CHAPTER 2

LITERATURE REVIEW

2.1 Waste

Waste is defined as useless or unwanted material which is produced from human activity. The amount of waste has increased simultaneously due to the increase of human populations. Waste management has become more complicated with the increase in the amount of waste generated. According to Agamuthu (2001) waste are divided into three categories; organic or inorganic, combustible or non combustible wastes and compostable or non compostable wastes. Solid Waste and Public Cleansing Management Act 2007, defined solid waste as any scrap substantial or other unwanted surplus substance or rejected products arising from the application of any process; any substance required to be disposed of as being broken, worn out, contaminated or otherwise spoiled; or any other material that according to this Act or any other written law is required by the authority to be disposed off (NSWMD, 2012). Municipal Solid Waste (MSW) is basically sourced from different types of organic and inorganic components such as food, paper, vegetables, wood and other materials (Wilshusen *et al.*, 2004).

2.2 MSW Generation

The amount of MSW generated in Malaysia is continuously increasing due to the population growth and higher living standards, accelerated urbanization and industrial process (Chua *et al*., 2011; Zamali *et al*., 2009). Daily MSW generation in Malaysia is 1.30 kg per capita per day (Agamuthu *et al*., 2009) while in US it is 1.96 kg per capita per day, Sweden 1.40 kg per capita per day, Germany 1.58 kg per capita per day, and U.K 1.54 kg per capita per day (USEPA, 2012). According to Siraj (2006), in the year of 2006 the amount of solid waste generated in Malaysia was about 7.34 million tonnes and in recent years the amount of solid waste has reached 30 million tonnes (Fauziah and Agamuthu, 2009). MSW generated globally in year 1997 was 0.49 billion tonnes with annual growth of 3.2-4.5% in developed countries and 2-3% in developing countries (Suo Cheong *et al*., 2001). Current global MSW generation levels from 161 countries are approximately 1.3 billion tonnes per year, and are expected to increase to approximately 2.2 billion tonnes per year by 2025 (World bank, 2012). This clearly indicates that the generation of MSW is increasing simultaneously with the development and urbanization except in few countries such as Japan or Denmark where recycling is at a very high level and this has reduced the net generation.

2.3 Source of MSW and Characterization

The MSW characterization is one of the important aspects in MSW management. Homogenous waste is easier to handle compared to heterogenous waste. MSW is heterogeneous and is sourced from residential, industrial, commercial, institutional, construction and demolition, municipal services and processes. Table 2.1 shows the source and types of MSW.

Table 2.1: Source and Types of Solid Waste

Source	Typical Waste Generators	Types of Solid Waste
Residential	Single and multifamily houses	Food waste, paper, cardboard, plastics, textiles leather, yard wastes, wood, glass, metals, ashes, special waste (electronic, batteries, oil, tires), and household hazardous waste.
Industrial	Light and heavy manufacturing, fabrication, construction sites, power and chemical plants.	Housekeeping wastes, packaging, food wastes, construction and demolition materials, hazardous wastes, ashes, special wastes.
Commercial	Stores, hotels, restaurants, markets, office buildings, etc	Paper, cardboard, plastics, wood, food wastes, glass, metals, special wastes, hazardous wastes.
Institutional	School, hospitals, prisons, government centers.	Same as commercial.
Construction and demolition	New construction sites, road repair, renovation sites, demolition of buildings.	Wood, steel, concrete, dirt, packaging waste etc.
Municipal services	Street cleaning, landscaping, parks, beaches, other recreational areas, water and wastewater treatment plants	Street sweepings, landscape and tree trimming, waste from parks, beaches, recreational areas, sludge.
Processes	Heavy and light manufacturing, refineries, chemical plants, power plants, mineral extraction and processing.	Industrial process wastes, scrap materials, off specification products, slag, tailings.

(Fauziah, 2009; Agamuthu *et al*., 2004; World bank, 1999)

2.4 MSW Composition

The MSW composition varies from one country to another depending on different lifestyles, populations and economic. The characteristics and composition is one of the important factors for selection of waste disposal method and also for quantification of amount of landfill gas generated. Table 2.2 shows the trend in the MSW composition for Malaysia in 1995-2010 where the amount of organic waste is higher compared to other types of waste. The composition of organic waste shows an increasing trend from 1995 to 2010. Recycling of metals and plastics could be one of the reasons for increasing trend of organic waste from 1995 to 2010.

Table 2.2: Waste Composition in Malaysia (1995-2010)

Waste composition	**1995**	**2000**	**2005**	**2010**
Organic	45.7	43.2	44.8	55.0
Paper	9.0	23.7	16.0	13.0
Plastic	3.9	11.2	15.0	19.0
Glass	3.9	3.2	3.0	2.0
Metal	5.1	4.2	3.3	3.0
Textiles	2.1	1.5	2.8	4.0
Wood	NA	0.7	6.7	1.0
Others	4.3	12.3	8.4	3.0

(Agamuthu, 2009; Agamuthu, 2011)

Table 2.3 shows the MSW composition of selected countries. Malaysia's MSW contains higher amount of organic waste compared to the other waste components and similar trend is also found in the composition of MSW of other developing countries.

Table 2.3: MSW Composition of selected countries

	Organic waste (%)	Paper (%)	Plastic (%)	Glass (%)	Metal (%)	Others (%)
Denmark	29	27	1	5	6	32
Indonesia	62	6	10	9	8	4
Thailand	48	15	14	5	4	14
Sri Lanka	76	11	6	1	1	5
Singapore	44	28	12	4	5	7
Nepal	80	7	3	3	1	7
India	35	3	2	1	-	59
China	38	26	19	3	2	12
Ghana	64	3	4	-	1	28

(World Bank, 2012)

2.5 Solid Waste Management

The Solid Waste management is a broad discipline that consists of solid waste generation, storage, collection, transfer and transport, process and disposal with the consideration on the environment, economic and publics (Agamuthu, 2001). Systematic waste management was introduced gradually in Malaysia in the 1990s (Fauziah and Agamuthu, 2012) but the amount of waste generated is still increasing at a rate of 3% annually. The increasing trend of the amount of MSW has put on pressure on the local authorities for proper waste management system. Besides that, the Solid Waste and Public Cleansing Management Act 2007 has been passed and implemented in September 2011 with two years grace period before strict enforcement. The main objective of this Act is to improve and provide high quality services for solid waste management.

2.6 Different Options for Solid Waste Treatment

The treatment and disposal of solid waste are key components of waste management. There are several options for solid waste treatment and disposal, such as waste prevention, recycling, composting, incineration and landfill as shown in Figure 2.1. Even though there are several options for solid waste disposal, landfill is the options widely used in Malaysia. Almost 95% of wastes generated are disposed into landfills while the options for recycling accounts for about 5%.

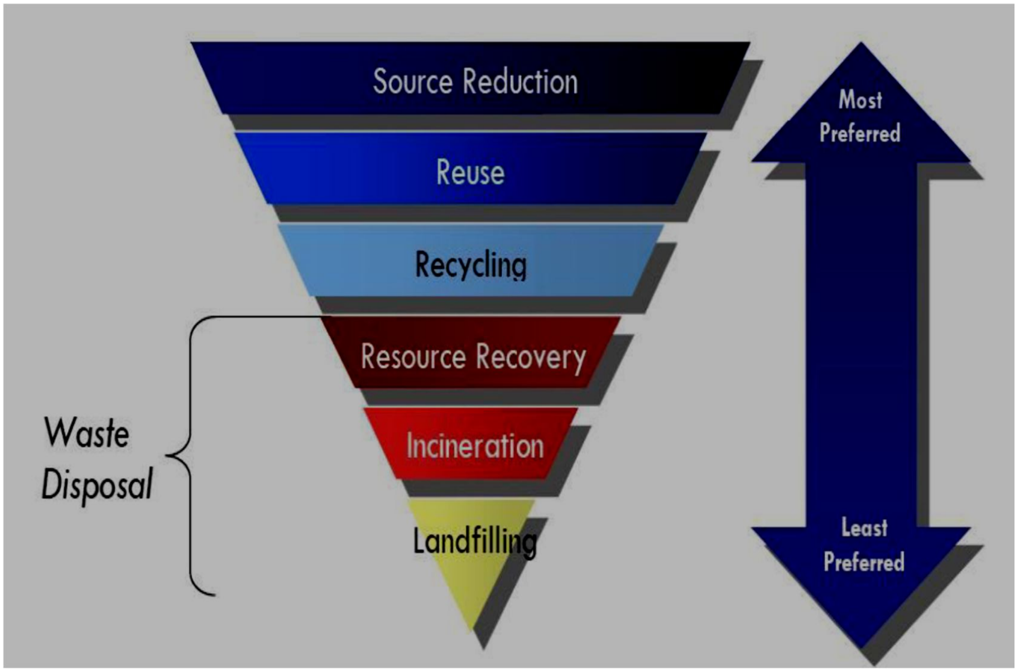


Figure 2.1: Waste disposal options

2.7 Landfilling As Disposal Method

Landfill is the option taken by almost all developing countries for the disposal of MSW. According to Agamuthu (2001), landfill is a method of significantly limiting the volume of waste and waste is systematically covered by layer of earth. It is also a place where waste is stored on a long term basis on land (Christensen *et al.*, 2007). Landfill has become one of the ultimate choices for waste disposal even though it poses hazards to the environment and public health. One of the advantages of landfilling is that, it can deal or accept all types of waste. Landfill is also considered as the simplest and cheapest waste disposal methods compared to other methods of waste disposal.

2.7.1 Landfilling in Malaysia

Landfilling is the most common way of disposing MSW in developing countries such as Malaysia. Malaysia began its operations of disposing waste into landfills or open dumps in the late 1970's (Fauziah and Agamuthu, 2012) and before that period the waste was burned or buried. The need for more landfills in Malaysia is due to the increase in the amount of waste generated simultaneously with population growth (Agamuthu and Fauziah, 2011). Most landfills were built near urban areas for the convenience of local authorities to collect and transport waste. Environmental impacts due to landfills, such as groundwater contamination, type of soil or distance from residential areas were paid less attention. In the early 1980's, new disposal sites were built to accommodate MSW generated where it is located in urban areas and as time goes by, modern landfill were constructed. Even though modern landfills are built to accommodate MSW, generation of waste was increasing and an improvement must take place for proper waste disposal because the current waste management system leads to several issues such as water and air pollution. Due to this, in 1995, the concept of sustainable development was adopted by Malaysian government to improve the waste disposal facilities. One of the outcomes from this development was the construction of sanitary landfill for disposing MSW (Fauziah and Agamuthu, 2012).The sectional view of municipal solid waste sanitary landfill is shown Figure 2.2.

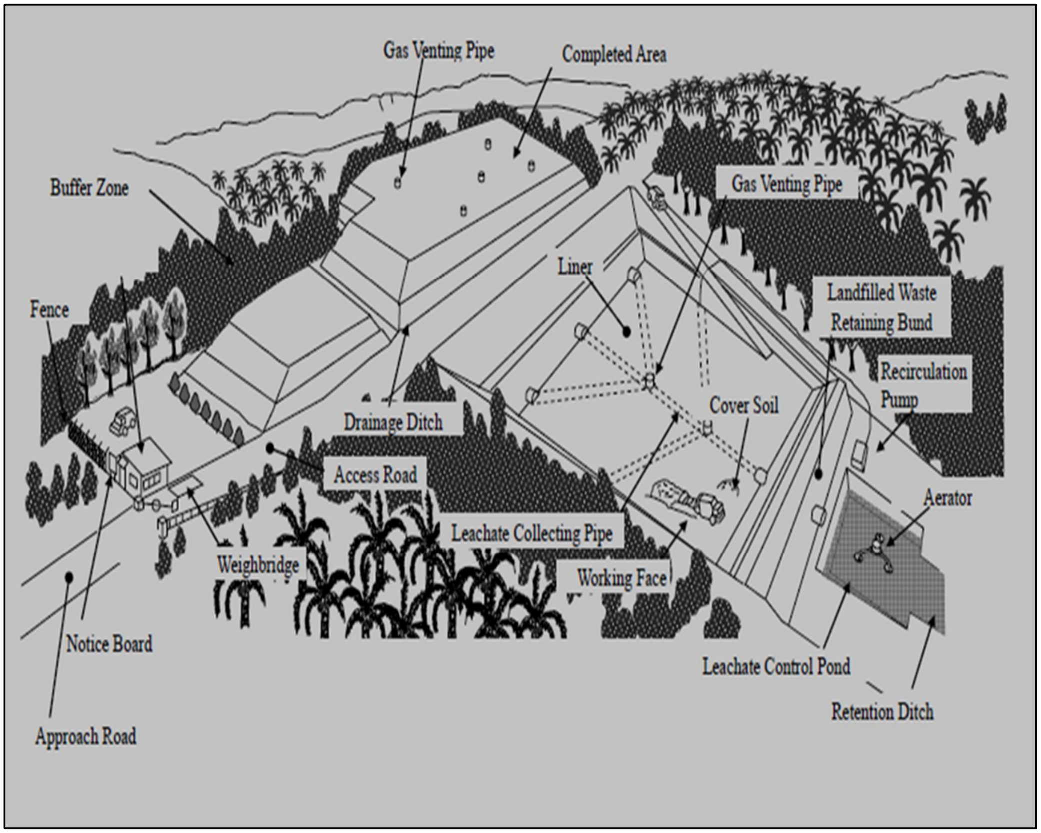


Figure 2.2: Sectional view of municipal solid waste sanitary landfill (NSWMD, 2012).

As In 2012, out of 165 operating landfill, Malaysia had 8 sanitary landfills located in Selangor, Johor and Sarawak (NSWMD, 2012). Table 2.4 shows the number of landfills according to states in Malaysia for both operating and non operating landfills. Almost 95% of landfills in Malaysia are non sanitary and lack proper gas and leachate collection systems and posed a real threat to the environment.

Table 2.4: Landfills in Malaysia as of 2012

State	Operating Landfills	Non operating landfills	Total
Kedah	8	7	15
Perak	17	12	29
Perlis	1	1	2
Pulau Pinang	2	1	3
Johor	14	23	37
Melaka	2	5	7
Negeri Sembilan	7	11	18
Pahang	16	16	32
Kelantan	13	6	19
Terengganu	8	12	20
Selangor	8	14	22
Kuala Lumpur	0	7	7
WP Labuan	1	0	1
Sabah	19	2	21
Sarawak	49	14	63
Total	**165**	**131**	**296**

(NSWMD, 2012)

2.8 Landfill Output

Solid waste and water are the major inputs into landfills, and landfill gas and leachate are the principal outputs. About10% of the released carbon from the landfill is the leachate while another 90% are found in landfill gas in terms of methane (60%) and carbon dioxide (40%) and less than 1% in trace gases (Huber, 2004). Landfill gas is a product of the anaerobic biological decomposition of the organic fraction of the waste.

2.9 Generation of LFG

Landfill gas is produced when the bacterial decomposition, volatilization and chemical reactions taken place in landfill after waste are deposited. The amount of LFG is dependent on the quantity and type of organic content within the waste because the decomposing organic wastes are the major source for all LFG produced. The biological decomposition of one tonne of deposited municipal solid waste produced 160 to 250 m^3 of landfill gas (Abichou *et al.*, 2004; Humer and Lechner, 1999). The moisture content within a landfill is considered to be one of the most important parameters controlling gas generation rates. The process of waste degradation is divided into five stages as shown in Figure 2.3. The production of LFG continues until the majority of the organic material in the waste is degraded and it could take several decades after the closing of landfills (Scheutz *et al.*, 2009). Landfill gas will continue to be generated for periods between 15 and 30 years after the final depositions of the waste and low-level gas production may continue up to 100 years (Huber-Humer *et al*., 2009; Williams, 2005).

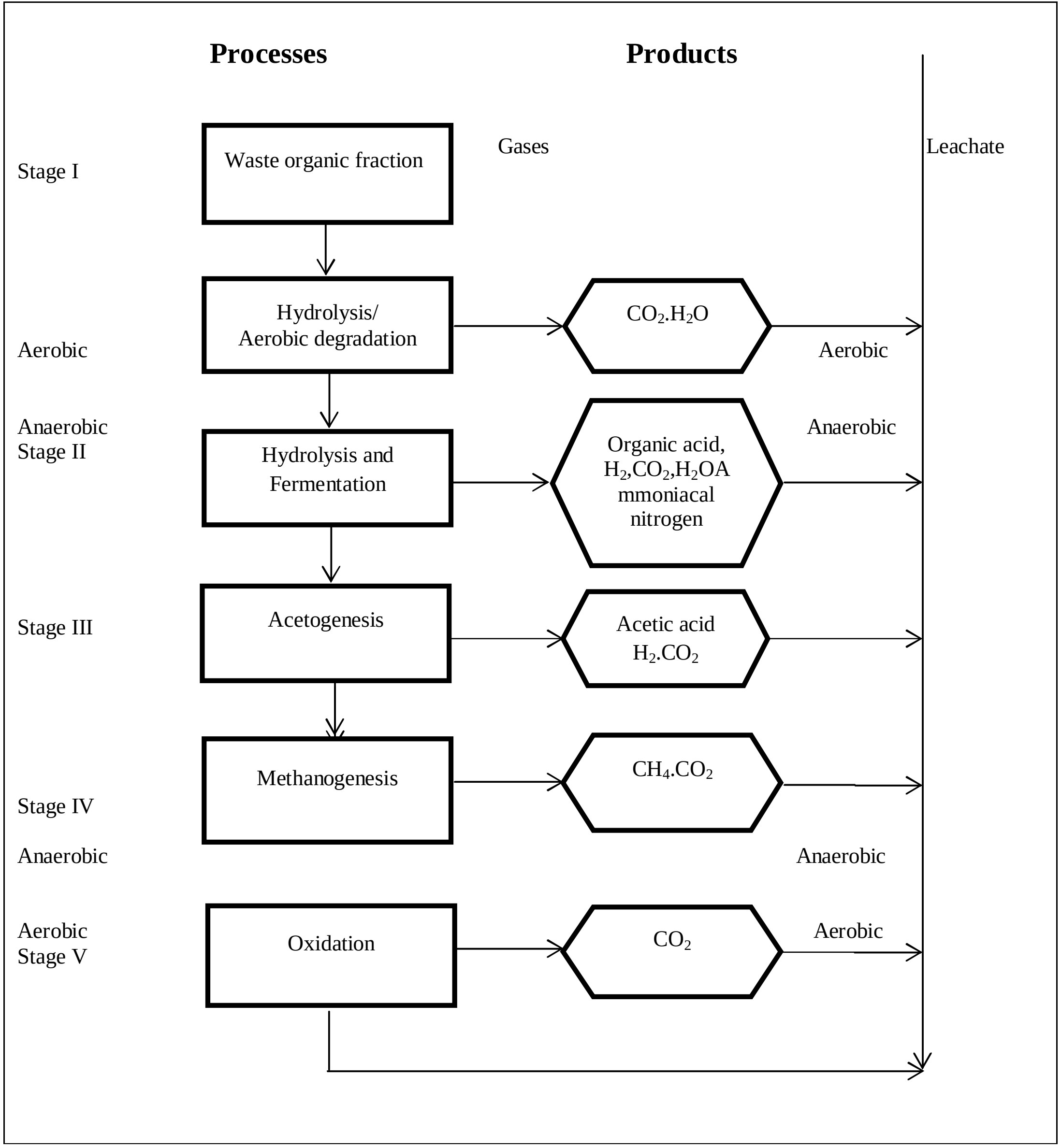


Figure 2.3: Major stages of waste degradation in landfills (Williams, 2005)

Five stages of waste degradation process in landfill and LFG production

i. First stage- Initial Adjustment

Degradation of organic matter from waste deposited by aerobic bacteria take places where it breaks down the long molecular chains of complex carbohydrates, proteins and lipids that are present in the organic waste while consuming oxygen and producing CO_2, water (H_2O) and heat (Steinlechner *et al.*, 1994). CO_2 is released as a gas or is absorbed in the H_2O to form carbonic acid (H_2CO_3), and pH of leachate generated to become more acidic. The process can last for days or months, depending on the amount of oxygen present in the waste.

ii. Second Stage- Transition phase

During the second stage, facultative bacteria are involved (can survive in aerobic and anaerobic conditions). Carbohydrates, proteins and lipids are hydrolyzed to glucose, amino acid, fatty acids by the extracellular enzyme, produced by facultative and obligatory anaerobic bacterium. Hydrolysis is a necessary process because solid organic compounds must be dissolved before bacteria could do the conversion process. The dissolved organic fragments are fermented to CO_2, hydrogen (H_2), Ammonia, and other organic acids (butyric acid, propionic acid, formic acid and valeric acid). The leachate produced is high in ammonia content due to the process of deamination of proteins.

iii. Third stage- Acidifying stage

During this stage, organic acid produced from second stage is transformed to Acetic acid (CH_3COOH), CO_2, and H_2 by the acetogenic microorganisms. During the anaerobic stages, hydrogen sulfide is also produced by the reduction of sulphate compounds by the sulphate reducing microorganisms. The LFG produced will have the “rotten egg smell”. The presence of organic acid cause the pH level to become 4 or less.

iv. Fourth stage- Methane fermentation phase

Fourth stage is the main stage of LFG production and takes longest time. Methanogenic microorganisms consume CO_2, and H_2 and acetic acid produced from third stage. The methanogenic process takes following pathway:

$4H_2 + CO_2 \longrightarrow CH_4 + 2H_20$ (Reductive methane formation) and

$CH_3COO- + H^+ \longrightarrow CH_4 + CO_2$ (Decarboxylation)

About 70% of CH_4 is produced from this process. During this process, LFG is generated over temperature range of 30-65˚C by both mesophilic and thermophilic microorganisms.

v. Final stage- Maturation phase

In the final stage, an aerobic condition occurred where aerobic microorganisms convert the CH_4 generated in the previous stage to CO_2 and H_2O; as well H_2S gas may forms in waste with high concentration of SO_4^{-2} (William, 2005; Duffy, 2012).

Figure 2.4 shows the time dependent methane production and recovery over a landfill lifetime.

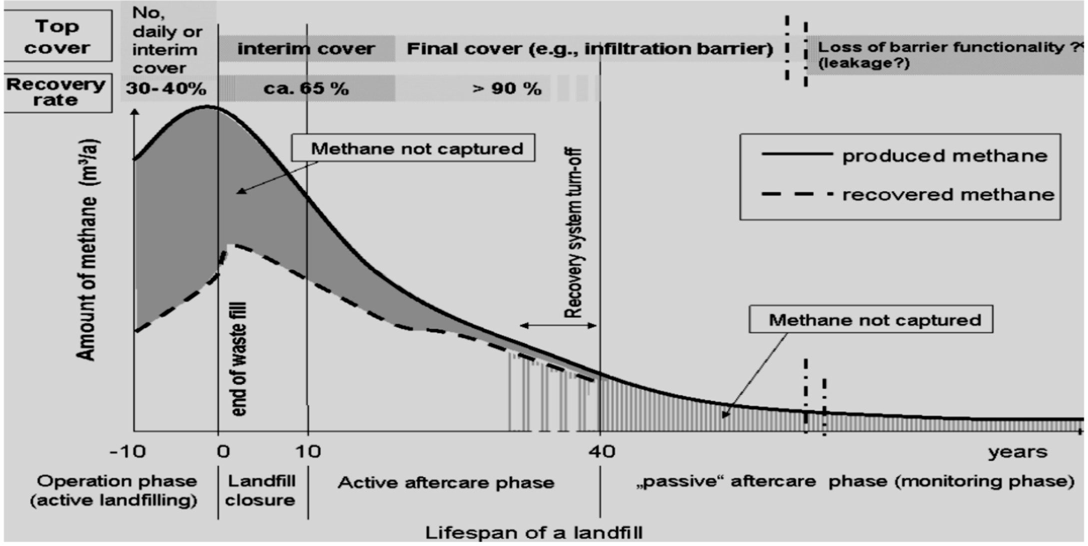


Figure 2.4: Time-dependent methane production and recovery over a landfill lifetime (Huber-Humer *et al*., 2008).

2.9.1 Factors that affect landfill gas generation

There are several factors that influenced the LFG generation. The rate and volume of landfill gas generated at a specific site depend on the characteristics of the waste and several environmental factors:

i. Waste composition - amount of organic waste present in a landfill plays significant role in landfill gas production.

ii. Age of waste - the deposition of waste in landfill more recently produced more landfill gas through bacterial degradation process, volatilization, and chemical reactions compared to older one. Peak gas production usually occurs from 5 to 7 years after the waste is buried.

iii. Presence of oxygen in the landfill - LFG, methane is produced when oxygen is depleted in the landfill.

iv. Moisture content - Moisture plays important role in landfill gas production.

v. Temperature - Temperature also plays an important role. When temperature in landfill increases, the bacterial activity is also increased and leads to increases in landfill gas production. Increased temperature may also increase rate of volatilization and chemical reaction (ATSDR, 2001).

2.10 Landfill gas composition

Typical constituents in MSW landfill gas are CH_4 (45-58%), CO_2 (35-45%), Nitrogen (N_2) (<1-20%), O_2 (<1-5&), H_2 (<1-5%), H_2O (1-5%), and trace constituents (<1-3%) (Qian *et al*., 2002). Table 2.5 indicates the characteristics of the landfill gas. The amount of gas generated is characterized by quantity and quality of gas generated. The estimation of gas produced depends on the amount and type of waste deposited and characteristic of landfill. In the degradation process of waste in landfill, the highest gas generation is expected in the early phase of stable methanogenic phase. The landfill gas composition over time within the 5 stages of degradation process is shown in Figure 2.5.

Table 2.5: Characteristics of Landfill gas

Components	**Characteristics**
Methane	Methane occurs naturally in the atmosphere. It is colourless and odourless, non-toxic, high energy content, lighter than air, can form an explosive mixture at certain concentrations has a negative effect on the atmosphere.
Carbon dioxide	In the atmosphere, carbon dioxide is found in a very small concentration of about 0.03%. It is odourless, colourless and slightly acidic, non-flammable, 1.5 heavier than dry air, concentrations of 8% in the ambient air can be fatal to humans, and concentrations of 4-5% in the ambient air can cause loss of consciousness in human and has a negative effect on the atmosphere.
Nitrogen	79% of the atmosphere consists of nitrogen. It is odourless, colourless and tasteless.
Oxygen	The concentration of oxygen in the atmosphere is 21%. It is also odourless, colourless and tasteless.
Ammonia	Ammonia is a colourless gas and has a pungent odour.
Non-methane organic compounds (NMOCs)	NMOCs are organic compounds that may occur naturally or formed by synthetic chemical processes. Examples of NMOCs found in the landfill are acrylonitrile, benzene, dichloromethane, carbonyl sulfide, hexane, tetrachloroethylene, toluene and others.
Sulfides	Sulfides are naturally occurring gases that provides the landfill gas a mixture of the rotten-egg smell. At very low concentrations, sulfides can also cause unpleasant odour.
Hydrogen	Hydrogen is odourless and colourless.
Carbon monoxide	Carbon monoxide is odourless and colourless.

(EPA, 1995)

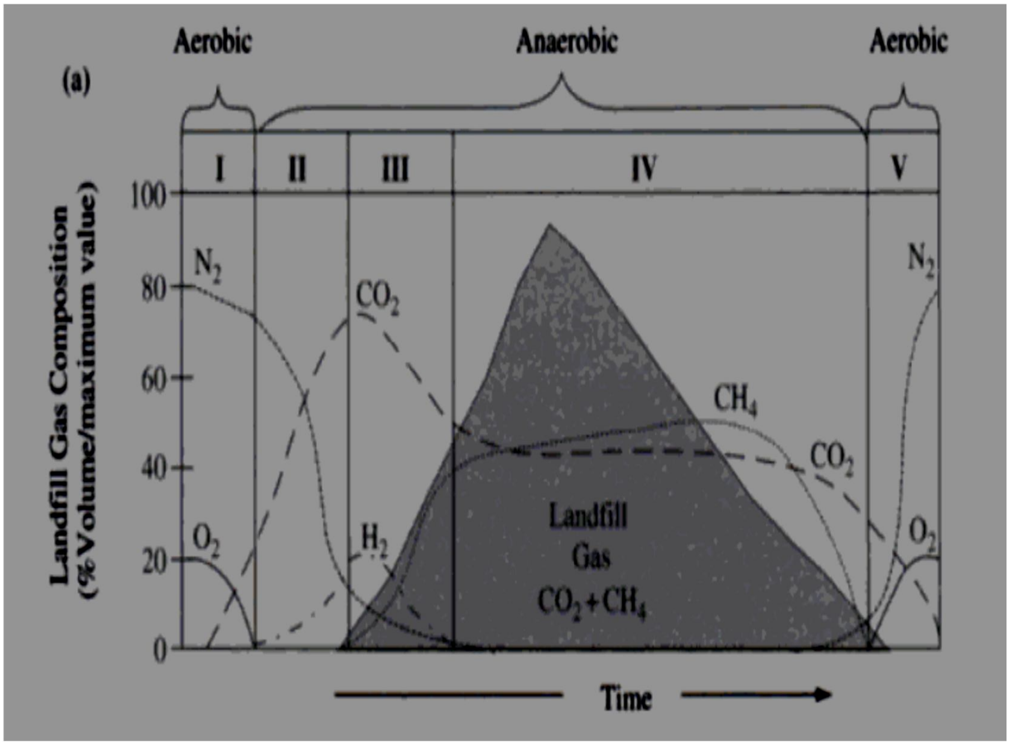


Figure 2.5: Landfill gas compositions over time (William, 2005)

2.11 Landfill CH_4 balance

The landfill CH_4 balance and quantities of CH_4 produced are controlled by several processes and factors (Scheutz *et al.*, 2009). According to Bogner and Spokas (1993), CH_4 balance is described by the relationship as following:

CH_4 production = CH_4 recovered + CH_4 emitted + Lateral CH_4 migration + CH_4 oxidized + ΔCH_4 storage

(all units = mass t^{-1}).

The LFG transportation is affected by several factors such as meteorological conditions, soil/cover conditions and the waste and landfill conditions.

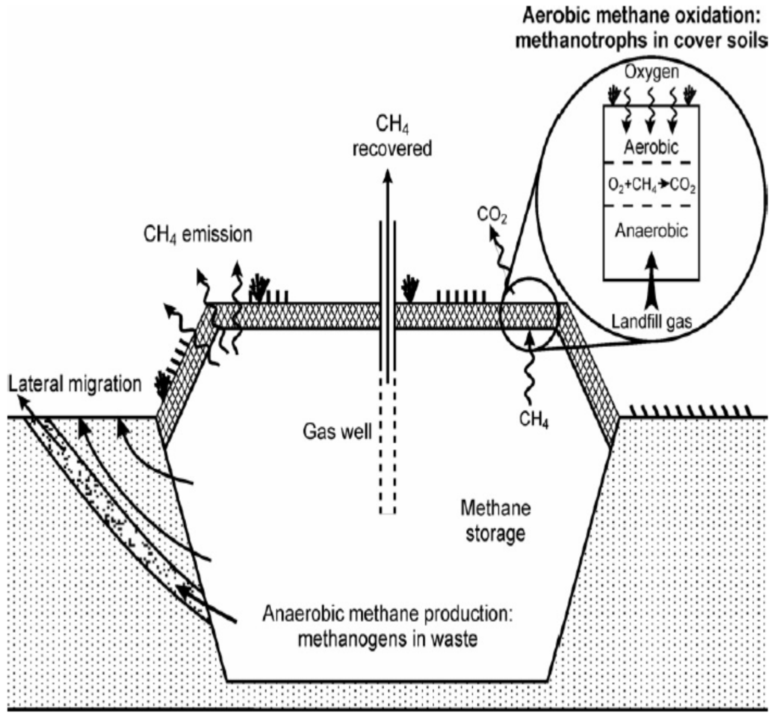


Figure 2.6: Landfill methane balance (Scheutz *et al.*, 2008)

2.12 Landfill Gas and the Impacts

LFG is a mixture of CH_4 and CO_2 at the final stage of waste degradation process, while at the early stage it contains H_2 and CO_2 (William, 2005). Besides that, landfill gas also contains small amounts of N_2, O_2, H_2, and less than one percent non methane volatile organic compounds (NMVOC's) and trace amounts of inorganic compounds. The LFG produced, released or escaped will slowly move from landfill. The movement of gas is by diffusion or pressure gradient. Gas movement is from high to low gas concentrations or low to high gas concentration depending on pressure gradient (Christensen *et al*., 2007). The movement of the LFG is affected by several factors such as the landfill soil or cover type, the speed and direction of wind, moisture content in the landfill and temperature. The movement of LFG leads to negative impacts to the environment and also to humans. The important effects of LFG is greenhouse gas effect, fire and explosion hazards, health risk to human, damages to vegetation, groundwater pollution and odor nuisances (Kjeldsen, 1994). The different scale of landfill effects are shown Figure 2.7.

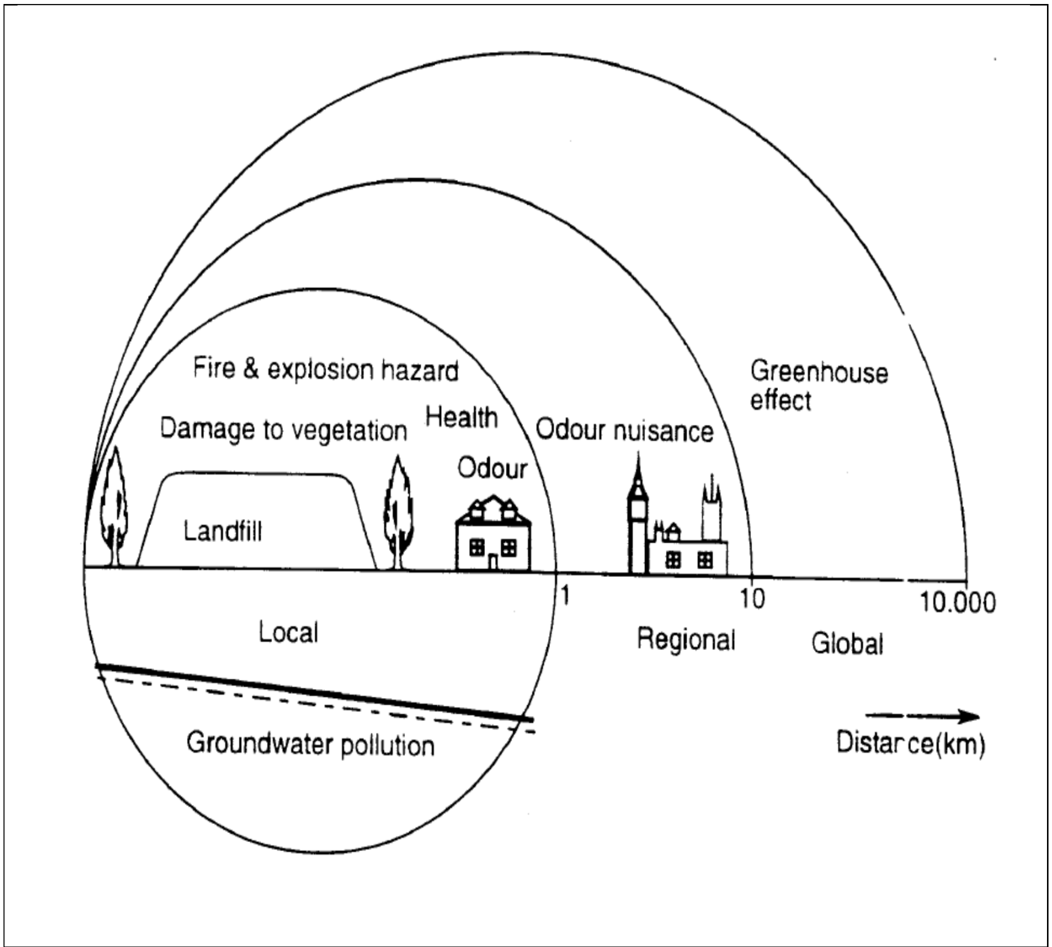
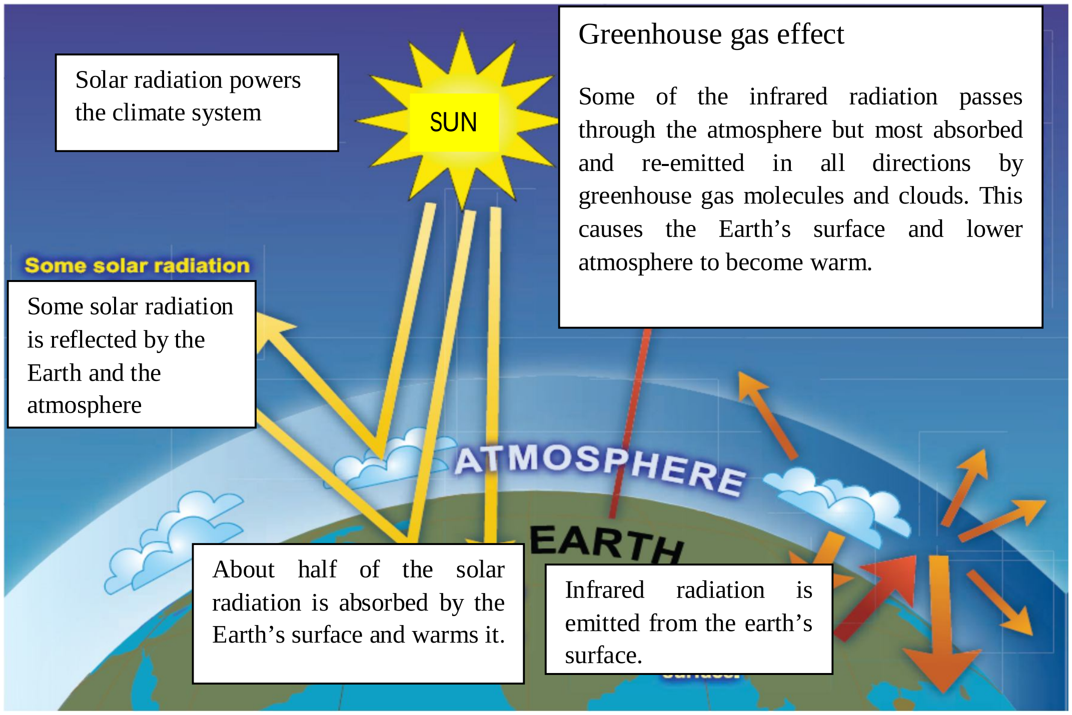


Figure 2.7: Different scales of landfill effects (Luning and Tent, 1993; Scheutz *et al*., 2009).

2.12.1 Greenhouse gas effect

Greenhouse gas effect is a process of thermal radiation from a planetary surface and is absorbed by atmospheric greenhouse gases. It is re-radiated in all directions back towards the surface and the lower atmosphere which results in an increase in the average surface temperature. Landfill is one of the significant greenhouse gas contributors. Landfill gas, CH_4 and CO_2 are classified as greenhouse gases because this gas has a very high capacity of absorbing infrared radiation reflected from the earth's surface. Natural greenhouse gas effect is shown in Figure 2.8. CH_4 has a global warming potential 25 times higher compared to CO_2 which is averaged over 100 years (IPCC, 2007). Global atmospheric concentration of CH_4 has increased from 715 ppb in early 1990 to 1774 ppb in 2005 (IPCC, 2007).



Greenhouse gas effect

Some of the infrared radiation passes through the atmosphere but most absorbed and re-emitted in all directions by greenhouse gas molecules and clouds. This causes the Earth's surface and lower atmosphere to become warm.

Solar radiation powers the climate system

Some solar radiation is reflected by the Earth and the atmosphere

About half of the solar radiation is absorbed by the Earth's surface and warms it.

Infrared radiation is emitted from the earth's surface.

Figure 2.8: Natural greenhouse gas effect (IPCC, 2007).

2.12.2 Ozone depletion

Ozone depletion is also one of the environmental impacts from landfill. The phenomenon of ozone depletion has been observed since late 1970s. Volatile chlorinated and fluorinated hydrocarbon compounds which are found in LFG poses a serious threat to the ozone and causes ozone depletions. When the volatile chlorinated and fluoride hydrocarbon are released from LFG to the environment, both gases are degraded photochemically in the upper atmosphere of the ozone producing free chlorine and fluorine that reacts with ozone and thereby deplete the ozone concentrations that protect the earth's surface from the ultra violet rays of the sun.

2.12.3 Fire and explosion hazards

Fire and explosion hazard is one of the threats from LFG. Landfill fire can occur from excessive influx of ambient air into the landfill. The CH_4 limit range for explosion is between 5% to 15% in air at atmospheric pressure and ambient temperature (ASME, 2011). An example of LFG explosion hazards is, when the LFG enters the residential home through cracks in foundations and penetrates crevices, it will mix with the air and it will cause explosion hazards (Kjeldsen, 1994). There were cases of fire explosions associated with LFG which cause property damage and injury to residents and landfill workers (USEPA, 2005).

2.12.4 Health risks due to Toxic VOC's in air

Inhalation of CH_4 can cause health risks where it causes nausea, vomiting, headache and loss of coordination and at very high concentration it may cause coma and death due to respiratory arrest (HPA, 2009a). CO_2 is the second major gas released from landfill after CH_4. When CO_2 level is high it is possible to displace O_2 in human respiratory system and cause disposition. LFG contain high level of CO_2 of about 500 ppm (Kjeldsen, 1994). If the CO_2 level is more than 6% by volume it can trigger headache, dizziness, mental confusion, palpitations, increase blood pressure, difficulty in breathing and central nervous system depression (HPA, 2010). A human cannot breathe air which contains more than 10% of CH_4 and will lose consciousness. Vinyl chloride, Benzene and H_2S are the trace compounds found in LFG. Even though they are produced in very small amounts it also poses hazards to humans. The effect of inhalation of CH_4 by people who stay closer in 100m distance from landfill can causes carcinogenic effect that can lead to cancer. At a low level, H_2S will result in irritation to the mucous membrane of the eyes and respiratory tract while exposure to high concentrations can results in depression of Central Nervous system, loss of consciousness and respiratory paralysis (HPA, 2009a).

2.12.5 Damages to vegetation

Damage to vegetation is reported from the surrounding of landfill. Damage to vegetation occurred when LFG removed the O_2 in root zone and causes asphyxia. Removal of O_2 may be due to displacement of O_2 by LFG or oxidation of CH_4. Damage to vegetation is reported for the plant situated around the landfills. CO_2 in LFG also can cause toxicity to plant if they are present in very high concentration. Other trace compounds such as H_2S are also toxic to plants exposed to LFG (Christensen and Kjeldsen, 1995).

2.12.6 Odour nuisances

Odour effects from landfill are causing a growing number of public complaints and concerns throughout the world. LFG cause offensive odours and affect the people around the landfill sites. H_2S and organic sulphur is the potential LFG that contributes to the odour nuisances. These compounds may be detected by sense of smell at very low concentrations (0.00047 and 0.47 parts per million, respectively), threshold levels where odour is significant and are often below levels where health effect arises (Iowa State University, 2004). Buffer zones between residential and landfill sites are not far enough is also reason for odour nuisances.

2.13 Global landfill gas CH_4 emission

Landfills are identified to be the principal source LFG emissions. The gradual decay of the carbon stock in a landfill generates gas emissions even after waste disposal has ceased. This is because the chemical and biochemical reactions take place. It results in production of LFG CH_4 and CO_2. Methanogenesis in landfills occur under strict anaerobic conditions by one of two mechanisms, acetate fermentation or CO_2 reduction. During acetate fermentation, equal proportions of CH_4 and CO_2 are produced, but during CO_2 reduction, CO_2 is removed and CH_4 is formed, which explains the higher CH_4 concentration compared to CO_2 which is normally found in landfill gas (Bogner *et al.*, 1996). Global sources of CH_4 to the atmosphere is showed in Table 2.6. Global CH_4 emission from waste sector is about 18% of the global anthropogenic CH_4 emission (Bogner *et al.*, 2007) while global estimates of CH_4 emissions from landfills are 35-69 Tg $CH_4 \cdot yr^{-1}$ out of 600 Tg CH_4 yr^{-1} released to the atmosphere. This is 6-8 % of the total emission of CH_4 including both natural and anthropogenic sources (Denman *et al*., 2007; Bogner *et al*., 2007). In developed country such as U.S, CH_4 emission from landfill was about 6329 Gg of CH_4 in year 2007 (USEPA, 2009) and in Europe, CH_4 emission was 3373 Gg in the year 2006 from landfilling (EEA, 2008). United States is the second largest anthropogenic methane emitter and the methane originates from landfills, making up 23% of the total anthropogenic methane emission (USEPA, 2009). CH_4 generation from one tonne of MSW is estimated to be 50Nm^3 (Einola *et al*., 2007). Global CH_4 emissions from landfills are expected to grow by 9 % between 2005 and 2020 (USEPA, 2006).

Table 2.6: Global sources of CH_4 to the atmosphere (% of the total emissions of 500-600Tg per year)

Source	% of total emissions
Natural source	
Wetlands	23
Plants	6
Termites	3
Ocean	3
Gas Hydrates	2
Anthropogenic source	
Rice fields	10
Ruminants	17
Landfills	7
Sewage treatment	4
Biomass burning	7
Fossil fuel	18
Total emission	100

(Conrad, 2009)

2.14 Potential application of LFG

Even though LFG is GHG it can be recovered and utilized as energy when it is available in large scale. Landfills must monitor their CH_4 production or collect and burn it to prevent air pollution. Therefore, using landfill CH_4 to generate electricity, fire boilers or substitute for other energy sources can turn a potential liability into a benefit. If the gas collected is not enough for energy production it can be flared. Gas utilization is only covering a part of LFG production in landfill lifespan.

2.14.1 Gas collection system

Landfill gas can be collected by passive gas collection system or active gas collection system. Both the gas collection systems are composed of a series of gas collection wells placed all the way through the landfill. The number and spacing of the wells depend on landfill-specific characteristics, such as waste volume, density, depth, and area. As gas is generated in the landfill, the collection wells offer preferred pathways for gas migration.

i. Passive gas collection system

Passive gas collection systems make use of the landfill gas pressure and the concentrations to vent the LFG into the atmosphere or control system. The system uses the extraction well to collect the LFG. The passive gas collection is installed during active operation of landfill and also after closure of the landfill. The extraction well is made of perforated or slotted plastic and fixed vertically throughout the landfill to depths ranging from 50% to 90% of the waste thickness. The efficiency of a passive collection system partly depends on how well the gas is contained within the landfill. Gas containment can be controlled and altered by the landfill collection system design. The other factor that affects passive gas collection system is the environmental conditions. Passive gas collection systems are not advisable to use in areas with a high risk of gas migration, especially where methane can accumulate to explosive levels in buildings and confined spaces (ATSDR, 2001). Figure 2.9 shows the system of passive gas collection system.

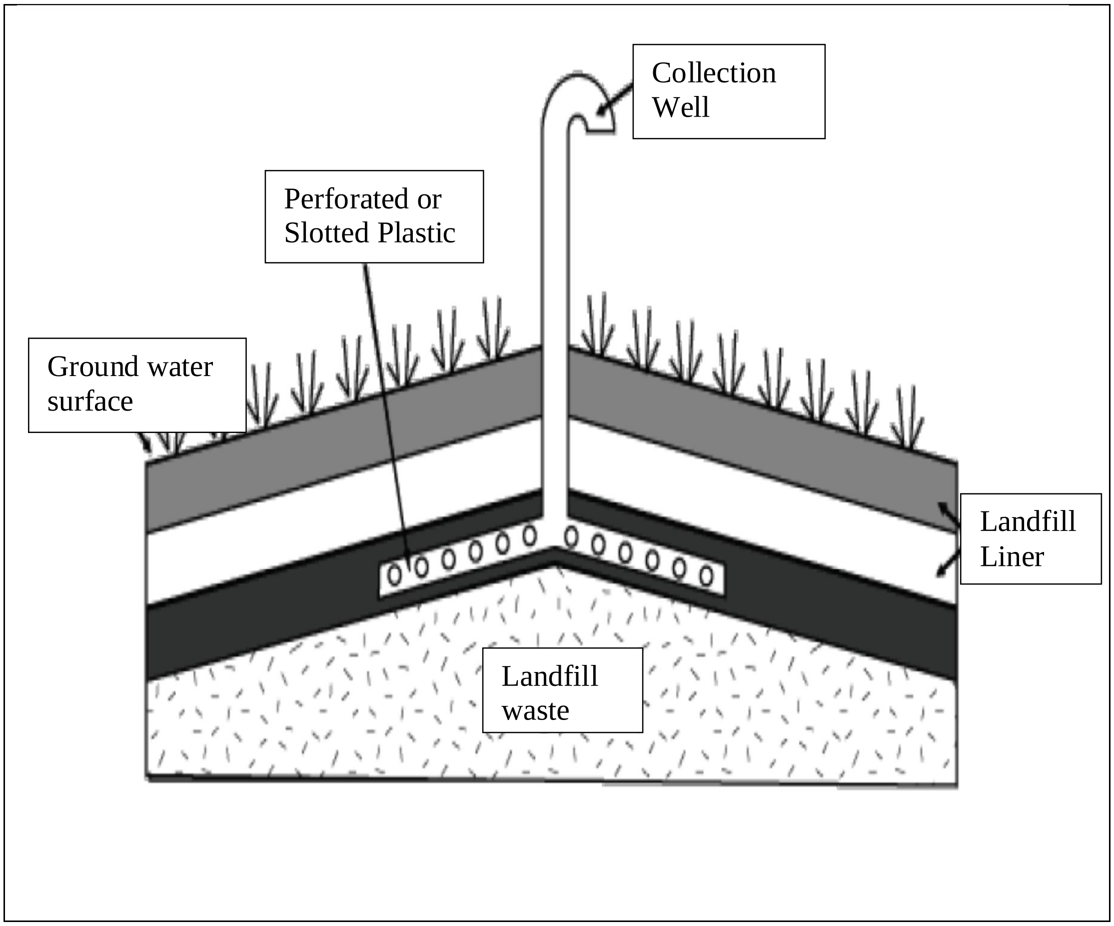


Figure 2.9: Passive gas collection system (ATSDR, 2001)

ii. Active gas collection system

Active gas collection system is a well designed and effective system for LFG collection. Figure 2.10 illustrates active gas collection systems. It consists of vertical and horizontal gas collection wells and installed with valves to regulate gas flow and serve as a sampling port. Sampling ports serve the purpose for measure gas generation, composition, and pressure. Besides that active gas collection systems are also equipped with vacuums or pumps to transport gas out of the landfill and piping system that connects the collection wells to the vacuum. The function of vacuums or pump is to pull the gas from the landfill by creating low pressure within the gas collection wells. Low pressure in the wells creates a preferred migration pathway for the landfill gas. The size, type, and number of vacuums required in an active system to pull the gas from the landfill depend on the amount of gas being produced. According to Environmental Protection Agency (EPA) an effective active gas collection system should equipped with

a) Gas-moving equipment, including vacuums and piping, capable of handling the maximum landfill gas generation rate.

b) Extraction wells placed to capture gas from all areas of the landfill. The number and spacing between each extraction well depends on the waste type, depth, and compaction; the pressure gradients created by the vacuums; and the moisture content of the gas.

c) The facilities to monitor and adjust flow from individual extraction wells. Inclusion of a valve, pressure gauge, condenser, and sampling port at each collection well allows a landfill operator to monitor and adjust pressure and to measure gas generation and content.

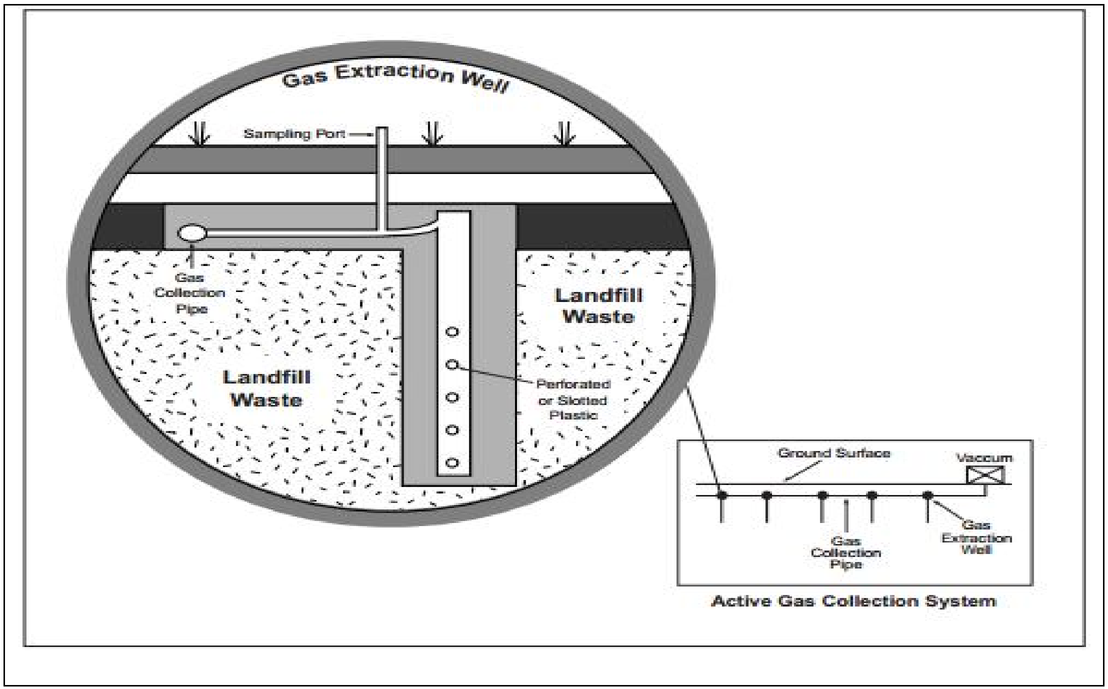


Figure 2.10: Active gas collection systems (ATSDR, 2001)

2.14.2 Power generation from LFG

LFG can be used in a gas engine running as an electric generator producing power. Besides gas engine, gas or steam turbines can also be used. According to Stachowitz (2003) electricity may be generated by LFG with a minimum of 35% methane content. Reciprocating internal combustion engines is one of the latest technologies used for electric energy generation from LFG. It is capable of producing between 1–3 MW. The two principal methods used to ignite the gas and air mixture in the combustion chamber of a reciprocating engine are by high voltage sparks (spark ignition engines) and by injection of a small quantity of diesel fuel (dual-fuel engines).

2.14.3 Direct use of LFG

LFG can be directly utilized for several purposes such as boiler, dryer and kilns. LFG is also cheaper than natural gas and holds about half the heating value at 16,785 – 20,495 kJ/m^3 (450 – 550 Btu/ft^3) as compared to 35,406 kJ/m^3 (950 Btu/ft^3) of natural gas (Shrestha *et al*., 2008). LFG is normally replaced with the utilization such as coal, oil, propane and other natural gas. Efficiency of LFG utilization depends on the gas quality, use and supply of the gas. Disadvantages of boilers, dryers, and kilns are that they need to be retrofitted in order to accept the gas and the end user has to be nearby (within roughly 8 kilometers) as pipelines will need to be built.

2.15 Issues in LFG use

LFG recovery systems can only achieve efficiency of up to 50 to 60% (Borjesson *et al*., 2009). Even though gas collection systems reduce the environmental impacts of landfills, the systems are not 100% efficient and to increase the efficiency of LFG recovery, a landfill must be designed with effective CH_4 controls such as a low-permeability liner and a low-permeability cover. Besides that, the LFG characteristics towards recovery process can arise impacts on equipment and operations system and trace elements found in LFG also can cause corrosion in gas collection systems. Another reason for other alternative is because, the LFG recovery is basically for large scale landfill and smaller landfill needs another alternative for mitigating the LFG generated. Besides that, low cost technologies are necessary that limits LFG gas release from landfills where gas collection system or recovery system have not been implemented or not economically feasible (Kjeldsen *et al*., 2007).

2.16 Methanotrophic activity in CH_4 oxidation

An alternative way to control CH_4 emissions to the atmosphere is the process of CH_4 oxidation. Microbial CH_4 oxidation occurs in the biosphere wherever CH_4 and O_2 are present at the same time. CH_4 can be oxidized in the soil into other forms of carbon via microorganisms. Methanotrophs are a group of bacteria that utilize CH_4 as its sole carbon and energy source in the presence of O_2. According to Pawloska (2008), the annual global CH_4 emission is many times higher than the annual amount of CH_4 accumulating in the atmosphere which indicates the natural process of CH_4 occurs. It has been estimated that anywhere from 10 to 100 % of the CH_4 generated in landfills is oxidized by these bacteria (Borjesson *et al*., 2001). Czepiel *et al*., (1996) reported that 10% CH_4 oxidation in a landfill in a cold climate is assumed to be lower (NE USA), suggesting that, in warm climates CH_4 oxidation is assumed to be higher. Under certain circumstances, the landfill cover can even consume atmospheric CH_4 rather than emitting CH_4 to the atmosphere (Bogner *et al*., 1995; Bogner *et al*., 1997a; Borjesson and Svensson, 1997; Borjesson *et al*., 1998; Abichou *et al*., 2006). Field data have also documented that point measurements of both CH_4 emissions and oxidation can vary over six orders of magnitude (e.g. Bogner *et al*., 1997). The mechanisms of oxidation process in troposphere is chemical reactions of CH_4 with OH radical$^{\cdot}$.IPCC data showed that the microbial contribution to CH_4 oxidation from the atmosphere is about 5% and amounted 30Tg annual basis (IPCC, 2007).

2.16.1 Methanotrophic bacteria

Microorganisms responsible for CH_4 oxidation is recognized as methanotrophic bacteria. Methanotrophic bacteria are subset of physiological group of bacteria known as methyltrophs that can utilize CH_4 as a sole carbon and energy source. One of the important characteristics of methanotrophic bacteria is the use of enzyme CH_4 monooxygenases (MMOs) to catalyze the oxidation of CH_4 to methanol (CH_3OH). Complete pathways of the microbial oxidation of CH_4 to CO_2 by methanotrophs are shown in Figure 2.11. The pathway includes the intermediate steps for oxidation of CH_4 to methanol, followed by oxidation of methanol to formaldehyde (CHOH) and the subsequent oxidation of formaldehyde to formate (CHOOH) (Scheutz *et al*., 2009). First methane oxidizing bacteria was isolated in 1906 by Sohngen 1906. Methanotrophs are classified into two major groups based on their formaldehyde assimilation pathway: type I uses ribulosemonophosphate (RuMP), whereas type II uses serine (Hanson and Hanson 1996). Type I include genera of Methylococcus, Methylomicrobium, Methylobacter, and Methylomonas and formed family of Methylococcaceae while type II includes genera of Methylosinus and Methylocystis. Type I methanotrophs form cysts and are incapable of fixing nitrogen while type II methanotrophs on the other hand, assimilate formaldehyde via the serine pathway and are capable of fixing nitrogen (Hanson and Hanson 1996; Scheutz *et al*., 2009). More methanotrophic bacteria were isolated and characterized in 1995 (Bowman *et al*., 1995). A total of eleven genera of methanotrophic bacteria have been identified as in 2009 (Scheutz *et al*., 2009). The phylogenetic relationship of 11 genera of methanotrophic bacteria identified and morphological and physiological properties are shown in Table 2.7 (Scheutz *et al.*, 2009). Methanotrophic bacteria activity is very effective in many natural systems.

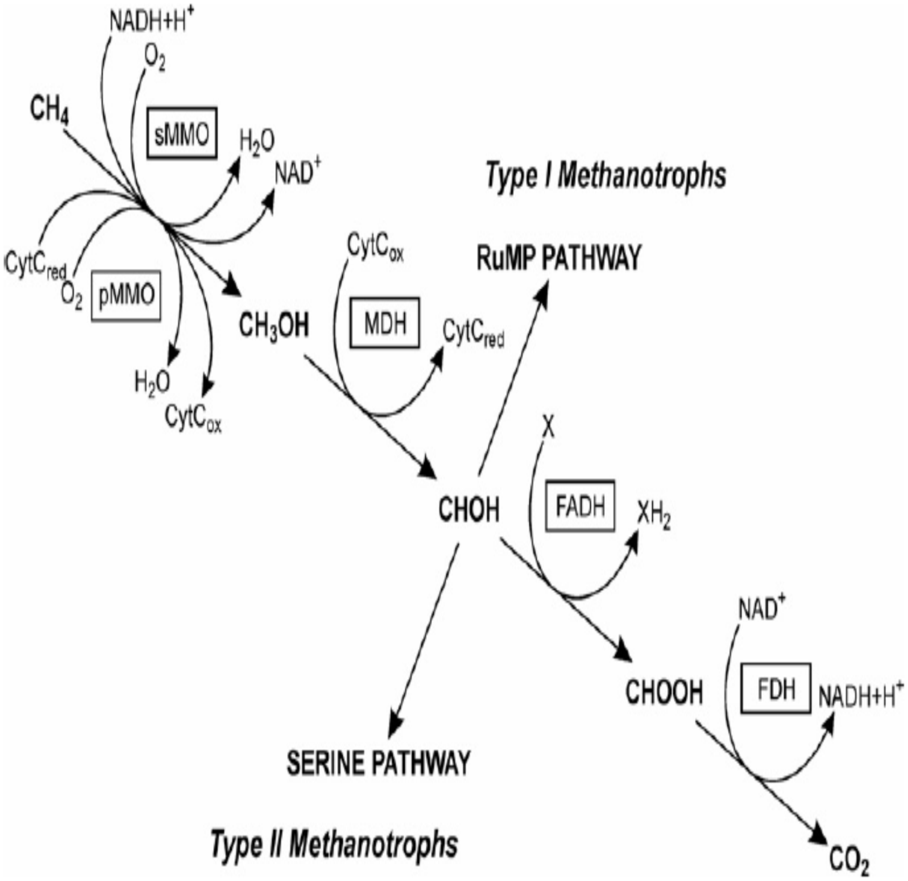


Figure 2.11: Complete pathway of the microbial oxidation of CH_4 to CO_2 by methanotrophs (Scheutz *et al.*, 2009).

Table 2.7: The phylogenetic relationship of 11 genera of methanotrophic bacteria and their morphological and physiological properties.

Genus	Phylogenetic position	ICM-arrangement (Type)	C-Assimilation	Types of MMO	N_2 fixation
Methylobacter	γ-Proteobacteria	Stacks(I)	RuMP	pMMO	no
Methylocaldum	γ-Proteobacteria	Stacks(I)	RuMP	pMMO	no
Methylocapsa*	α-Proteobacteria	Typ III	Serine	pMMO	yes
Methylocella	α-Proteobacteria	Peripheral II	Serine	sMMO	yes
Methylococcus	γ-Proteobacteria	Stacks I	RuMP	pMMO	yes
Methylocystis	α-Proteobacteria	Peripheral II	Serine	sMMO/ pMMO	yes
Methylomicrobium	γ-Proteobacteria	Stacks I	RuMP	pMMO	no
Methylomonas	γ-Proteobacteria	Stacks I	RuMP	pMMO	no
Methylosinus	α-Proteobacteria	Peripheral II	Serine	sMMO/ pMMO	yes
Methylosphaera	γ-Proteobacteria	Stacks I	RuMP	pMMO	no
Methylothermus*	γ-Proteobacteria	n.d	n.d	pMMO	n.d

ICM-Intracytoplasmatic membranes; RuMP-Ribulose monophosphate path; Serine – Serine pathway; pMMO-particulate methane monooxygenase; sMMO-Soluble methane monoxygenase;*genus so far represent by only one species; n.d- not determined (Scheutz *et al*., 2009; Hanson and Hanson, 1996).

2.16.2 Factors that affect methanotrophic activity

Environmental factors play a very important role for methanotrophic bacterial activity in CH_4 oxidation. Methanotrophic bacteria are adaptive to the environment but certain basic factors are required for the organisms to carry out the CH_4 oxidation activities. Factors that influence the activity of CH_4 oxidation includes soil texture, temperature, moisture content, CH_4 and O_2 supply, pH, and nutrient (Hilger *et al.*, 2000).

2.16.2.1 Temperature

CH_4 oxidation activity by methanotrophs can be affected by the soil cover temperature. The study on temperature effect on CH_4 oxidation activity is necessary to improve the landfill cover. According to De VisshER *et al* (2001), CH_4 oxidation activity increases as the temperature increases while at lower temperature it inhibits the CH_4 oxidation activity (Whalen *et al.*, 1990). Methanotrophic bacteria prefers mesophilic condition. Mesophilic bacteria grow best in moderate temperature, neither too hot nor too cold, typically between 20°C and 45 °C. According to Gebert *et al* (2003) most of methanotrophic bacteria are mesophilic, the optimum temperature for CH_4 oxidation is in the range of 20-38°C while findings by Whalen *et al.*, (1990) showed that optimum temperature was around 31°C and further decrease in the temperature showed a smooth decline on the CH_4 oxidation activity. Meanwhile, increase in the temperature from the optimum range showed a rapid drop in the CH_4 oxidation activity. The drop in the CH_4 oxidation is due to denaturation process of proteins contained in methanotrophic cells.

A study conducted by Huber Huber (2004) on CH_4 oxidation using matured sewage sludge at different incubation temperature ranging from 4-30°C showed complete CH_4 oxidation for all 8-30°C while at 4°C the oxidation was only around 70-80%. In tropical conditions, the optimum temperature for maximum CH_4 oxidation activity is reported between 30-36°C (Visvanathan *et al.*, 1999). Boeckx and Van Cleemput (2000) suggested that CH_4 oxidation does not occur at temperatures below 0 °C. Investigation by Boeckx *et al* (1996) using sandy clay soil as landfill cover showed that temperature optimum value depends on moisture content of the soil material. Quantification on the influence of temperature is calculated by Q10 value(ratio of rates of a reaction or process or biological reaction), where the value on how many times the oxidation rate increases when temperature is increased by 10°C. By using this value, the evaluation on the effect of temperature on CH_4 oxidation is easily quantified. Higher Q10 indicates that temperature dominates CH_4 oxidation more than other factors. Temperature effect is exponential at temperature 10°C to 30°C with Q10 values ranging from 1.7 to 4.1 (Boeckx *et al.*, 1996; Scheutz and Kjeldsen, 2004; Börjesson *et al.*, 2004; Park *et al.*, 2005). Christophersen *et al* (2000) have reported that Q10 values for CH_4 oxidation in landfill cover soil can be as high as 4.10 to 7.26.

Researchers identified that the CH_4 oxidation activity depends on variation of temperature. Most methanotrophic bacteria grow and multiply at temperature range of 15 to 30°C. Laboratory experiments showed significant increased in CH_4 oxidation activity when the temperature is increased from 20°C to 30°C and to 40°C (Buivid, 1980; Scharf, 1982; Ehrig, 1984). Bacteria grows in low temperature environments belong to the type I methanotroph(Borjesson *et al.*, 2004) while type II grows in high optimum temperature. This shows that methanotrophic activity can happen in both high and low temperature within the optimum conditions.

2.16.2.2 Moisture content

Moisture content is one of the important factors that strongly control CH_4 oxidation capacity rates in landfill cover. According to Boeckx *et al* (1996), the moisture content in landfill cover have more influence in CH_4 oxidation rate compared to other environmental factors such as temperature. Three important of roles of moisture content in landfill cover is, firstly, it provides the optimum environment for methanotrophic bacteria, second, its affects the penetration of oxygen into the cover material. If the moisture content is higher than optimum level, it will hinder the penetration process. Finally, moisture content also tend to affect the air filled porosity of the soil and influences the gas transport through the soil (Boeckx *et al*., 1996).

Several researchers reported that laboratory investigation showed an increase in production of CH_4 with increase in the moisture content (Buvid, 1980; Rees, 1980). Tests carried out with different cover materials showed optimum condition for CH_4 oxidation was found in areas with relatively high moisture content (Figueroa, 1993). There is strong correlation between the actual water content and oxygen permeability and its impact on CH_4 oxidation. CH_4 oxidation in soil with low moisture content is lower compared to soil with higher moisture content (Figuoera, 1993). Previous research reports that gas permeability decreased when moisture content increased (Humer and Lechner, 2000). Jones and Nedwell (1993) suggested that the capacity of cover soil to sustain substantial moisture content throughout its depth is likely to promote more uniform methanotrophic distribution and greater opportunity for methane removal throughout the cover depth. When the moisture content in landfill soil is less than 13% of the maximum water capacity, methanotrophic bacteria tends to be inactive state (Bender, 1992) while when the moisture content is between 40-80% using bio waste compost it showed higher CH_4 oxidation activity. Boeckx *et al* (1996) indicated that moisture content regulates the activity of methanotrophic bacteria and found that optimum moisture content for maximum oxidation activity was at 50% water content capacity. Optimum moisture content for maximum CH_4 oxidation depends on temperature and other environmental factors. High CH_4 oxidation activity was also observed by Humer and Lechner (1999b) at moisture content of 45% (w/w) when MSW compost was used as landfill cover. Mor *et al* (2006) concluded that the optimum moisture content for CH_4 oxidation activity to take place ranged from 45% to 110% dry weight. However, according to Scheutz *et al* (2009), very high moisture content can block the gas transport and reduce the CH_4 oxidation. Moisture content of cover soil has more influence on CH_4 oxidation activity compared to other environmental factors, such as temperature (Boeckx *et al*., 1996).

2.16.2.3 pH

pH of landfill cover is another important factor for achieving maximum CH_4 oxidation. Methanotrophic bacteria are mainly neutrophilic where their optimum growth to carry out CH_4 oxidation activity ranged between pH 5.5 to 8.5 (Figueroa, 1993). A study by Hutsch *et al* (1994) showed a significant CH_4 oxidation in soil taken from Woodland with pH 7.5 compared to soil adjusted to pH 4.1 and this was supported by another study by Amaral *et al* (1998) where forest soil with pH 4.5 to

7.5 showed optimal CH_4 oxidation at pH near to neutral. The pH value of the soil cover depends on the characteristics of the type of landfill cover used. Methanotrophic bacteria are capable of carrying out CH_4 oxidation at wide pH range. Highest CH_4 oxidation rate was observed at pH values of 6-7(Hutsch *et al.*, 1994; Dunfield *et al.*, 1993). According to Pawloska (1999), no significant CH_4 oxidation activity was observed with pH range from 7.61 to 8.89. Methane oxidation activity was also observed in highly alkaline environment of pH 10-11 (Sorokin *et al.*, 2000) and at very acidic environment (Dedysh *et al.*, 2004) which shows that methanotrophs are adaptive to different environment.

2.16.2.4 CH_4 Concentration

CH_4 oxidation activity is highly influenced by amount of CH_4 present. According to Visvanathan *et al* (1999), if CH_4 concentration is high, higher CH_4 oxidation activity took place. Higher CH_4 oxidation was also observed when both O_2 and CH_4 overlapped (Kightley *et al.*, 1995). In man made environments, like landfill cover soils, methane can be oxidized efficiently, because of high methane concentrations leading to high microbial methane uptake (Kightley *et al.*, 1995; Bogner *et al.*, 1997a). The population of methanotrophs was also found to increase when the amount of CH_4 increased (Jones and Nedwell, 1993) which showed that methanotrophic activity is highly influenced by the amount of CH_4 present in the environment. In general, CH_4 oxidation occurs when suitable environment exists with the presence of methanotrophic bacteria, O_2 and CH_4 ratio and the retention time.

2.16.2.5 Oxygen supply

CH_4 oxidation by methanotrophs is the conversion of CH_4 with presence of O_2 into CO_2 and H_2O. The equation of CH_4 oxidation is:

$CH_4 + 2O_2 \longrightarrow CO_2+2H_20 +2108kCal\ mol^{-1}$.

This equation explains that one molecule of CH_4 is oxidized to one molecule of CO_2 by making use of 2 molecule of O_2 (Humer and Lechner, 1999). Previous study reported that if the O_2 level is less than 3%, CH_4 oxidation will be hindered (Bender and Conrad, 1994). CH_4 oxidation is an aerobic microbial process and oxygen availability is one of the major factors that control CH_4 oxidation (Stralis *et al*., 2006).

Study by Wilshusen *et al* (2004), showed for pure methanotrophic bacterial cultures, a O_2 range from 0.45% to 20% supports maximum CH_4 oxidation activity. Penetration of O_2 into the landfill cover is very important because it will limit the CH_4 oxidation process if the penetration is not deep enough.

2.16.2.6 Organic contents and nutrients

Organic matter in cover soil is important because it improves the soil properties and serves as a main carrier for microrganisms (Sparks, 1995) and has a strong influence in CH_4 oxidation activity. Landfill cover with organic content about 35% (w/w) shows higher CH_4 oxidation rate up to 10 to 100 fold compared to landfill cover with low organic content (0-10%w/w) (He *et al*., 2008; Zeiss, 2006). High organic content such as in compost is suggested to be used as a support medium for CH_4 oxidation in landfill as landfill cover (Einola *et al*., 2008; Stern *et al*., 2007). In a study by Kightley *et al*. (1995), it was observed that by adding sewage sludge to coarse-grained sand raised the specific CH_4 oxidation rate by 26%, while adding peat led to an increase by 27%, and adding compost derived from green waste led to an increase in CH_4 oxidation rate by 41%. Nutrient content in cover material is also important to build up the methanotrophic biomass to carry out CH_4 oxidation activity. Addition of nutrients such as Phosphate is reported to increase CH_4 oxidation in landfill cover soil (Albanna *et al*., 2007). Nutrient content in cover soil with optimum moisture content showed maximum CH_4 oxidation rate. Significant CH_4 oxidation activity with increase in methanotrophic bacterial population was observed when soil was amended with nutrients (Kightley *et al*., 1995).

2.17 Landfill components

A complete landfill component is designed with final cover, leachate collection and management facilities and final landfill cover (Pawloska and Stepniewski, 2006). MSW landfills have the following components and the schematic diagram of a MSW landfill system is as in Figure 2.12.

i. Bottom and lateral system
ii. Leachate collection and removal system
iii. Gas collection and control system
iv. Final cover system
v. Storm water management system
vi. Groundwater monitoring system
vii. Gas monitoring system

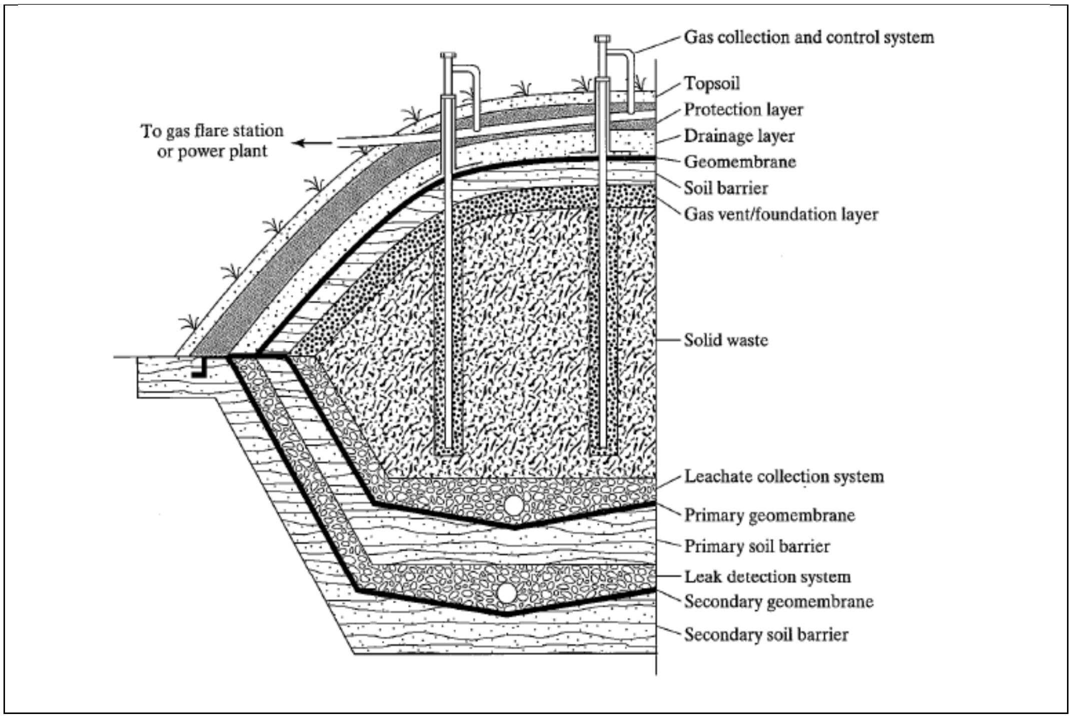


Figure 2.12: Schematic diagrams of MSW landfill containment systems (Sharma and Reddy, 2004).

2.18 Landfill cover

Landfill cover is a cover material used in landfill to cover the waste deposited in daily basis, intermediate basis or as final cover. The three important functions of landfill cover are

i. Minimize infiltration: Water that percolates through the waste may dissolve contaminants and form leachate, which can pollute both soil and groundwater as it travels from the site.

ii. Isolate wastes: A cover over the wastes prevents direct contact with potential receptors at the surface.

iii. Control landfill gas: Landfills may produce explosive or toxic gases that, if accumulated or released, can create a hazard in the vicinity.

The application of landfill cover is identified as one of the options for controlling gas emission by the natural process of bacterial oxidation. Landfill cover is also identified as cost effective compared to other technologies. A bacterium that is involved in the oxidation process in a landfill cover is the methanotrophs (Kightley *et al*., 1995).

Landfill covers that have optimum conditions for methanotrophic bacteria to carry out and enhance CH_4 consumptions is also known as “Biocover”. Biocovers is a filter material that supports the growth of methanotrophs which is placed above a gas distribution layer typically made of gravel. The gas distribution layer must have higher gas penetrability and porosity than the filter material in order to regulates and distribute the CH_4 released landfill (Scheutz *et al*., 2009a; Hilger and Humer, 2003).The selection of Biocover and its component as landfill cover is based on several factors such as the cost, erosion and stability concerns, selection of cover materials, slope and the thickness of the material, estimation of runoff quantities from the land, long term durability, and estimation of percolation quantities (McBean, 1995). Table 2.8 shows the design parameters and structures of landfill cover for optimization of CH_4 oxidation

Table 2.8: Design parameters and structures of landfill cover for optimization of CH_4 oxidation.

Parameters/structure	Significance	Examples (from field studies)
Material of support medium	To provide favourable conditions for methanotrophic activity, gas flow and oxygen penetration. Important parameter includes materials porosity, particle size, nutrient content, water holding capacity and biological stability.	Examples of materials are sludge compost(Huber Huber, 2004), yard waste compost(Stern *et al.*, 2007)
Compaction of oxidation layer	Influences the air filled pore volume and gas permeability.	Compost as landfill cover did not required compaction. Recommended bulk density is 0.8-1.1 tm^{-3}.
Thickness of oxidation layer	Thickness of Cover material has effect on the CH_4 oxidation rate. As the thickness of landfill cover increases the CH4 oxidation rate also increases. Retention time of gas also take longer with stable moisture and temperature maintained in the deeper layers.	Minimum requirement of landfill cover is 40-50cm (Martikkala and Kettunen, 2003) and 120cm (Huber Huber, 2004) *Thickness of cover material required depends on the CH4 oxidation activity and climatic conditions.
Gas distribution layer or system	To equalize the methane loading rate in the cover layer across the landfill area and to avoid gas escapes.	Landfill with non permeable layer (Stern *et al.*, 2007) Landfill with impermeable layer with vertical and horizontal gas distribution systems (Ettala and VaiSanen, 2002; Martikkala and Kettunen, 2003)

(Einola, 2010)

The effectiveness of biocover depends on the use of a suitable carrier and proper technical design and dimensioning of the landfill cover in order to oxidize variable rates of CH_4 which are produced from landfill (Bogner *et al.*, 2010; Huber-Humer *et al.*, 2008a; Humer and Lechner, 2001). Figure 2.13 shows the schematic diagram of a methane oxidation layer in a biocover system (Huber-Humer *et al.*, 2008b).

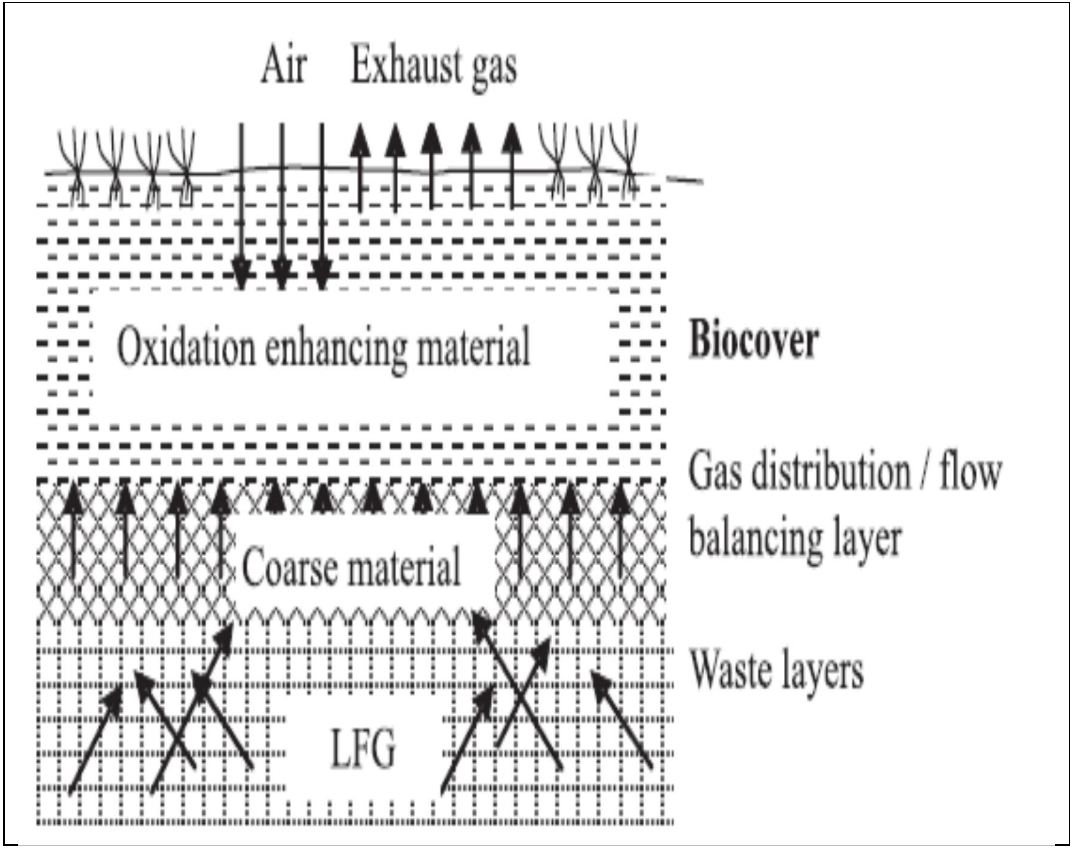


Figure 2.13: Schematic diagram of a methane oxidation layer in a biocover system (Huber-Humer *et al*., 2008)

2.18.1 Different Cover Material

Landfill cover can be divided into 3 types as daily, intermediate and final cover.

i. Daily cover is cover material that is placed in waste deposited in landfill at end of working days and is usually 15cm thick of soil. The purposes of daily cover is to control the moisture content in the landfill, helps in reducing the landfill odours and prevent fires; capped the refuse and as litter control measures, limits the animals and birds contact with the waste materials, as an operational condition for vehicle access to the active face and decreases the nastiness of the facilities.

ii. Intermediate cover also less provides the same functions as daily cover with main function is to reduce the moisture in the landfill from entering the waste. Sometimes this cover could be removed when more waste is deposited and is usually 10-100cm thick.

iii. Final cover is layer which is compacted, uniformly applied, and sloped to enhance surface runoff as opposed to allowing infiltration. The several purposes of final cover is :

   a. Reduce or enhance landfill gas migration
   b. Encourage surface runoff and control erosion of the cover and provide low permeability cover in the landfill that serves to regulate the infiltration of surface water into the waste and limit the generation of leachate.
   c. Retain the water content in the landfill and regulate the growth of vegetation root
   d. Provides base for establishment of suitable ground cover.
   e. Provides final shaping and contouring of the landfill site.

(Mc Bean, 1995).

2.19 Compost as Landfill cover/Biocover

Compost is organic matter that has been decomposed or recycled and rich in nutrients. Compost is identified to perform as a high CH_4 oxidation capacity compared to other cover materials such as soil (Humer and Lechner, 1999). Compost used as cover material must be matured and well structured to achieve maximum CH_4 oxidation activity (Wilshusen *et al.*, 2004a). The higher CH_4 oxidation capacity by compost compared to other material such as soil is most probably due to rich in nutrient and organic content that supports the growth of methanotrophic bacteria and enhance the CH_4 oxidation activity (Rozej and Stepniewski, 2008). Besides that, other factor such as their water holding capacity, the porosity of the compost, and their thermal insulation properties also enhanced CH_4 oxidation (Hilger and Humer, 2003). Preliminary field experiments by researchers also indicate that the suitability of compost as biocover in landfills is because of their high efficiency in CH_4 oxidation. Several types of compost has been assessed by researchers on CH_4 oxidation such as MSW compost, sewage sludge compost, biowaste compost, compost mix with soil or sand, leaf compost, commercial compost, and woodchip compost(Huber Huber, 2004; Felske, 2003; Wilshusen *et al.*, 2004).

Compost is capable of oxidizing CH_4 at a very high rate where the rates increase two or three times higher than soil (Wilshusen *et al.*, 2004). Besides that, compost also act as fertilizer for vegetation growth in landfills and enhance the stability of landfill cover. It also has high water retention capacity due to high organic content and specific surface area. This helps the compost to retain the moisture content for methanotrophic bacteria because excess water can block the gas transport and reduce the CH_4 uptake and in some cases it also reported to produce CH_4 (Scheutz *et al*., 2009).

Microbial CH_4 oxidation in landfills can be enhanced by using compost as landfill cover instead of clay (Stern et al., 2007). Previous study by Humer and Lechner (2001) on CH_4 oxidation using MSW compost and sewage sludge compost as landfill cover showed that increase in CH_4 oxidation and found that complete CH_4 oxidation is possible. Compost also provides favorable environments for the growth of methanotrophic bacteria. Compost applied as landfill cover must be fully matured in order to for maximum CH_4 oxidation. Compost also has the ability to control the influence of temperature and moisture content. It controls the water infiltration into the landfill and enhanced waste degradation and establishes optimal conditions for methanotrophic community (Scheutz *et al*., 2009; Stern *et al*., 2007; Huber Humer, 2004).

2.20 CH_4 oxidation

Landfills are one of the main contributors to CH_4 emission (Borjesson *et al*., 2000). CH_4 produced from landfills can be converted to CO_2 by oxidation process by making use of the methanotrophic properties. CH_4 oxidation depends on several environmental factors such as temperature, moisture content, pH, organic content and other factors (Christophersen *et al*., 2000). CH_4 oxidation is also differing within and between landfill sites due to seasonal climate change, physical heterogeneities of the cover soil, and the CH_4 concentrations (Borjesson *et al.*, 2004). Concept of microbial CH_4 oxidation is one of effective method for GHG reduction from landfill (Stern *et al.*, 2007). CH_4 oxidation occurs at the interface of aerobic and anaerobic zones, where CH_4 is generated in anaerobic regions below, and methane uptake occurs in aerobic zones above. High methane oxidation capacity could be found in porous, coarse and organic-rich substrates (Croft and Emberton, 1989).

Studies on CH_4 oxidation have been widely done by researchers. The first experiment to quantify methane oxidation in landfill cover was done by Whalen *et al* (1990) using laboratory batch experiments. CH_4 45g CH_4/m^2d (= 63 l CH_4/m^2d) were rapidly oxidized in a landfill topsoil in a closed municipal solid waste landfill where the CH_4 concentration was between 1 ppm to 10,000 ppm. Capacity for CH_4 oxidation is observed in landfill cover soil in column experiments, with rates as high as >200 g CH_4/m^2d (Scheutz *et al.*, 2003; De Visscher *et al.*, 1999). Batch studies by Fauziah and Agamuthu (2002) reported that using landfill cover soil at different temperature showed complete CH_4 oxidation within 28 hours. Column experiment conducted in landfill recorded maximum CH_4 oxidation activity at depth of 60cm (Rozej and Stepniewski, 2008).

CH_4 oxidation depth in landfill is highly dependent on the availability and diffusion of O_2. According to Nozhevnikova and Lebedev (1995) oxygen diffusion is observed to a depth of one meter in landfill experiment conducted in Poland. Field studies with installation of biocovers showed increase in the CH_4 oxidation rate compared to uncovered landfill or covered with conventional soil (Barlaz *et al.*, 2004; Huber

Humer, 2004; Stern *et al*., 2007; Ait Benichou *et al*., 2009). CH_4 oxidation rate (>400 g CH_4/m^2d) in simulated landfill covers is rich in organic matter such as mature compost materials (Haubrichs and Widmann, 2006; Humer and Lechner, 2001b). The type of material used as landfill cover is also equally important to determine the CH_4 oxidation. In a previous study by Rozej and Stepniewski (2008), they observed that higher CH_4 oxidation rate of $387dm^3m^{-2}d^{-1}$ was observed when sewage sludge compost was used in column experiment while Pawloska (1999) observed a CH_4 oxidation rate of 227 $dm^3m^{-2}d^{-1}$ when using sand as cover material. Different cover material observed to have different CH_4 oxidation rate, where the rate ranged from 256 to 447 $dm^3m^{-2}d^{-1}$ (DeVisscher *et al*., 1999; Stein and Hettiarachi, 2001). Figure 2.14 shows the conceptual CH_4 oxidation zone in a landfill cover soil. The optimum zone in landfill cover for CH_4 oxidation is observed to occur when gas concentration profile of CH_4 and O_2 encounters. The distribution of O_2 into the CH_4 oxidation zone is controlled by the gas filled porosity of the porous medium. Additionally the depth of the CH_4 oxidation depends on the flow of landfill gas (LFG). When the LFG flow from the landfill increased the CH_4 oxidation zone will be pushed upwards towards the surface and becomes shallower (Scheutz and Kjeldsen, 2003; Rannaud *et al*., 2009). CH_4 concentrations also have significant influence on oxidation. In addition to climate and soil type, the methane loading to the cover soil also has influence on CH_4 oxidation rate, where below a certain methane loading rate, oxidation can be 100% as stated by Abichou *et al* (2008). The amount of CH_4 load caused the methanotrophic bacteria to multiply and carry out CH_4 oxidation. Large population of methanotrophs is observed in landfill cover soil by Stein and Hettiaratchi (2001).

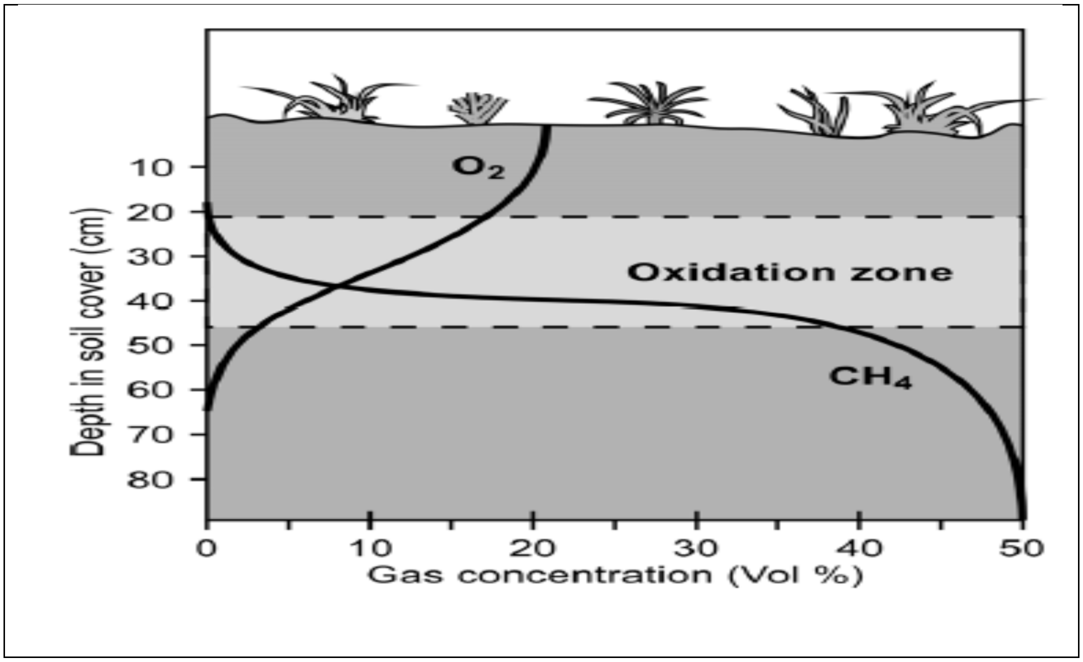


Figure 2.14: Conceptual CH_4 oxidation zone in a landfill cover soil (Scheutz, 2002).

2.21 Kinetics of CH_4 oxidation

Kinetics of the CH_4 oxidation can be described by Michaelis-Menten equation (Pawloska and Stepniewski, 2006).

$$V = V_{max} \frac{1}{1 + \frac{K_m}{C}}$$

where,

V= Actual CH_4 oxidation rate ($m^3m^{-3}s^{-1}$)

V_{max} = Maximum CH_4 oxidation rate ($m^3m^{-3}s^{-1}$)

K_m = Michaelis Constant ($m^3m^{-3}s^{-1}$)

C =CH_4 Concentration ($m^3m^{-3}s^{-1}$)

The kinetics of CH_4 explains the rate of CH_4 oxidation and the potential methanotrophic activity. From the Michaelis-Menten equation, K_m can be used to quantify the capacity of CH_4 oxidation. Pawloska and Stepnieswski (2006) conducted column experiment with continuous flow of CH_4 to study the kinetics on CH_4 oxidation and concluded that CH_4 oxidation rate or reaction increased when the amount of CH_4 concentration increased. The reaction continues until the time became constant. When landfill cover is exposed to high concentration of CH_4 the methanotrophic activity is also high and results in high Km value. The maximum CH_4 oxidation rate obtained by using different cover materials such as soil, sand or compost ranged between $0.11X10^{-3}$ to $0.86X10^{-3}cm^3kgdw^{-1}s^{-1}$(Whalen *et al.*, 1990) while Kightley *et al* (1995) reported that the maximum CH_4 oxidation was in the range of $6.49X10^{-3}$-$7.29X10^{-3}$ using sand taken from landfill cover. CH_4 oxidation reaction is also in line with the First order kinetics (Streese and Stegmann, 2003). Table 2.9 summarized the kinetic studies on the CH_4 oxidation.

Table 2.8: Kinetic studies of CH_4 oxidation

Cover material examined	Range of CH_4 concentration (vol%)	$V_{max}/cm^3kg^{-1}s^{-1}$	K_m (%)	References
Landfill cover soil	1.7 $X10^{-4}$-1.0	0.88-1.09$X10^{-3a}$	0.18-0.7	Bogner and Spokas (1993)
Landfill cover topsoil	1.6$X10^{-2}$-8.0	4.65 $X10^{-3}$	2.54	Kightley *et al.*, (1995)
Loam from landfill cover	<10	4.8$X10^{-3}$-6.2$X10^{-3}$	0.75	Wilshusen *et al.*, (2004)
Coarse sand soil from landfill cover	0.05-5.0	6.2 $X10^{-3}$ ± 0.36 $X10^{-3}$	0.6-2.9	Bender and Conrad (1995)
Clay layer biofilter	0.2-10	1.1 $X10^{-2}$	1.2	Powelson *et al.*, (2006)
Sand material	1-16	1.1 $X10^{-4}$-8.3 $X10^{-4}$	0.6-2.9	Pawloska and Stepnieswski (2006)
Sand loamy soil	<3	1.5 $X10^{-3}$-1.7 $X10^{-2}$	0.17-0.58	Stein and Hettiarachi (2001)
Forest cambi soil	0.2 $X10^{-5}$-0.03	2.2 $X10^{-5a}$	2.2 $X10^{-3}$	Whalen and Reeburgh (1996)
Bog soil	1.7 $X10^{-4}$-0.1	1.48 $X10^{-3}$	0.084	Streese and Stegmann (2003)

*a=per kg of wet weight

(Cao and Staszwska, 2011)

2.22 Summary of Literature Review

Generation of waste is increasing due to population growth, urbanization and affluence. Current global MSW generations for 161 countries are approximately 1.3 billion tonnes per year (World Bank, 2012). Even though there are several methods available for disposal of MSW, landfilling is the most employed method in developing countries such as Malaysia. Landfill gas (LFG) and leachate are the major outputs from landfill. Most of the LFG IS passively released to the atmosphere which contributes to global warming. Global CH_4 emission from landfill is about 35-69 Tg CH_4 yr^{-1}.

There are several options for recovery or utilization of LFG but the efficiency is only up to 60%. An alternative way to reduce CH_4 emission is by CH_4 oxidation which can be enhanced by the microbial CH_4 oxidation process. Methanotrophs use CH_4 as sole energy and carbon source in the presence of O_2. Factors which affect CH_4 oxidation includes temperature, moisture content, $CH_{4,}$ O_2 concentration and pH. Biocover material is used in landfill to minimize infiltration, isolate waste and to control landfill gas. Biocover could provide optimum conditions for methanotrophs to carry out CH_4 oxidation. Compost has been identified to perform high CH_4 oxidation activity compared to other materials. Therefore this study aims to optimize landfill CH_4 oxidation using compost as biocover material supplemented with methanotroph.