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Estimation of Methane Emission from Landfills in Malaysia using the IPCC 2006 FOD Model

[1]M.F.M. Abushammala, [1]N.E.A. Basri, [1]H. Basri, [2]A.A.H. Kadhum and [1]A.H. El-Shafie
[1]Department of Civil and Structural Engineering,
[2]Department of Chemical and Process Engineering, Faculty of Engineering and Built Environment,
Universiti Kebangsaan Malaysia, 43600 Bangi, Selangor, Malaysia

Abstract: Decomposition of municipal solid waste in landfills under anaerobic conditions produces gas containing approximately 50-60% methane (CH_4) and 30-40% carbon dioxide (CO_2) by volume. CH_4 is one of the most important greenhouse gases because its global warming potential is more than 21 times CO_2, which has adverse effects on the environment and human life. The CH_4 emission from landfills is continually increasing due to increasing population growth and per capita waste generation. This study attempted to assess, in quantitative terms, the amount of CH_4 that would be emitted from landfills in Malaysia over the years 1981-2024 using the Inter-governmental Panel on Climate Change 2006 First Order Decay Model. Furthermore, it tends to assess the effects of landfill gas collection system and waste recycling on CH_4 emission. In order to attain accurate CH_4 emission estimation, waste generation estimation over the years 1981-2024 were performed in two scenarios. Each scenario was used by the model to estimate CH_4 emission either taken into account CH_4 capturing amounts and increasing waste recycling over the study period or not, to evaluate their effect on CH_4 emission reductions. Based on this, global CH_4 emission in 2024, included 1,078 and 1,365 Gg CH_4 emission reduction from the emission estimated using the first and the second waste generation scenarios, respectively, which indicated that increasing landfill gas collection system projects and amount of waste recycling provide greatest potential for controlling CH_4 emission from landfills.

Key words: CH_4 emission, Malaysia landfills, IPCC, Malaysia emission, emission estimation, landfill gas

INTRODUCTION

Municipal Solid Waste (MSW) generally contains degradable (food waste, yard waste, paper, etc.), partially degradable (wood and sludge) and non-degradable materials (plastics, rubbers, leather, metals, glass and ash). Decomposition of these materials under anaerobic conditions in landfills produces gas containing approximately 50-60% methane (CH_4) and 30-40% carbon dioxide (CO_2) by volume (Abushammala *et al*., 2009a). CH_4 is one of the most important greenhouse gases (GHG) because its global warming potential more than 21 times carbon dioxide, which has adverse effects on the environment. Furthermore, migrates of CH_4 gas from landfills to the surrounding environment can potentially affect the human life, whereas gas explosion incidents were reported at Loscoe village in England in 1986 and Skellingsted Landfill in Denmark (Christophersen *et al*., 2001), due to CH_4 gas migration. The CH_4 emission from landfills is continually increasing due to increasing population growth and per capita waste generation. Currently, landfills are the major source of CH_4 emissions in Malaysia (53%) followed by palm-oil mill effluent (38%), swine manure (6%) and industrial effluent (3%) (Ministry of Energy, Water and Communications, Malaysia Energy Center, 2004; Kamarudin, 2008).

Estimation of CH_4 emissions from landfills entails large uncertainties due to the inadequate availability of data on waste management and emissions. The First Order Decay (FOD) model is one of the most important and widely used models for estimation of CH_4 emissions. It was used by many researchers for estimation of CH_4 emission from landfills (Wangyao *et al*., 2009; Chiemchaisri *et al*., 2007; Kumar *et al*., 2004). The FOD model has been formalised as the IPCC Waste Model by Inter-Governmental Panel on Climate Change (2006) and a Landfill Gas Emission Model (LandGEM) by the US Environmental Protection Agency (USEPA, 1998). Both the IPCC and USEPA recommend this model as a standard tool for the estimation of CH_4 emissions from landfills. The FOD model provides a time-dependent emission profile reflecting the pattern of waste degradation over

Corresponding Author: Mohammed F.M. Abushammala, Department of Civil and Structural Engineering, Faculty of Engineering and Built Environment, Universiti Kebangsaan Malaysia, 43600 Bangi, Selangor, Malaysia Tel: +60172509821

time. It assumes that the DOC in waste decays slowly over time during which CH_4 and CO_2 are formed. Thus, the CH_4 emission from deposited waste is highest during the first few years after deposition then gradually declines with the decline of DOC content in the waste (Inter-Governmental Panel on Climate Change, 2006). The FOD model is referred to herein as the IPCC 2006 FOD Model. The IPCC 2006 F OD Model provides a spreadsheet interface to facilitate its implementation for national emission estimations. The user can enter country name, region and specific activity data on waste deposited in landfills into the model spreadsheet and this information is used by the model to select default DOC- and CH_4-generation rate (k) values for waste, a regional per capita waste-generation rate and default waste composition.

This study attempted to assess, in quantitative terms, the amount of CH_4 that would be emitted from landfills in Malaysia over the years 1981-2024 using the IPCC 2006 FOD Model. Furthermore, it tends to assess the effects of landfill gas (LFG) collection system and waste recycling on emission reduction. To accomplish this, different scenarios were used to estimate annual waste generation in Malaysia, which used by the IPCC 2006 FOD Model in order to estimate total CH_4 emission. The total CH_4 emission was estimated with different waste recycling amounts to study the effect of waste recycling on CH_4 emission reduction. The total emission were estimated with assumption that zero LFG are collected through the study years and re-estimated with entering the real and expected amount of LFG collection into the IPCC 2006 FOD Model in order to study the effect of LFG collection system on emission reductions.

CH_4 ESTIMATION METHOD

Landfilling and open dumping are the most common methods for MSW disposal in developing countries. In Malaysia, about 30% of MSW are disposed by landfilling, 50% by open dumping, 10% by composting, 5% by incineration and 5% by others (Tan J.S.E., 2009). In Malaysia Action Plan 1988, Malaysian government tried to increase waste disposal sites efficiency, they classified waste disposal into four levels of landfills: (1) level 1: controlled dumping, (2) level 2: sanitary landfill with daily cover, (3) level 3: sanitary landfill with leachate circulation, (4) level 4: sanitary landfill with leachate treatment (Manaf *et al*., 2009). In 2002, Malaysia had 77 open dumps, 49 controlled-tipping landfills (Level 1) and 35 landfills (Level 2, 3 and 4) (Idris *et al*., 2004). Figure 1 shows landfilling sites in Peninsular Malaysia.

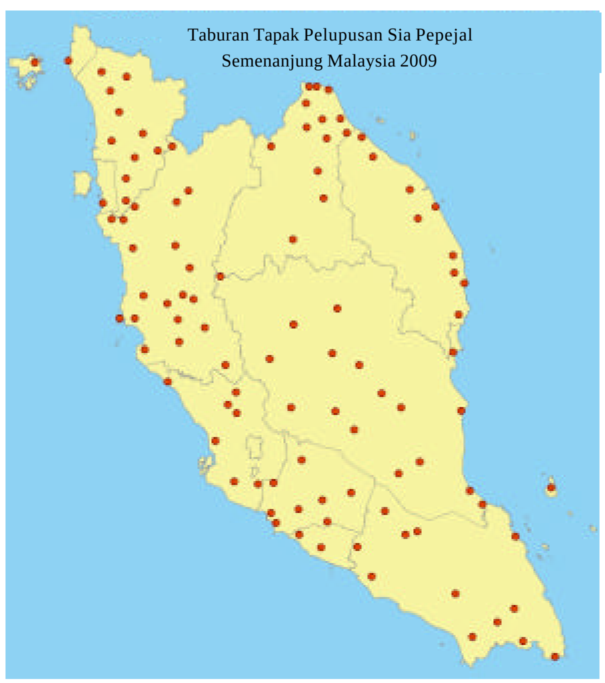

Fig. 1: Location of waste disposal sites in Peninsular Malaysia. The Map in Fig. 1 was collected from Ministry of Housing and Local Government Malaysia by personal communication. Source: (Bin-Hasnan, M-Z., Personal Communication, April 14, 2010)

Estimation of total CH_4 emission from waste disposal sites in Malaysia was performed using IPCC 2006 FOD Model. In the model, CH_4 emission from landfills for a single year can be estimated using the following equation Eq. 1 (Inter-Governmental Panel on Climate Change, 2006):

$$CH_4\ \text{Emissions} = \left[\sum_x CH_4\ \text{generated}_{x,T} - R_T\right] \times (1 - OX_T) \quad (1)$$

where, the CH_4 emission is the amount of CH_4 emitted in year T (Gg), T is the inventory year, x is the waste category or type of material, R_T is the CH_4 recovered in year T (Gg) and OX_T is the oxidation factor in year T (fraction). The OX value reflects the amount of CH_4 oxidised in the soil or other material covering the waste. The amount of CH_4 generated from decomposable material is estimated by multiplying the CH_4 fraction in the generated LFG and the molecular weight ratio of CH_4 and C as follows Eq. 2:

$$CH_4\ \text{generated}_T = \text{DDOCm decomp}_T \times F \times 16/12 \quad (2)$$

where, CH_4 generated $_T$ is the amount of CH generated from decomposable material in year T (Gg), DDOCm decomp_T is the mass of decomposable DOC decomposed in year T (G), F is the fraction of CH_4 by volume in the generated LFG (fraction) and 16/12 is the molecular weight ratio of CH_4 to C. The IPCC 2006 Model takes into account the amount of decomposable DOC deposited each year and the amount remaining from previous years Eq. 3 and 4:

$$\text{DDOCm decomp}_T = \text{DDOCma}_{T-1} \times \left(1 - e^{-k}\right) \quad (3)$$

$$\text{DDOCma}_T = \text{DDOCmd}_T + \left(\text{DDOCma}_{T-1} \times e^{-k}\right) \quad (4)$$

where, DDOCma_{T-1} is the mass of decomposable DOC deposited (DDOCm) and accumulated in the landfill at the end of year T-1 (Gg), DDOCma_T is the DDOCm accumulated in the landfill at the end of year T (Gg), DDOCmd_T is the DDOCm deposited into the landfill in year T (Gg), k is a reaction constant ($k=\ln(2)/t_{1/2}$) (year^{-1}) and $t_{1/2}$ is the half-life of the DOC (year). The mass of decomposable DOC deposited (DDOCm), Gg, can be calculated as follows Eq. 5:

$$\text{DDOCm} = W \times DOC \times DOC_f \times MCF \quad (5)$$

where, W is the mass of waste deposited (Gg), DOC is the degradable organic carbon in the year of deposition (fraction, Gg C / Gg waste) and MCF is the CH_4 correction factor for aerobic decomposition in the year of deposition (fraction).

The basic equation for the IPCC 2006 model used in the present study, using the bulk waste option and a time delay, is shown below Eq. 6; this is the simplest inventory calculation performed by the model due to the absence of Malaysian historical waste-composition data.

$$CH_4\text{Emissions}_T\left(\text{Gg/year}^{-1}\right) = \left[\sum_{x=S}^{T-1}\left\{\text{MSWT}_x \text{MSWF}_x L_{o,x}\left(e^{-k(T-x-1)} - e^{-k(T-x)}\right)\right\} - R\right] \times (1 - OX) \quad (6)$$

where, x is the year in which waste was deposited, S is the starting year of inventory estimation, MSWT is the total MSW generated (Gg year^{-1}) and MSWF is the fraction of MSW disposed of in landfills. L_o (Gg) can be estimated as shown in the Eq. 7:

$$L_o = \text{DDOCm} \times F \times 16/12 \quad (7)$$

A simple FOD spreadsheet model provided in the 2006 IPCC Guidelines for National Greenhouse Gas Inventories was used in this study for running the emission calculations. In the spreadsheet model there are three drop-down menus that set the appropriate default values. First, users select the country and region; next, users indicate the type of waste data used (waste composition data or bulk waste data); then, users choose a climate (dry temperate, wet temperate, dry tropical, or moist and wet tropical). The model uses this information to select default DOC and k values for waste, a regional per capita waste-generation rate and default waste composition. Furthermore, the model can also be used to estimate industrial waste emissions, where the users have to enter industrial waste generation which correlated with Gross Domestic Product (GDP). The model dose not provides any regional default values for industrial waste.

Depending on the level of data available, a model based on bulk waste was selected for this study where waste composition data were unavailable in Malaysia. The moist and wet tropical climate was selected based on the Malaysian climate. The annual quantities of waste disposed of in unmanaged shallow, unmanaged deep, managed, managed semi-aerobic and uncategorised landfills were 25, 30, 25, 5 and 15%, respectively, based on the model default values. In the activity data sheet, two scenarios were used in order to estimate historic and projected annual MSW generation, however, the amounts of industrial waste generation were set to zero where no information available on historic and projected industrial waste generation.

The first scenario for estimation of MSW generation followed Bogner and Matthews (2003) method, which estimates annual per capita waste generation based on annual per capita energy consumption. Two liner regression models were provided by Bogner and Matthews (2003) for estimating per capita waste generation from per capita energy consumption. The first linear model was for developed countries with per capita energy consumption higher than 1500 kg cool equivalent per annum, while the second for developing countries with per capita energy consumption less than 1500 kg cool equivalent per annum. Annual energy consumption in Malaysia from 1981 till 2006 and annual historic and projected Malaysian population from 1981 till 2024 were collected from the US. Energy Information Administrator (US. Energy Information Administration, Independent Statistics and Analysis, 2009) and the Department of Statistics Malaysia (Wan-Ahmad, A-R., Personal Communication, October 1, 2009), respectively, in order to estimate annual per capita energy consumption from 1981 till 2006. These energy consumption data were entered later on into the models provided by Bogner and Matthews (2003) for developed and developing countries to estimate the annual per capita waste generation from 1981 to 2006. The results from both models were compared with existed annual per capita waste generation data for the years 1998, 2000 and 2004 provided by Ministry of Housing and Local Government (Bin-Hasnan, M-Z., Personal Communication, April 14, 2010), in order to select the best fit model resulting in a minimum error value. Finally, a linear regression model was fitted the estimated annual per capita waste generation data from 1981 till 2006 in order to predict the per capita annual waste generation from 2006 till 2024.

The second scenario of annual MSW estimation assumes that 292 kg is the annual per capita waste generation during the years 1981 till 2000, which starts to increase in 2000 by 2.5% annually till 2024. Thus, the annual MSW generation from 1981 till 2024 can be estimated by multiply the annual historic and projected population by the annual per capita MSW generation.

In the IPCC 2006 FOD Model application, assumptions on percentage of waste recycled were used in order to study the effect of waste recycling on estimated annual CH_4 emission. Two assumptions were used; first, it was assumed that 76% of annual MSW generated since 1981 till 2024 are collected with 1% constant rate of recycling and the second assumption takes into account 76% of waste are collected and initiates by 1% of waste recycled from 1981 to 2000, which start to increase annually by 1% in 2000 to reach 24% in 2024.

Finally, zero CH_4 oxidation was set in the model as a regional default value, the amount of CH_4 recovered were entered in the model starts from 2007 till 2024, where CDM projects were in operation in the beginning of 2007 with annual average CH_4 emission reduction 21.4 Gg (United Nations Framework Convention on Climate Change, 2009).

RESULTS AND DISCUSSION

Using the IPCC 2006 FOD Model, emissions and emissions projections were calculated for the time series 1981-2024 with the model default values: DOC = 0.17, $DOC_f = 0.5$, F = 0.5, k = 0.17 year^{-1} (average half-life of 4.1 year) and six months as time delay. The model default values were automatically selected by the model based on Malaysia region (Southeast Asia) and climate condition. Furthermore, depending on the regional classification the quantities of waste disposed of in unmanaged shallow, unmanaged deep, managed, managed semi-aerobic and uncategorised disposal sites were selected by the model to be 25, 30, 25, 5 and 15%, respectively, which yielding MCF values of 0.4, 0.8, 1, 0.5 and 0.6, respectively.

Based on the energy consumption data provided from US. Energy Information Administration, Independent Statistics and Analysis (2009) from 1981 until 2006, the annual per capita waste generation estimated using Bogner and Matthews (2003) models prepared for developed and developing countries. The annual per capita waste generation resulted from Bogner and Matthews (2003) models and per capita waste generation data collected from MHLG for the years 1998, 2000 and 2004, show in Fig. 2.

Although, Malaysia is one of the developing countries, the data provided by MHLG for annual per capita waste generation are relatively closed to the annual per capita waste generation estimated using the model prepared for developed countries rather than that prepared for developing countries (Fig. 2). This was due to the annual per capita energy consumption in Malaysia and developed countries are higher than 1500 kg cool equivalent per annum (US. Energy Information Administration, Independent Statistics and Analysis, 2009). The Root Mean Square Error (RMS) between the data collected from MHLG for 1998, 2000 and 2004 and the annual per capita waste generation estimated by the models prepared for developed and developing countries was estimated based on Eq. 8:

$$RMS = \sqrt{\frac{\sum_{i=1}^{3}\left(f(x_i) - y_i\right)^2}{n}} \tag{8}$$

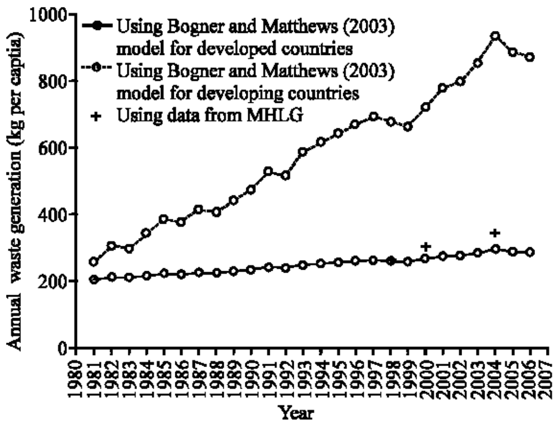

Fig. 2: Annual waste generation estimation. In Fig. 2, the dash line is the annual waste generation (kg per capita) estimated using Bogner and Matthews (2003) model which prepared for developing countries to estimate per capita waste generation from per capita energy consumption. The solid line is the annual waste generation (kg per capita) estimated using Bogner and Matthews (2003) model which prepared for developed countries to estimate per capita waste generation from per capita energy consumption. The dark color scatter points are represented the annual per capita waste generation available from Ministry of Housing and Local Government Malaysia

where, $f(x_i)$ is the per capita waste generation collected from the MHLG in the year i, y_i is the amount of waste generation estimated using the models prepared for developed and developing countries for the year i and n is the number of years. The results shown that the model prepared for developed countries fitted the data collected from MHLG with RMS equal 33.1 kg waste per capita, while that prepared for developing countries had RMS equal 479.6 kg waste per capita. Thus, the model prepared for developed countries was used in this study to estimate annual waste generation in Malaysia from 1981 till 2006 depending on annual energy consumption available. The annual per capita waste generation data produced from the model were then fitted to a linear regression model with correlation coefficient (R^2) 0.98 in order to predict the annual per capita waste generation from the year 2006 till 2024 (Fig. 3).

Using the annual historic and projected population data provided from the Department of Statistics Malaysia and the annual per capita waste generation estimated in the two scenarios; the historic and projected waste generation for the time series 1981-2024 were estimated for both scenarios (Fig. 4).

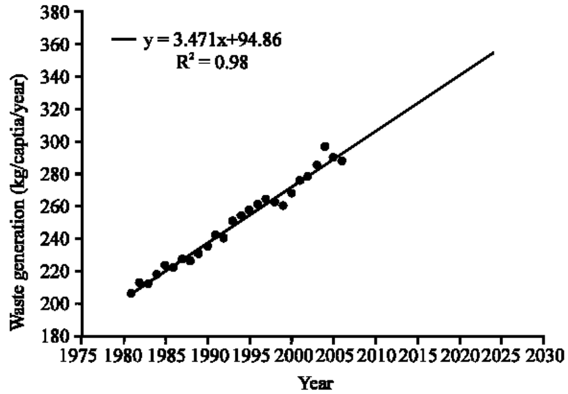

Fig. 3: Simple linear prediction model. The data in Fig. 3 is the result shown in solid line in Fig. 2 and was used in order to predict future waste generation using simple linear regression model

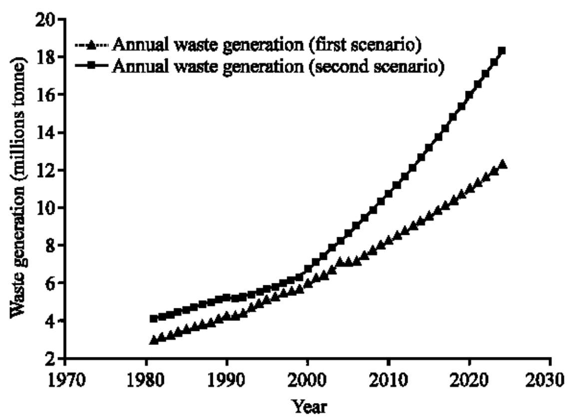

Fig. 4: Annual waste generations estimated using the two scenarios. In Fig. 4, dash line is the annual waste generation in Malaysia resulting from Bogner and Matthews (2003) model for developed country and from the model shown in Fig. 3 (first waste generation scenario), while the solid line is the annual waste generation in Malaysia estimated from population data from 1981 to 2024 collected from Department of Statistics Malaysia and the assumptions of annual per capita waste generation (0.8 kg/capita/day from 1981 till 2000 and increasing per capita waste generation by 2.5% annually from 2000 till 2024)

The first scenario for waste generation estimation is underestimated the waste generation compared with the second scenario. The average of waste increment between 1981 and 2000 for the first and the second scenarios were 4.8 and 2.7% per year, respectively. In the year between 2000 and 2024, the amount of waste

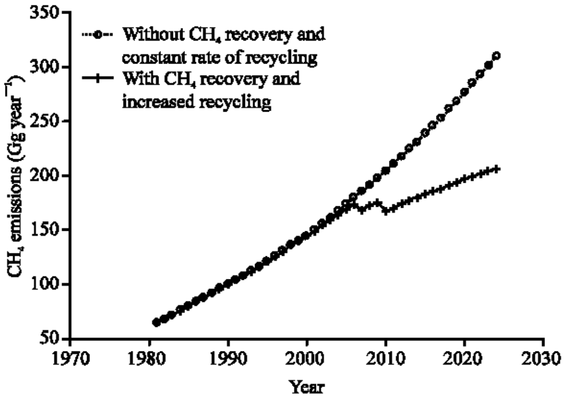

Fig. 5: The annual CH_4 emission in Malaysia estimated using the IPCC 2006 FOD Model for the first waste generation scenario shown in Fig. 4. The dash line represented the annual CH_4 emission from landfills in Malaysia (Gg). It is estimated from the IPCC 2006 FOD Model, with assumptions that 1% waste recycled annually and zero LFG collection. The solid line represented the annual CH_4 emission from landfills in Malaysia estimated using the IPCC 2006 FOD Model taken into account the LFG collection system starting from 2007 till 2024, with 21.4 Gg average annual CH_4 collections and increasing amount of waste recycling annually by 2.5% from 2000 till 2024

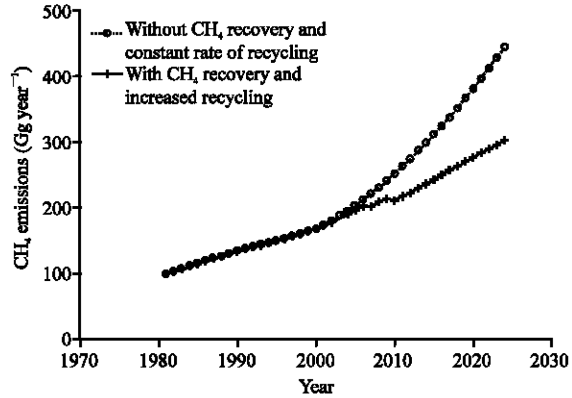

Fig. 6: The annual CH_4 emission in Malaysia estimated using the IPCC 2006 FOD Model for the second waste generation scenario shown in Fig. 4. The dash line represented the annual CH_4 emission from landfills in Malaysia (Gg). It is estimated from the IPCC 2006 FOD Model, with assumptions that 1% waste recycled annually and zero LFG collection. The solid line represented the annual CH_4 emission from landfills in Malaysia estimated using the IPCC 2006 FOD Model taken into account the LFG collection system starting from 2007 till 2024, with 21.4 Gg average annual CH_4 collections and increasing amount of waste recycling annually by 2.5% from 2000 till 2024

generation was increased in the first and the second scenarios by 4.4 and 7.1% respectively (Fig. 4).

The CH_4 emissions were estimated for both waste generation estimated scenarios with constant (1%) waste recycling and zero LFG collection over the study period and re-estimated with constant (1%) waste recycling between 1981 and 2000, increasing annually by 1% from 2000 to reach 24% in 2024 and with 21.4 Gg average annual CH_4 collection started from 2007 till 2024. The CH_4 emission produced by the model with constant waste recycling and zero LFG collection estimated to be 310 Gg in 2024 from the first scenario (Fig. 5), while 443 Gg from the second scenario (Fig. 6).

As shown in Fig. 5 and 6, LFG collection system and increasing amount of waste recycling provide greatest potential for controlling future CH_4 emission from landfills. The total emission reduction in the first scenario (Fig. 5) was 1,078 Gg, represented 20% of the total emission produced during 2000 till 2024. Increasing amount of waste recycling was contributed 64.3% of the total amount of CH_4 reduction, while 35.7% due to LFG collection system. Comparing with the second waste generation scenario (Fig. 6), the total emission reduction from the second scenario was relatively low, where 1,365 Gg reduction of CH_4 emission, represented 19.6% from the total emission produced, this was due to big amount of waste generated from the second waste generation scenario, where the waste generation were assumed to increase by 2.5% annually from 2000 till 2024. In the second scenario, increasing rate of waste recycling and LFG collection system were contributed to the total emission reduction by 71.8 and 28.2%, respectively. Abushammala *et al.* (2009b) reported the factors affect CH_4 emission to the atmosphere, where they stated that reduction amount of waste in place and increasing of LFG collection system result in emission reductions.

CONCLUSIONS

Estimation of CH_4 emission from landfills is important for assessing landfills emission inventories. The IPCC 2006 FOD Model allows countries with limited waste management data to estimate national CH_4 emissions over a time series, using the FOD model. The projected emission produced by the IPCC 2006 FOD Model in 2024 for the first waste estimation scenario was lower than that estimated from the second scenario, where the first scenario for waste generation estimation is underestimated the waste generation compared with the second scenario. Increasing LFG collection system projects and amount of waste recycling appear to provide greatest potential for controlling CH_4 emission from landfills, whereas during this study LFG collection projects and increasing waste recycling contributed by 35.7 and 64.3%, respectively, from the total emission reduction in the first scenario, while 28.2 and 71.8%, respectively, in the second scenario.

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