11.50	36.5	35.5	26.0	
		12.20	38.0	36.0	26.0	
		12.50	38.0	36.0	26.0	
		1.20	38.0	36.0	26.0	
	Middle	11.20	34.0	31.5	26.0	
		11.50	36.5	33.0	26.0	
		12.20	38.0	34.0	26.0	
		12.50	38.0	34.0	26.0	
		1.20	38.0	33.0	26.0	
	Out	11.20	34.0	33.0	26.0	
		11.50	36.5	34.5	26.0	
		12.20	38.0	35.5	26.0	
		12.50	38.0	36.0	26.0	
		1.20	38.0	36.0	26.0	
12/12/2007	Inlet	12.45	35.0	35.0	29.0	
		1.15	37.0	36.0	29.0	
		1.45	37.0	35.5	29.0	
		2.15	37.0	35.5	29.0	
		2.45	35.0	33.5	29.0	
	Middle	12.45	35.0	34.0	29.0	
		1.15	37.0	34.0	29.0	
		1.45	37.0	34.0	29.0	
		2.15	37.0	34.0	29.0	
		2.45	35.0	33.5	29.0	
	Out	12.45	35.0	34.5	28.5	
		1.15	37.0	36.0	28.5	
		1.45	37.0	35.0	28.5	
		2.15	37.0	35.0	28.5	
		2.45	35.0	33.0	28.5	
20/12/2007	Inlet	11.00	33.0	33.0	28.0	
		11.30	35.0	34.0	28.0	
		12.00	37.5	36.0	28.0	
		12.30	39.5	38.0	28.0	
		1.00	41.0	39.0	28.0	
	Middle	11.00	33.0	33.0	28.0	
		11.30	35.0	33.0	28.0	
		12.00	37.5	34.0	29.0	
		12.30	39.5	34.0	29.0	
		1.00	41.0	34.0	29.0	
	Out	11.00	33.0	34.0	28.0	
		11.30	35.0	34.0	28.0	
		12.00	37.5	34.0	28.0	
		12.30	39.5	36.0	28.0	
		1.00	41.0	39.0	28.0	

Appendix Table A2_ (Continued)

Date	Position	Time	Temperature/(^{0}C)			Remarks
			Air	Chamber	Soil	
28/12/2007	Inlet	12.00	38.0	34.0	26.0	
		12.30	35.0	34.0	26.0	
		1.00	38.0	35.0	26.0	
		1.30	39.0	36.0	26.5	
		2.00	40.5	38.0	26.5	
	Middle	12.00	38.0	32.5	27.0	
		12.30	35.0	32.5	27.0	
		1.00	38.0	33.0	27.0	
		1.30	39.0	33.0	27.5	
		2.00	40.5	33.5	27.5	
	Out	12.00	38.0	33.0	27.0	
		12.30	35.0	34.0	27.0	
		1.00	38.0	35.0	27.0	
		1.30	39.0	35.5	27.5	
		2.00	40.5	36.5	27.5	
11/1/2008	Inlet	12.30	38.0	33.0	26.0	New Leachate
		1.00	35.0	34.0	26.0	
		1.30	38.0	35.0	26.0	
		2.00	39.0	36.0	26.5	
		2.30	40.0	38.0	26.5	
	Middle	12.30	38.0	32.0	27.0	
		1.00	35.0	32.0	27.0	
		1.30	38.0	33.0	27.0	
		2.00	39.0	33.0	27.5	
		2.30	40.0	32.5	27.5	
	Out	12.30	38.0	33.0	27.0	
		1.00	35.0	34.0	27.0	
		1.30	38.0	35.0	27.0	
		2.00	39.0	35.5	27.5	
		2.30	40.0	36.5	27.5	
17/1/2008	Inlet	12.40	34.0	32.0	26.0	
		1.10	36.0	33.0	26.0	
		1.40	38.0	34.0	26.0	
		2.10	39.0	35.5	26.5	
		2.40	35.0	35.0	26.5	
	Middle	12.40	34.0	31.0	26.0	
		1.10	36.0	30.0	26.0	
		1.40	38.0	30.0	26.0	
		2.10	39.0	30.0	26.0	
		2.40	35.0	30.0	26.0	
	Out	12.40	34.0	33.0	27.0	
		1.10	36.0	34.0	27.0	
		1.40	38.0	5.0	27.0	
		2.10	39.0	35.0	27.0	
		2.40	35.0	34.0	27.0	

Appendix Table A2 (Continued)

Date	Position	Time	Temperature/(^{0}C)			Remarks
			Air	Chamber	Soil	
24/01/2008	Inlet	11.40	35.0	34.0	27.5	
		12.10	36.0	34.0	27.5	
		12.40	36.0	34.0	28.0	
		1.10	37.5	35.0	28.0	
		1.40	37.5	35.0	28.0	
	Middle	11.40	35.0	33.0	28.0	
		12.10	36.0	33.0	28.0	
		12.40	36.0	32.5	28.0	
		1.10	37.5	33.5	28.0	
		1.40	37.5	34.0	28.0	
	Out	11.40	35.0	33.0	27.5	
		12.10	36.0	32.0	27.5	
		12.40	36.0	33.0	27.5	
		1.10	37.5	34.0	27.5	
		1.40	37.5	34.5	27.5	
30/01/2008	Inlet	12.00	35.0	35.0	27.5	
		12.30	36.0	35.0	27.5	
		1.00	36.0	35.0	28.0	
		1.30	37.5	36.0	28.0	
		2.00	37.5	36.0	28.0	
	Middle	12.00	35.0	34.0	28.0	
		12.30	36.0	34.0	28.0	
		1.00	36.0	33.5	28.0	
		1.30	37.5	34.0	28.0	
		2.00	37.5	34.0	28.0	
	Out	12.00	35.0	34.0	27.5	
		12.30	36.0	33.0	27.5	
		1.00	36.0	33.0	27.5	
		1.30	37.5	34.0	27.5	
		2.00	37.5	34.0	27.5	

Appendix Table A3 Temperature variation on sampling during Run I - System A

Date	Position	Time	Temperature/(^{0}C)			Remarks
			Air	Chamber	Soil	
13/07/2007	Inlet	10.30	36.0	36.0	30.0	
		11.00	37.5	37.0	30.0	
		11.30	38.0	36.0	30.5	
		12.00	38.0	37.0	30.5	
		12.30	40.0	38.0	31.0	
	Middle	10.30	36.0	37.0	31.0	
		11.00	37.5	38.0	31.0	
		11.30	38.0	37.5	31.0	
		12.00	38.0	37.5	31.5	
		12.30	40.0	37.0	32.0	
	Out	10.30	36.0	34.0	30.0	
		11.00	37.5	35.5	30.0	
		11.30	38.0	35.5	30.0	
		12.00	38.0	35.5	30.0	
		12.30	40.0	36.0	30.0	
19/07/2007	Inlet	11.20	38.0	38.0	28.0	
		11.50	40.5	39.0	28.5	
		12.20	41.0	39.0	28.5	
		12.50	42.0	40.0	29.0	
		1.20	42.5	41.0	29.0	
	Middle	11.20	38.0	38.0	29.0	
		11.50	40.5	40.0	30.0	
		12.20	41.0	41.0	31.0	
		12.50	42.0	41.0	31.5	
		1.20	42.5	40.0	31.0	
	Out	11.20	38.0	38.0	29.0	
		11.50	40.5	39.0	29.0	
		12.20	41.0	38.0	29.0	
		12.50	42.0	39.0	29.0	
		1.20	42.5	40.0	29.5	
26/07/2007	Inlet	11.00	35.0	35.0	29.0	
		11.30	36.5	35.5	29.0	
		12.00	39.5	38.0	29.0	
		12.30	42.0	40.5	29.5	
		1.00	41.5	40.0	29.0	
	Middle	11.00	35.0	35.0	28.5	
		11.30	36.5	35.0	28.5	
		12.00	39.5	38.0	29.0	
		12.30	42.0	40.0	29.0	
		1.00	41.5	40.0	29.0	
	Out	11.00	35.0	34.0	29.0	
		11.30	36.5	35.0	29.0	
		12.00	39.5	37.0	29.0	
		12.30	42.0	38.5	29.5	
		1.00	41.5	40.0	30.0	

Appendix Table A3 (Continued)

Date	Position	Time	Temperature/(^{0}C)			Remarks
			Air	Chamber	Soil	
3/8/2007	Inlet	11.00	31.0	31.0	28.0	
		11.30	33.0	32.0	28.0	Cut the plants
		12.00	34.5	33.0	28.0	
		12.30	36.5	35.0	28.5	
		1.00	35.0	33.5	28.5	
	Middle	11.00	31.0	32.0	29.0	
		11.30	33.0	33.0	29.0	
		12.00	34.5	34.0	29.5	
		12.30	36.5	36.0	29.5	
		1.00	35.0	34.0	29.0	
	Out	11.00	31.0	32.0	29.0	
		11.30	33.0	33.5	29.0	
		12.00	34.5	34.5	29.0	
		12.30	36.5	35.0	29.0	
		1.00	35.0	34.5	29.0	
8/8/2007	Inlet	12.15	29.5	29.5	28.0	
		12.45	30.0	29.5	28.0	Not a hot day.
		1.15	30.5	30.0	28.0	
		1.45	30.5	30.0	28.0	
		2.15	29.5	30.0	28.0	
	Middle	12.15	29.5	29.0	28.0	
		12.45	30.0	29.0	28.0	
		1.15	30.5	29.5	28.0	
		1.45	30.5	29.5	28.0	
		2.15	29.5	29.5	28.0	
	Out	12.15	29.5	29.0	28.0	
		12.45	30.0	29.0	28.0	
		1.15	30.5	29.5	28.0	
		1.45	30.5	29.5	28.0	
		2.15	29.5	29.5	28.0	
16/08/2007	Inlet	12.45	40.0	39.0	31.0	
		1.15	40.0	41.0	31.5	very hot day.
		1.45	38.0	41.0	31.5	
		2.15	38.0	40.5	31.5	
		2.45	40.0	42.0	31.5	
	Middle	12.45	40.0	38.0	31.5	
		1.15	40.0	39.5	31.5	
		1.45	38.0	39.5	31.5	
		2.15	38.0	38.5	31.5	
		2.45	40.0	40.5	31.5	
	Out	12.45	40.0	39.0	31.5	
		1.15	40.0	41.0	31.5	
		1.45	38.0	41.0	31.5	
		2.15	38.0	40.5	31.5	
		2.45	40.0	41.5	31.5	

Appendix Table A3 (Continued)

Date	Position	Time	Temperature/(^{0}C)			Remarks
			Air	Chamber	Soil	
22/08/2007	Inlet	11.30	35.0	35.0	30.0	
		12.00	39.0	38.0	30.0	
		12.30	43.5	42.0	30.5	
		1.00	44.5	43.0	30.5	
		1.30	43.0	40.5	30.0	
	Middle	11.30	35.0	35.0	32.0	
		12.00	39.0	37.5	33.0	
		12.30	43.5	41.0	33.5	
		1.00	44.5	42.0	33.5	
		1.30	43.0	38.0	33.0	
	Out	11.30	35.0	35.0	30.0	
		12.00	39.0	37.0	30.0	
		12.30	43.5	41.0	30.5	
		1.00	44.5	42.0	30.5	
		1.30	43.0	39.0	30.5	
29/08/2007	Inlet	10.45	32.0	32.0	29.0	
		11.15	34.5	33.0	29.0	
		11.45	35.0	33.0	29.0	
		12.15	37.0	35.5	29.0	
		12.45	37.5	36.0	29.0	
	Middle	10.45	32.0	32.0	30.0	
		11.15	34.5	32.0	30.0	
		11.45	35.0	32.0	30.0	
		12.15	37.0	34.0	31.0	
		12.45	37.5	34.0	31.0	
	Out	10.45	32.0	32.0	29.0	
		11.15	34.5	32.5	29.0	
		11.45	35.0	33.0	29.0	
		12.15	37.0	34.0	29.0	
		12.45	37.5	34.5	29.0	
5/9/2007	Inlet	11.10	35.0	35.0	28.0	
		11.40	40.0	38.5	28.5	
		12.10	39.0	37.0	28.5	
		12.40	37.0	36.0	28.5	
		1.10	35.0	34.0	28.0	
	Middle	11.10	35.0	35.0	30.0	
		11.40	40.0	39.0	31.0	
		12.10	39.0	37.0	31.0	
		12.40	37.0	35.0	31.0	
		1.10	35.0	34.0	30.0	
	Out	11.10	35.0	34.0	29.0	
		11.40	40.0	36.0	29.0	
		12.10	39.0	34.5	29.0	
		12.40	37.0	34.5	29.0	
		1.10	35.0	33.5	28.0	

Appendix Table A3 (Continued)

Date	Position	Time	Temperature/(^{0}C)			Remarks
			Air	Chamber	Soil	
12/9/2007	Inlet	11.30	35.0	35.0	30.0	
		12.00	40.5	39.0	30.0	No leachate to
		12.30	43.0	41.5	30.0	system
		1.00	42.0	40.0	30.5	
		1.30	42.0	41.0	30.5	
	Middle	11.30	35.0	35.5	31.0	
		12.00	40.5	38.0	31.0	
		12.30	43.0	39.5	31.5	
		1.00	42.0	38.0	31.5	
		1.30	42.0	38.0	31.0	
	Out	11.30	35.0	33.5	30.0	
		12.00	40.5	35.5	30.0	
		12.30	43.0	37.5	30.0	
		1.00	42.0	36.0	30.0	
		1.30	42.0	36.0	30.0	
26/09/2007	Inlet	10.30	34.0	34.0	29.5	
		11.00	37.0	36.0	30.0	New leachate
		11.30	39.5	38.5	30.0	
		12.00	41.0	39.0	30.0	
		12.30	38.5	37.0	30.0	
	Middle	10.30	34.0	39.0	31.0	
		11.00	37.0	41.0	31.5	
		11.30	39.5	41.0	32.0	
		12.00	41.0	39.0	32.0	
		12.30	38.5	37.0	32.0	
	Out	10.30	34.0	33.0	29.0	
		11.00	37.0	34.0	29.0	
		11.30	39.5	34.0	29.0	
		12.00	41.0	33.0	29.0	
		12.30	38.5	33.0	29.0	
3/10/2007	Inlet	10.40	34.5	34.5	29.0	
		11.10	36.0	35.0	29.0	
		11.40	35.5	34.0	29.0	
		12.10	35.0	34.0	29.0	
		12.40	35.0	34.0	29.0	
	Middle	10.40	34.5	35.0	30.5	
		11.10	36.0	35.5	31.0	
		11.40	35.5	35.0	31.0	
		12.10	35.0	34.5	31.0	
		12.40	35.0	34.5	31.0	
	Out	10.40	34.5	33.5	29.0	
		11.10	36.0	33.0	29.0	
		11.40	35.5	33.0	29.0	
		12.10	35.0	33.0	29.0	
		12.40	35.0	32.5	29.0	

Appendix Table A3 (Continued)

Date	Position	Time	Temperature/(^{0}C)			Remarks
			Air	Chamber	Soil	
12/10/2007	Inlet	10.00	29.0	29.0	27.5	
		10.30	30.0	29.0	27.5	
		11.00	31.5	30.0	27.5	
		11.30	33.0	31.0	27.5	
		12.00	33.0	31.0	27.5	
	Middle	10.00	29.0	28.0	28.0	
		10.30	30.0	28.0	28.0	
		11.00	31.5	28.5	28.0	
		11.30	33.0	30.0	28.0	
		12.00	33.0	30.5	28.0	
	Out	10.00	29.0	28.0	28.0	
		10.30	30.0	28.0	28.0	
		11.00	31.5	28.5	28.0	
		11.30	33.0	30.0	28.0	
		12.00	33.0	30.5	28.0	

Appendix Table A4 Temperature variation on sampling during Run I - System B

Date	Position	Time	Temperature/(^{0}C)			Remarks
			Air	Chamber	Soil	
13/7/2007	Inlet	1.45	36.0	36.0	30.0	
		2.15	37.0	36.0	30.0	
		2.45	37.5	37.0	31.0	
		3.15	37.0	37.0	31.0	
		3.45	37.0	37.0	31.0	
	Middle	1.45	36.0	34.0	30.0	
		2.15	37.0	34.0	30.0	
		2.45	37.5	33.5	30.0	
		3.15	37.0	33.0	30.0	
		3.45	37.0	32.5	30.0	
	Out	1.45	36.0	36.0	29.5	
		2.15	37.0	36.0	29.5	
		2.45	37.5	36.0	30.0	
		3.15	37.0	36.0	30.0	
		3.45	37.0	36.0	30.0	
19/7/2007	Inlet	1.55	43.0	40.5	29.5	
		2.25	42.0	40.5	29.5	
		2.55	37.0	38.0	29.0	
		3.25	35.0	36.5	29.0	
		3.55	34.0	35.0	29.0	
	Middle	1.55	43.0	36.5	29.5	
		2.25	42.0	35.5	29.5	
		2.55	37.0	34.0	29.0	
		3.25	35.0	33.0	29.0	
		3.55	34.0	32.0	29.0	
	Out	1.55	43.0	40.0	29.0	
		2.25	42.0	40.0	29.0	
		2.55	37.0	39.0	29.0	
		3.25	35.0	38.0	29.0	
		3.55	34.0	36.5	28.5	
26/7/2007	Inlet	1.30	41.0	41.0	30.0	
		2.00	42.0	40.5	30.0	
		2.30	41.5	39.5	30.0	
		3.00	39.0	37.5	29.5	
		3.30	36.0	34.0	29.5	
	Middle	1.30	41.0	38.0	29.0	
		2.00	42.0	35.5	29.0	
		2.30	41.5	35.0	29.0	
		3.00	39.0	32.0	29.0	
		3.30	36.0	31.0	29.0	
	Out	1.30	41.0	39.5	29.0	
		2.00	42.0	40.0	29.0	
		2.30	41.5	39.5	29.0	
		3.00	39.0	35.5	29.5	
		3.30	36.0	33.0	29.5	

Appendix Table A4 (Continued)

Date	Position	Time	Temperature/(^{0}C)			Remarks
			Air	Chamber	Soil	
3/8/2007	Inlet	1.30	34.0	34.0	28.0	
		2.00	35.0	34.0	28.0	
		2.30	35.5	34.5	28.0	
		3.00	36.5	35.0	28.0	
		3.30	35.0	34.0	28.0	
	Middle	1.30	34.0	34.0	29.0	
		2.00	35.0	33.0	29.0	
		2.30	35.5	33.0	29.0	
		3.00	36.5	33.0	29.5	
		3.30	35.0	32.0	29.5	
	Out	1.30	34.0	32.0	28.0	
		2.00	35.0	33.0	28.0	
		2.30	35.5	33.0	28.5	
		3.00	36.5	35.0	28.5	
		3.30	35.0	35.0	28.0	
8/8/2007	Inlet	12.15	28.5	28.5	27.5	
		12.45	28.5	28.5	27.0	
		1.15	28.0	28.5	27.0	Not a hot day.
		1.45	28.0	28.0	27.0	
		2.15	27.5	28.0	27.0	
	Middle	12.15	28.5	28.0	27.0	
		12.45	28.5	28.0	27.0	
		1.15	28.0	28.0	27.0	
		1.45	28.0	28.0	27.0	
		2.15	27.5	28.0	27.0	
	Out	12.15	28.5	28.5	27.0	
		12.45	28.5	28.5	27.0	
		1.15	28.0	28.5	27.0	
		1.45	28.0	28.5	27.0	
		2.15	27.5	28.0	27.0	
16/8/2007	Inlet	12.45	40.0	37.5	31.0	
		1.15	40.0	38.0	31.0	
		1.45	38.0	38.5	31.0	
		2.15	38.0	38.5	31.0	
		2.45	40.0	39.0	31.0	
	Middle	12.45	40.0	36.5	31.0	
		1.15	40.0	37.0	31.0	
		1.45	38.0	37.0	31.0	
		2.15	38.0	37.0	31.0	
		2.45	40.0	37.5	31.0	
	Out	12.45	40.0	37.5	31.5	
		1.15	40.0	37.0	31.5	
		1.45	38.0	36.5	31.5	
		2.15	38.0	36.5	31.5	
		2.45	40.0	37.0	31.5	

Appendix Table A4 (Continued)

Date	Position	Time	Temperature/(^{0}C)			Remarks
			Air	Chamber	Soil	
22/8/2007	Inlet	1.45	37.0	37.0	30.0	
		2.15	36.5	35.0	30.0	
		2.45	36.0	34.5	30.0	
		3.15	34.0	33.0	30.0	
		3.45	32.5	31.5	30.0	
	Middle	1.45	37.0	35.0	30.0	
		2.15	36.5	34.5	30.0	
		2.45	36.0	32.0	30.0	
		3.15	34.0	30.5	30.0	
		3.45	32.5	30.0	30.0	
	Out	1.45	37.0	37.0	29.0	
		2.15	36.5	33.0	29.0	
		2.45	36.0	33.0	29.0	
		3.15	34.0	32.5	29.0	
		3.45	32.5	30.0	29.0	
29/8/2007	Inlet	1.10	36.0	36.0	30.0	
		1.40	37.0	36.0	30.0	
		2.10	36.5	35.0	30.0	
		2.40	34.5	34.0	30.0	
		3.10	31.5	31.0	29.5	
	Middle	1.10	36.0	34.0	29.0	
		1.40	37.0	34.0	29.0	
		2.10	36.5	32.5	29.0	
		2.40	34.5	31.0	28.0	
		3.10	31.5	29.0	28.0	
	Out	1.10	36.0	35.0	30.0	
		1.40	37.0	36.0	30.0	
		2.10	36.5	35.0	30.0	
		2.40	34.5	32.5	29.5	
		3.10	31.5	29.0	29.5	
12/9/2007	Inlet	1.50	40.0	40.0	30.5	
		2.20	42.0	41.0	30.5	
		2.50	42.0	40.5	30.5	
		3.10	41.5	39.0	30.5	
		3.50	39.5	38.0	30.5	
	Middle	1.50	40.0	37.0	30.0	
		2.20	42.0	34.5	30.0	
		2.50	42.0	33.0	30.0	
		3.10	41.5	32.0	30.0	
		3.50	39.5	32.0	30.0	
	Out	1.50	40.0	40.0	29.0	
		2.20	42.0	40.0	29.5	
		2.50	42.0	40.0	29.5	
		3.10	41.5	39.0	29.0	
		3.50	39.5	38.0	29.0	

Appendix Table A4 (Continued)

Date	Position	Time	Temperature/(^{0}C)			Remarks
			Air	Chamber	Soil	
26/9/2007	Inlet	1.00	34.0	34.0	30.0	
		1.30	36.0	34.5	30.0	
		2.00	36.0	35.0	30.0	
		2.30	36.0	35.0	29.5	
		3.00	32.0	31.0	29.5	
	Middle	1.00	34.0	33.0	30.0	
		1.30	36.0	32.5	30.0	
		2.00	36.0	32.0	30.0	
		2.30	36.0	32.0	29.5	
		3.00	32.0	32.5	29.5	
	Out	1.00	34.0	33.0	30.0	
		1.30	36.0	33.5	30.0	
		2.00	36.0	33.5	30.0	
		2.30	36.0	33.0	29.5	
		3.00	32.0	32.0	29.5	
3/10/2007	Inlet	1.05	32.0	32.0	29.0	
		1.35	33.5	32.5	29.0	
		2.05	33.5	32.0	29.0	
		2.35	33.0	32.5	29.0	
		3.05	32.5	32.0	29.0	
	Middle	1.05	32.0	32.0	28.5	
		1.35	33.5	32.5	28.5	
		2.05	33.5	32.5	28.5	
		2.35	33.0	33.0	28.5	
		3.05	32.5	32.0	28.5	
	Out	1.05	32.0	32.5	29.5	
		1.35	33.5	33.0	29.5	
		2.05	33.5	34.0	29.5	
		2.35	33.0	34.0	29.5	
		3.05	32.5	33.0	29.5	

Appendix Table A5 Gas emission rate in system A and B (fresh leachate)

Month	Gas Emission Rate/($g/m^2.d$)					
	Inlet/ CH_4	Middle/CH_4	Outlet/ CH_4	Inlet/ CO_2	Middle/CO_2	Outlet/ CO_2
June	0.532	0.017	0.006	3.266	1.192	1.866
July	0.089	0.000	0.000	0.726	0.104	0.467
August	0.304	0.043	0.000	0.700	0.311	0.091
September	0.713	0.086	0.000	2.385	0.622	0.104
October	0.079	0.000	0.000	0.648	0.441	0.207

Month	Gas Emission Rate/($g/m^2.d$)					
	Inlet/ CH_4	Middle/ CH_4	Outlet/ CH_4	Inlet/ CO_2	Middle/CO_2	Outlet/ CO_2
June	0.285	0.014	0.000	2.281	1.400	0.467
July	0.114	0.012	0.000	0.694	0.259	0.233
August	0.532	0.062	0.000	0.829	0.700	0.622
September	0.105	0.000	0.000	0.622	0.363	0.285
October	0.019	0.000	0.000	0.441	0.285	0.156

Appendix Table A6 ORP values in system A and B (fresh leachate)

System A	Depth from surface					
	A	60	45	30	15	0
Distance from inlet	0.5	-258	-215	-184	64	92
	2.5	-220	-198	-173	75	105
	5.5	-212	-175	-125	97	141

System B	Depth from surface					
	B	60	45	30	15	0
Distance from inlet	0.5	-248	-165	-114	101	151
	2.5	-217	-158	-123	112	165
	5.5	-212	-155	-125	135	189

Appendix Table A7 Gas emission rate in system A & B- (Mixed leachate)

System A/ B Date	Week	Inlet				Middle				Out			
		CH_4 flux/ ($g/m^2.s$)	CH_4 flux/ ($g/m^2.d$)	CO_2 flux/ ($g/m^2.s$)	CO_2 flux/ ($g/m^2.d$)	CH_4 flux/ ($g/m^2.s$)	CH_4 flux/ ($g/m^2.d$)	CO_2 flux/ ($g/m^2.s$)	CO_2 flux/ ($g/m^2.d$)	CH_4 flux/ ($g/m^2.s$)	CH_4 flux/ ($g/m^2.d$)	CO_2 flux/ ($g/m^2.s$)	CO_2 flux/ ($g/m^2.d$)
14/11/2007	1	0.0054	0.2614	0.0227	1.0886	0.0019	0.0903	0.0073	0.3499	0.0000	0.0000	0.0065	0.3110
19/11/2007	2	0.0061	0.2946	0.0248	1.1923	0.0010	0.0475	0.0059	0.2851	0.0000	0.0000	0.0032	0.1555
26/11/2007	3	0.0111	0.5322	0.0464	2.2291	0.0036	0.1711	0.0092	0.4406	0.0000	0.0000	0.0027	0.1296
29/11/2007	4	0.0081	0.3897	0.0313	1.5034	0.0030	0.1426	0.0086	0.4147	0.0000	0.0000	0.0027	0.1296
3/12/2007	5	0.0008	0.0380	0.0081	0.3888	0.0006	0.0285	0.0038	0.1814	0.0000	0.0000	0.0054	0.2592
10/12/2007	6	0.0008	0.0380	0.0146	0.6998	0.0006	0.0285	0.0097	0.4666	0.0000	0.0000	0.0081	0.3888
17/12/2007	7	0.0026	0.1236	0.0097	0.4666	0.0010	0.0475	0.0081	0.3888	0.0000	0.0000	0.0070	0.3370
27/12/2007	8	0.0030	0.1426	0.0130	0.6221	0.0012	0.0570	0.0092	0.4406	0.0000	0.0000	0.0081	0.3888
8/1/2008	9	0.0034	0.1616	0.0270	1.2960	0.0016	0.0760	0.0049	0.2333	0.0000	0.0000	0.0043	0.2074
14/01/2008	10	0.0036	0.1711	0.0286	1.3738	0.0014	0.0665	0.0108	0.5184	0.0000	0.0000	0.0081	0.3888
21/01/2008	11	0.0055	0.2661	0.0313	1.5034	0.0019	0.0903	0.0135	0.6480	0.0000	0.0000	0.0086	0.4147
28/01/2008	12	0.0050	0.2424	0.0300	1.4386	0.0013	0.0637	0.0127	0.6078	0.0000	0.0000	0.0052	0.2514
15/11/2007	1	0.0048	0.2281	0.0329	1.5811	0.0007	0.0333	0.0108	0.5184	0.0000	0.0000	0.0049	0.2333
22/11/2007	2	0.0059	0.2851	0.0432	2.0736	0.0000	0.0000	0.0097	0.4666	0.0000	0.0000	0.0054	0.2592
29/11/2007	3	0.0006	0.0285	0.0227	1.0886	0.0000	0.0000	0.0054	0.2592	0.0000	0.0000	0.0043	0.2074
30/11/2007	4	0.0018	0.0855	0.0302	1.4515	0.0008	0.0380	0.0059	0.2851	0.0000	0.0000	0.0049	0.2333
6/12/2007	5	0.0008	0.0380	0.0373	1.7885	0.0000	0.0000	0.0065	0.3110	0.0000	0.0000	0.0054	0.2592
12/12/2007	6	0.0018	0.0855	0.0205	0.9850	0.0008	0.0380	0.0205	0.9850	0.0000	0.0000	0.0049	0.2333
20/12/2007	7	0.0067	0.3231	0.0448	2.1514	0.0016	0.0760	0.0167	0.8035	0.0000	0.0000	0.0038	0.1814
28/12/2007	8	0.0012	0.0570	0.0108	0.5184	0.0012	0.0570	0.0097	0.4666	0.0000	0.0000	0.0041	0.1944
10/1/2008	9	0.0014	0.0665	0.0313	1.5034	0.0008	0.0380	0.0092	0.4406	0.0000	0.0000	0.0081	0.3888
17/01/2008	10	0.0016	0.0760	0.0189	0.9072	0.0010	0.0475	0.0097	0.4666	0.0000	0.0000	0.0043	0.2074
24/01/2008	11	0.0028	0.1331	0.0259	1.2442	0.0013	0.0618	0.0146	0.6998	0.0000	0.0000	0.0065	0.3110
30/01/2008	12	0.0031	0.1473	0.0230	1.1042	0.0011	0.0523	0.0103	0.4925	0.0000	0.0000	0.0044	0.2104

Appendix Table A8 Leachate characteristics in system A & B- (Mixed leachate)

		Inlet					Middle					Out				
Date/ System A	Week	pH	COD/ (mg/L)	BOD/ (mg/L)	TKN/ (mg/L)	NH3-N/ (mg/L)	pH	COD/ (mg/L)	BOD/ (mg/L)	TKN/ (mg/L)	NH3-N/ (mg/L)	pH	COD/ (mg/L)	BOD/ (mg/L)	TKN/ (mg/L)	NH3-N/ (mg/L)
14/11/2007	1	4.92	1875				6.68					7.05				
19/11/2007	2	4.99	4736	2412			6.72	989	578			6.99	366	82		
26/11/2007	3	5.01	5768	3240	142	115	6.64	1154	740	77	65	6.82	908	145	75	56
29/11/2007	4	4.85	3221	1638			6.85	895	472			7.12	715	55		
3/12/2007	5	4.47	7040	3540	122	85	6.72	2252	901	73	51	7.03	1296	143	50	38
10/12/2007	6	5.12	4312	2340			6.79	1139	514			7.23	905	85		
17/12/2007	7	5.06	5838	3172	160	132	7.01	1488	841	85	79	7.31	872	125	78	63
28/12/2007	8	5.08	5449	2985			6.98	1265	856			7.15	491	78		
8/1/2008	9	4.23	5860	3652	198	157	6.88	1357	785	104	91	7.18	472	121	99	70
14/01/2008	10	5.33	3675	2100			6.96	887	521			6.71	260	55		
21/01/2008	11	5.18	4612	2348	176	143	6.89	969	564	89	75	7.15	345	70	85	71
28/01/2008	12	5.28	4285	2272			6.99	943	523			7.05	302	69		
15/11/2007	1	5.15	1805				6.65					7.11				
22/11/2007	2	5.03	4124	2324	132	98	6.79	1105	579	70	58	7.03	855	137	68	46
29/11/2007	3	4.86	4050	2220			6.82	1074	562			7.04	831	125		
30/11/2007	4	4.93	3985	2077	140	116	6.93	1096	551	67	62	7.23	765	95	63	51
6/12/2007	5	4.84	3840	2040			6.75	980	562			7.36	654	160		
12/12/2007	6	5.45	2534	1380	118	95	6.95	704	340	53	44	7.00	355	79	51	40
20/12/2007	7	4.81	6616	3514			6.98	1752	825			7.42	856	147		
28/12/2007	8	4.96	5720	3152	172	102	7.02	1385	773	81	65	7.24	498	108	76	41
10/1/2008	9	4.53	5752	3425			6.94	1323	770			7.17	460	95		
17/01/2008	10	5.21	4913	2940	162	128	6.96	1375	718	76	61	7.21	295	98	73	53
24/01/2008	11	5.15	4715	2512			7.01	1038	566			7.09	307	100		
30/01/2008	12	5.24	4358	2309			7.06	959	485			7.11	262	70		

Appendix Table A9 Temperature variation during diurnal sampling- (fresh leachate)

Date	System (A/B)	Time	Temperature/(°C)			Remarks
			Inside chamber	Soil	Air	
	A	5.00 pm	29.0	31.0	30.0	
26/9/2007	Middle	8.00 pm	27.5	30.5	28.0	5.00 pm to
27/9/2007		11.00 pm	27.5	30.5	26.0	5.00 pm
		2.00 am	27.0	30.0	26.0	
		5.00 am	26.5	30.0	25.0	
		8.00 am	29.5	30.0	30.0	
		11.00 am	35.5	31.5	38.5	
		2.00 pm	35.0	31.5	39.0	
		5.00 pm	31.5	31.0	31.0	
	B	5.00 pm	28.5	30.0	30.0	
	Inlet	8.00 pm	27.0	30.0	28.0	
		11.00 pm	27.0	30.0	26.0	
		2.00 am	27.0	30.0	26.0	
		5.00 am	26.5	30.0	25.0	
		8.00 am	28.0	30.0	30.0	
		11.00 am	35.5	30.0	38.5	
		2.00 pm	36.0	30.0	39.0	
		5.00 pm	30.0	30.0	31.0	
	B	5.00 pm	29.0	30.0	30.0	
	Middle	8.00 pm	28.0	30.0	28.0	
		11.00 pm	28.0	30.0	26.0	
		2.00 am	28.0	29.0	26.0	
		5.00 am	27.0	29.0	25.0	
		8.00 am	29.0	29.0	30.0	
		11.00 am	33.5	29.5	38.5	
		2.00 pm	33.0	29.5	39.0	
		5.00 pm	31.0	29.0	31.0	

Appendix Table A10 Gas composition on diurnal variation- (fresh leachate)

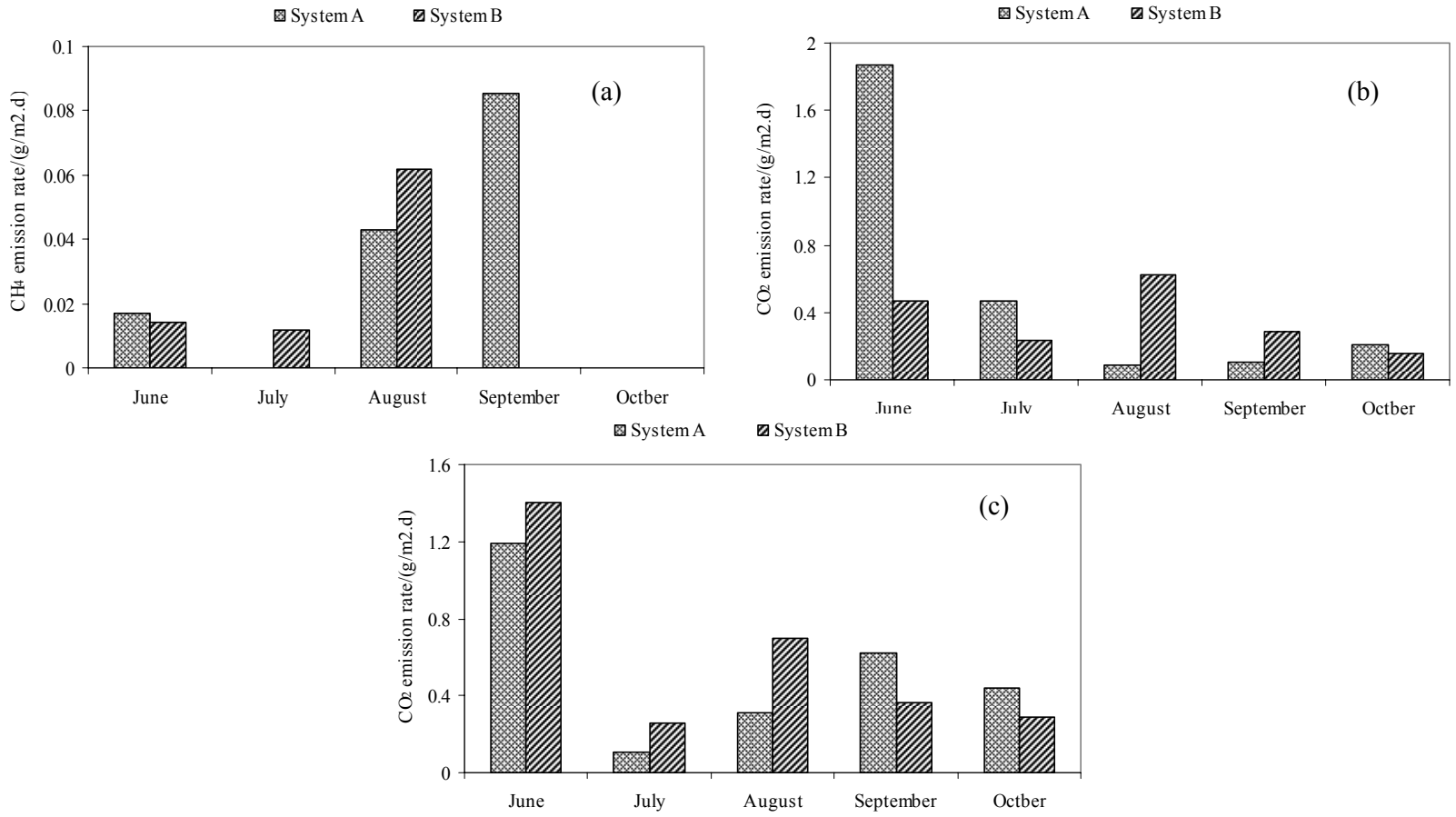
	Middle A/(%)		Inlet B/(%)		Middle B/(%)	
Time	CH_4	CO_2	CH_4	CO_2	CH_4	CO_2
5.00 pm	0.0212	0.1617	0.0329	0.3131	0.0039	0.3696
8.00 pm	0.0990	0.5101	0.1654	1.0613	0.0198	0.5848
11.00 pm	0.1738	0.6927	0.1802	1.2906	0.0216	0.6734
2.00 am	0.2329	0.9494	0.1618	1.7712	0.0194	0.7972
5.00 am	0.2621	1.1373	0.1301	2.1324	0.0156	0.9236
8.00 am	0.1889	0.8627	0.0916	2.3125	0.0110	0.9942
11.00 am	0.3456	1.0090	0.0638	2.7477	0.0077	1.0614
2.00 pm	0.4108	1.1808	0.0424	2.5981	0.0051	1.0988
5.00 pm	0.3901	1.2032	0.0425	3.3971	0.0051	1.3171

Appendix Table A11 Temperature variation during diurnal sampling- (Mixed lea.)

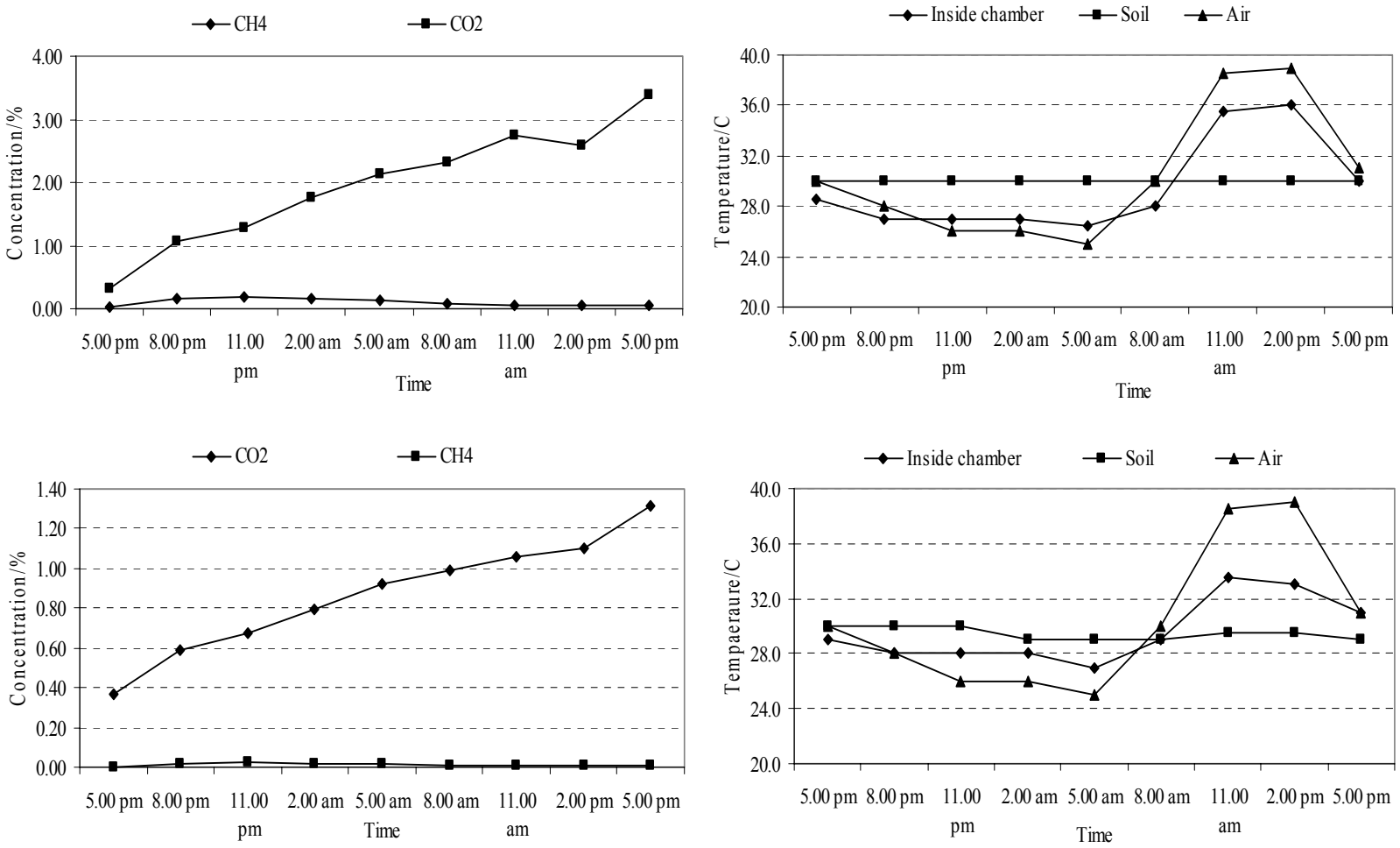
Date	System (A/B)	Time	Temperature/ (^{o}C)			Remarks
			Inside chamber	Soil	Air	
19/12/2007	A	6.00 am	23.5	28.0	24.0	
20/12/2007	Middle	9.00 am	33.5	28.0	33.0	6.00 am to
		12.00 noon	37.0	29.0	40.0	6.00 am
		3.00 pm	33.0	29.0	38.0	
		6.00 pm	29.0	29.0	29.0	
		9.00 pm	26.0	28.0	27.0	
		12.00 MN	26.0	27.0	27.0	
		3.00 am	24.0	27.0	25.0	
		6.00 am	24.0	27.0	24.0	
	B	6.00 am	24.0	27.0	24.0	
	Inlet	9.00 am	28.0	27.0	33.0	
		12.00 noon	36.0	28.0	40.0	
		3.00 pm	35.0	28.0	38.0	
		6.00 pm	30.0	28.0	29.0	
		9.00 pm	28.0	28.0	27.0	
		12.00 MN	27.0	28.0	27.0	
		3.00 am	26.0	28.0	25.0	
		6.00 am	25.0	28.0	24.0	
	B	6.00 am	24.0	27.5	24.0	
	Middle	9.00 am	28.0	27.5	33.0	
		12.00 noon	34.0	27.0	40.0	
		3.00 pm	33.0	27.0	38.0	
		6.00 pm	29.0	27.0	29.0	
		9.00 pm	27.0	27.0	27.0	
		12.00 MN	27.0	26.0	27.0	
		3.00 am	26.0	26.0	25.0	
		6.00 am	25.0	26.0	24.0	

Appendix B

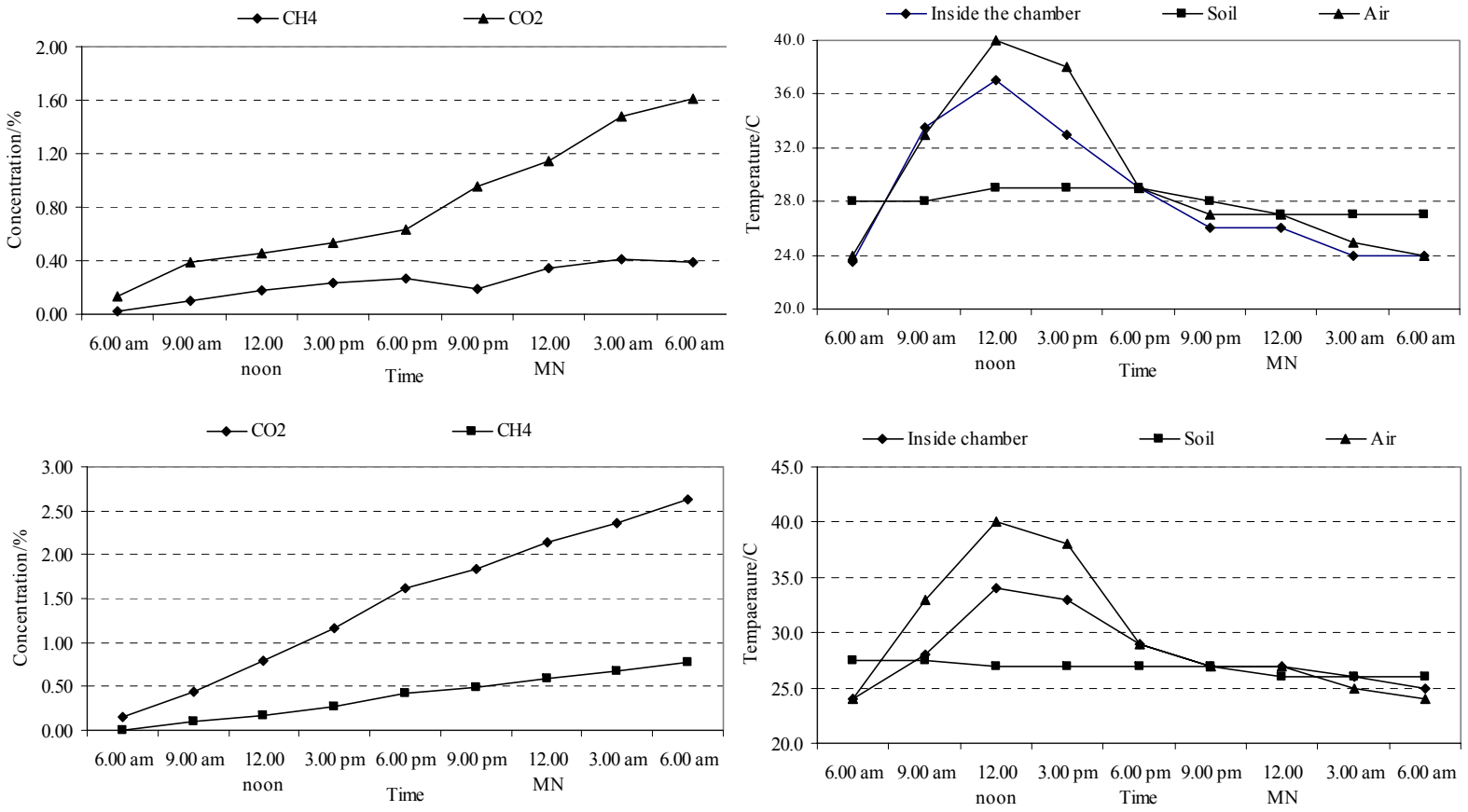
Figure



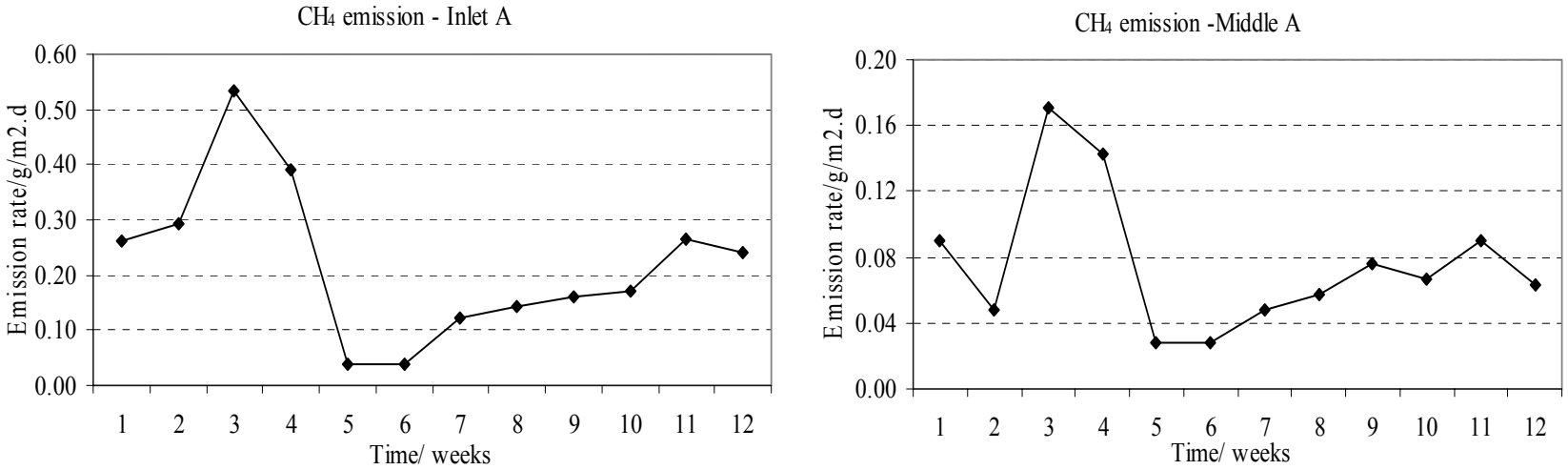
Appendix Figure B1 (a) CH_4, (b) and (c) CO_2 gas emission rate from wetlands- Fresh leachate



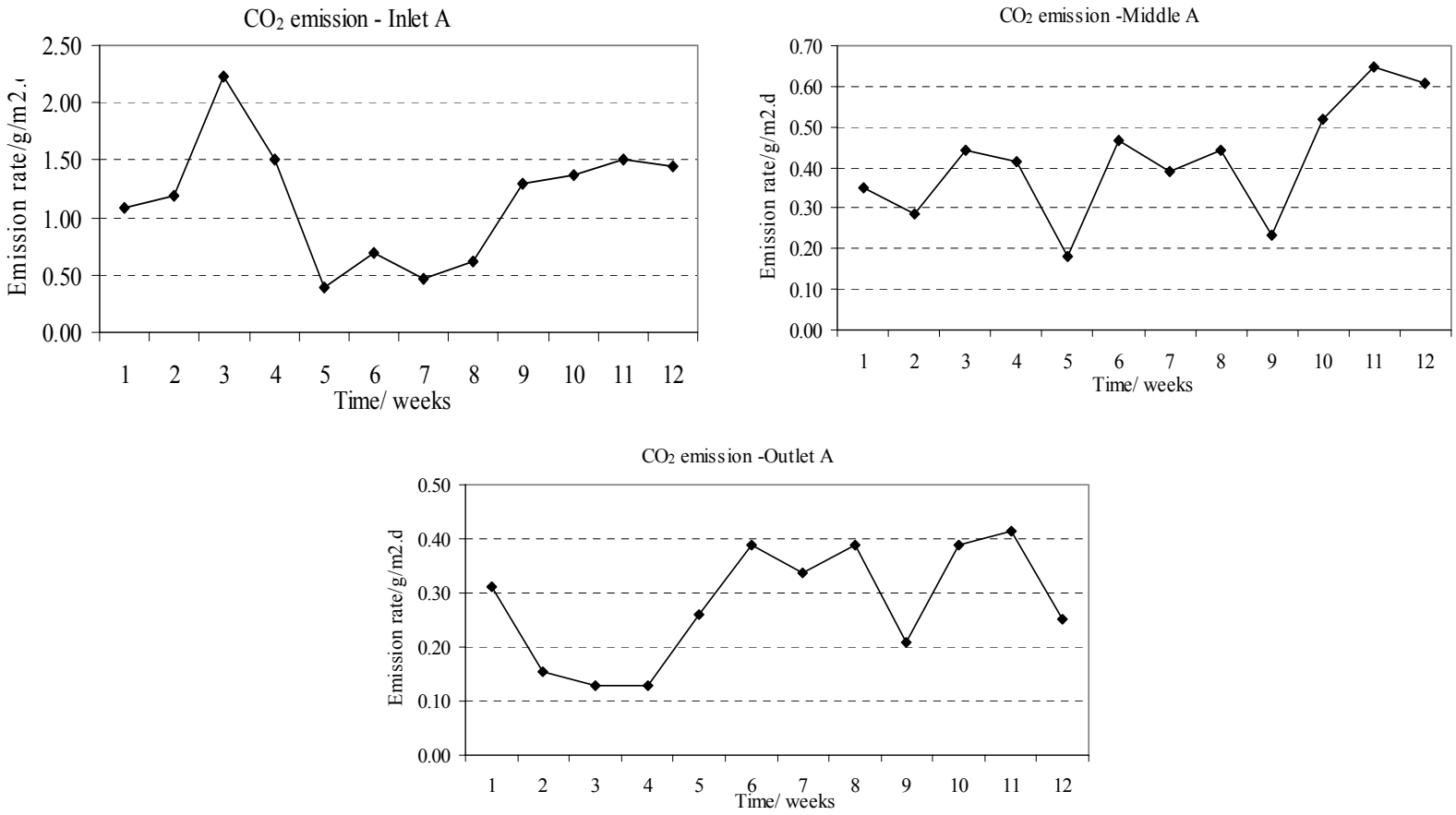
Appendix Figure B2 Gas concentration variation and correspondent temperatures on diurnal variation- Fresh leachate



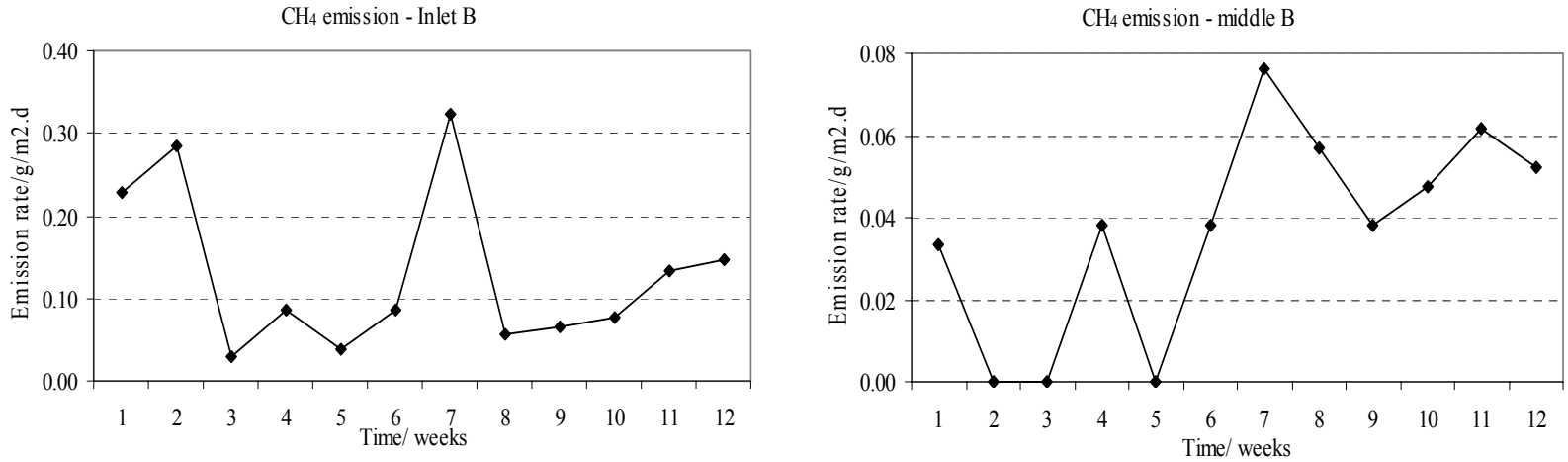
Appendix Figure B3 Gas concentration variation and correspondent temperatures on diurnal variation- mixed leachate



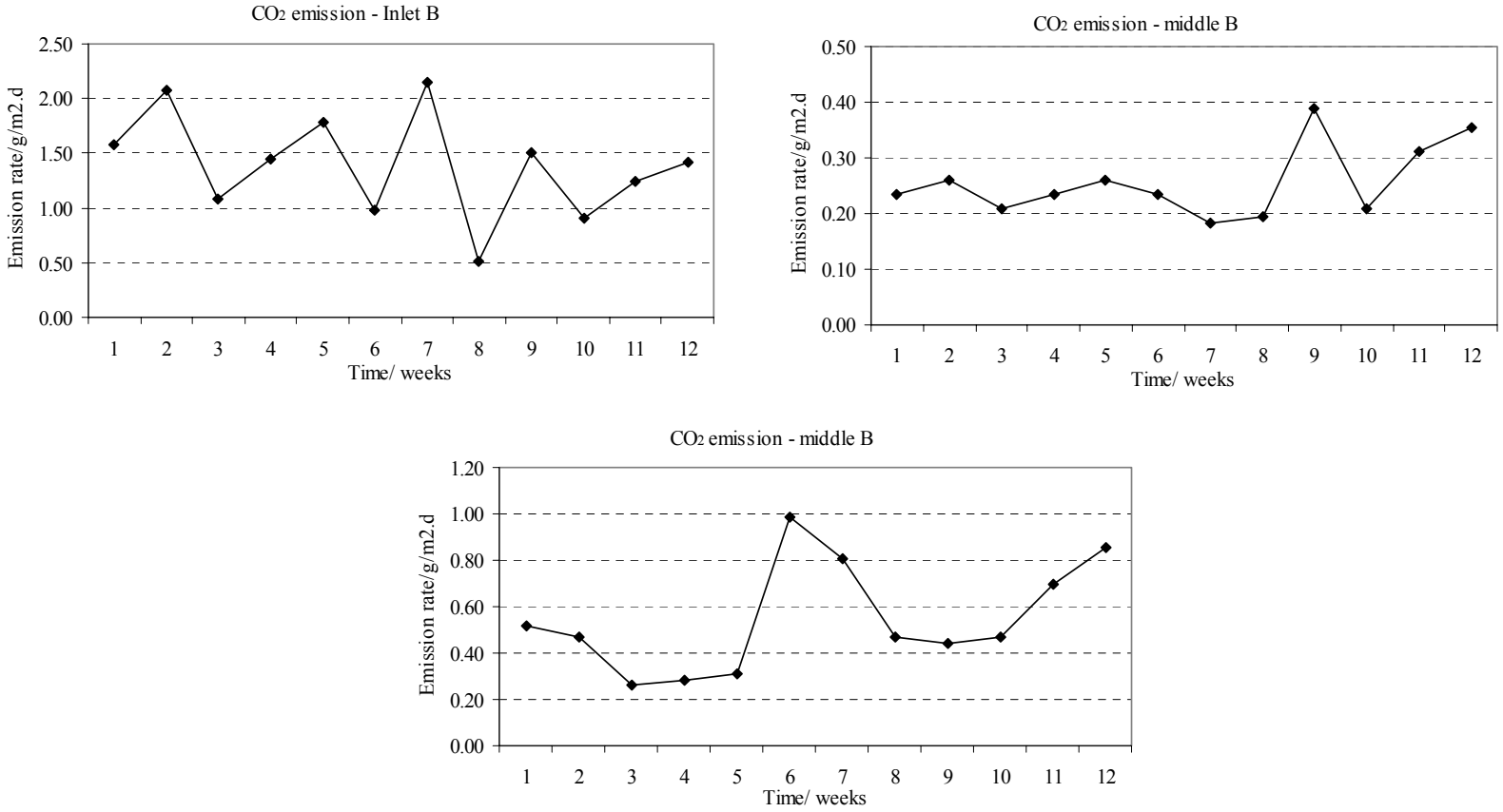
Appendix Figure B4 CH_4 emission rate from system A- mixed leachate



Appendix Figure B5 CO_2 emission rate from system A- mixed leachate



Appendix Figure B6 CH_4 emission rate from system B- mixed leachate



Appendix Figure B7 CO_2 emission rate from system A- mixed leachate

Appendix C

Specimen Calculation

Calculation of greenhouse gas flux rate.

Flux of CH_4, CO_2 and N_2O was calculated by Eq. 12. Linear regression of gas concentration is used for differentiation of gas concentration with time.

$$F = \frac{\rho V \Delta C}{A \Delta t}$$

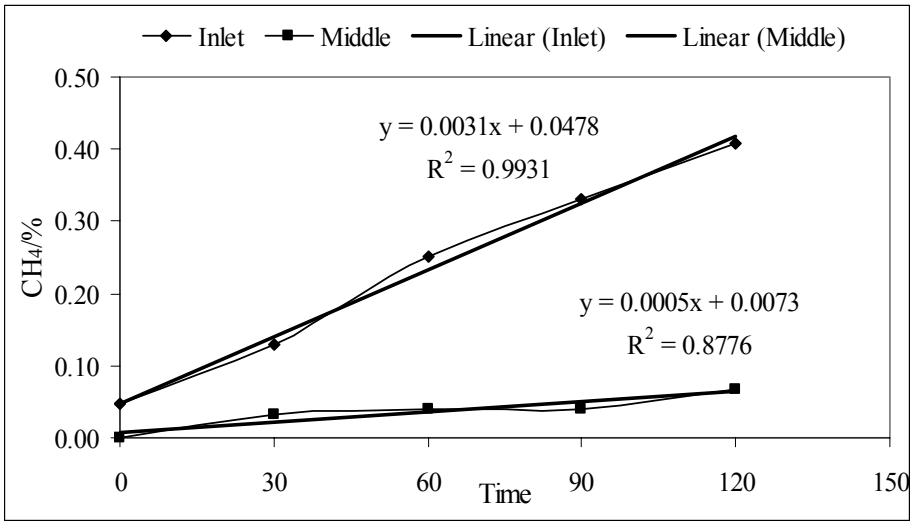
Where F is gas flux ($g/m^2/s$), ρ is gas density (kg/m^3), V is Chamber volume (m^3), A is chamber cover area (m^2); ΔC: gas concentration gradient (%) and Δt is gas sampling time (s).

Air density	=	1.2 kg/m^3		
Specific gravity of CH_4	=	0.55		
ρ_{CH4}	=	0.55*1.2	=	0.66kg/m^3
Specific gravity of CO_2	=	1.52		
P_{CO2}	=	1.52*1.2	=	1.83kg/m^3
Specific gravity of N_2O	=	1.53		
P_{N2O}	=	1.53*1.2	=	1.84kg/m^3
V/A	=	Height of chamber		
	=	0.3 m		
ΔC/Δt	=	slope made by liner regression		
Methane flux	=	[0.3 m]*[0.66 kg/m^3]*[1000/100]* ΔC/Δt		
	=	1.98* ΔC/Δt		
CO_2 flux	=	[0.3 m]*[1.83 kg/m^3]*[1000/100]* ΔC/Δt		
	=	5.49* ΔC/Δt		
N_2O flux	=	[0.3 m]*[1.84 kg/m^3]*[1000/100]* ΔC/Δt		
	=	5.52* ΔC/Δt		

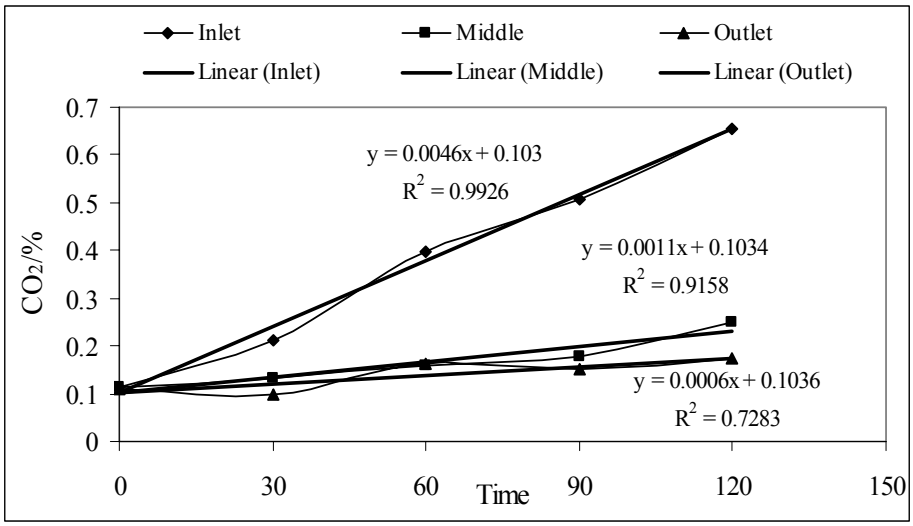
Let's take data set of system (A) on 19/11/2007 for specimen calculation. The following table C1 shows the gas concentration over the time period. (This is the data from gas chromatography).

Appendix Table C1 Gas concentration over time

Time	Cumulative time/(min)	Gas concentration					
		CH_4/ (%)			CO_2/ (%)		
		Inlet	Middle	Out	Inlet	Middle	Out
11.00	0	0.047	0.000	0.000	0.115	0.114	0.109
11.30	30	0.128	0.032	0.000	0.213	0.133	0.099
12.00	60	0.251	0.039	0.000	0.399	0.158	0.164
12.30	90	0.330	0.040	0.000	0.509	0.179	0.152
1.00	120	0.408	0.067	0.000	0.655	0.249	0.172



Appendix Figure C1 Linear regression of CH_4



Appendix Figure C2 Linear regression of CO_2

Methane flux (Inlet) = 1.98* $\Delta C/\Delta t$

= 1.98*0.0031 = 0.0061 g/m^2.(30min)

= 0.0061*48

= 0.2946 g/m^2.d

CO_2 flux (Middle) = 5.49* $\Delta C/\Delta t$

= 5.49*0.0011 = 0.006 g/m^2.(30min)

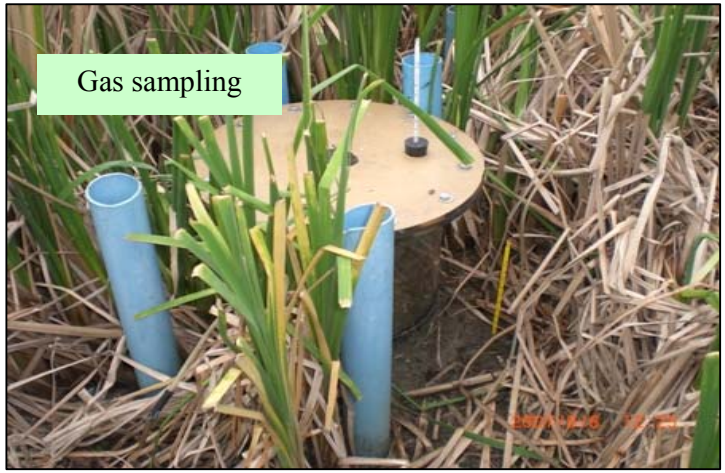
= 0.006*48

= 0.290 g/m^2.d

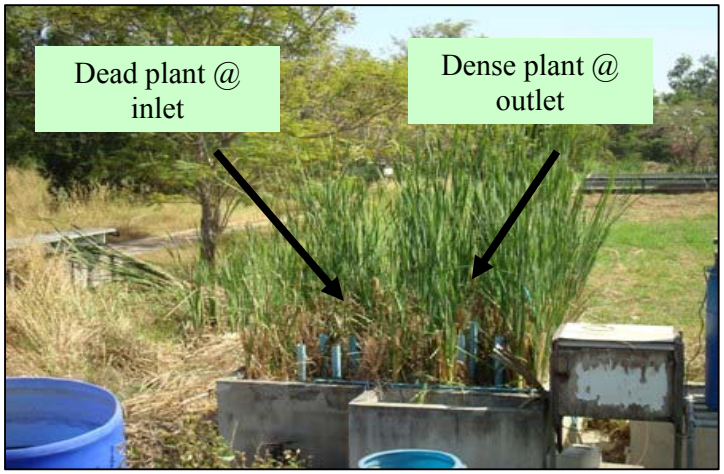
Likewise all CH_4 and CO_2 flux calculation can be calculated.

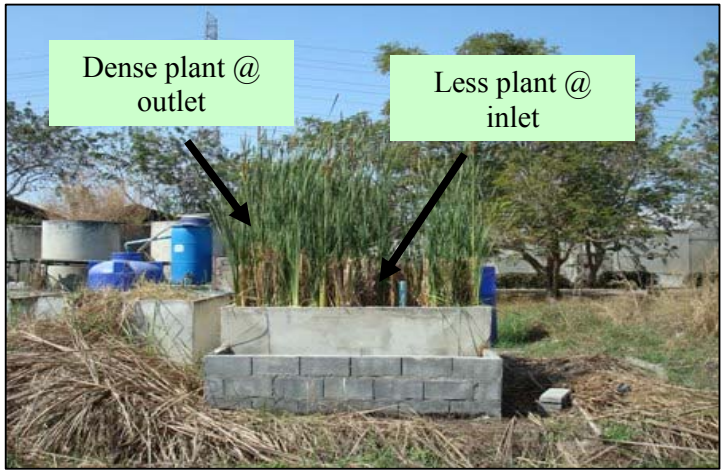
Appendix D

Photograph


Gas sampling


@ Plant harvesting


Dead plant @ inlet
Dense plant @ outlet


Dense plant @ outlet
Less plant @ inlet

CURRICULUM VITAE

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