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Application of the Triangular Model in Quantifying Landfill Gas Emission from Municipal Solid Wastes

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ABSTRACT: Municipal solid waste landfills are significant parts of anthropogenic greenhouse gas emissions. The emission of significant amount of landfill gas has generated considerable interest in quantifying such emissions. The chemical composition of the organic constituents and potential amount of landfill gas that can be derived from the waste were determined. The chemical formulae for the rapidly biodegradable waste (RBW) and slowly biodegradable waste (SBW) were determined as $C_{39}H_{62}O_{27}N$ and $C_{36}H_{56}O_{20}N$, respectively. The triangular method was used to calculate landfill gas obtainable from rapidly biodegradable waste over a 5-year period and for slowly biodegradable waste over a 15-year period. A plot was obtained for a landfill life span of 20 years. The volume of methane and carbon dioxide from RBW were 12.60 m^3 and 11.76 m^3 respectively while those from SBW were 6.60 m^3 and 5.48 m^3 respectively at STP. For the initial deposit of 2002 the highest landfill gas emission rate occurred in 2007 at 0.2829 Gg/yr with an average cumulative emission of 0.3142 Gg while for a landfill closed after five years the highest landfill gas emission rate was in 2010 at 1.2804 Gg/yr with an average cumulative emission of 1.5679 Gg while this cumulative emission will start declining by the year 2029.

Keywords: Solid waste, biodegradable, methane, carbon dioxide, leachate, trace gases

INTRODUCTION

The threat of global warming and its devastating consequences on climate change have been well documented (Cooper and Alley, 2002; Trenberth 2007). This global warming is caused by the increase in greenhouse gas (GHG) concentrations in the atmosphere largely as a result of human (anthropogenic) actions. Carbon dioxide (CO_2) and methane (CH_4) are the two gases with the greatest amount of impact on this global warming (Mackie and Cooper, 2009).

Municipal solid waste (MSW) landfills are one of the major sources of anthropogenic emissions arising from human activities (Kumar *et al.*, 2004, Papageorgiou, Barton *et al.*, 2009). Economic development and rising standards of living have led to increases in the quantity and complexity of waste

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generated (Franchetti, 2009) while waste generation rates vary from place to place and from season to season and have strong correlation with levels of economic development. The methods of disposal of these wastes are by open dumping (controlled and uncontrolled) and landfilling (sanitary and engineered). These have resulted in the generation of landfill gases (LFG), particularly methane (CH_4) and carbon dioxide (CO_2) and about 140 trace components (Parker *et al*., 2002) plus other volatile organic carbons (Urase *et al*., 2008) while (Deed *et al*., 2004) has identified more than 500 trace compounds in landfill gas. The main degradation products from a landfill are carbon dioxide (CO_2*)*, water and heat for the aerobic process, and methane (CH_4*)* and CO_2 for the anaerobic process (Wangyao *et al*., 2010). LFG is flammable and odorous and consists of about 45 – 60% methane (CH_4), the primary component of natural gas, about 40 – 50% carbon dioxide (CO_2), small amounts of nitrogen, oxygen, ammonia, sulphides, hydrogen, carbon monoxide and a trace amount of non-methane organic compounds (NMOCs) such as trichloroethylene, benzene, and vinyl chloride (ATSDR, 2001; Qin *et al*., 2001; Hurst *et al*., 2005, Tsai 2007).

Most landfill gas is produced by bacterial decomposition, which occurs when organic waste is broken down by bacteria naturally present in the waste and in the soil used to cover the landfill. These decompose organic waste in five phases with the composition of the gases changing in each phase (Veeken *et al*., 2000; ATSDR, 200l; Williams, 2005; Abushammala *et al*., 2009; Xiaoli *et al*., 2010). These five phases are:

I. Hydrolysis/Aerobic degradation: Solubilsation of complex solid organic material by the enzymes excreted by hydrolytic microorganisms
II. Hydrolysis and fermentation: Conversion of soluble organic components including the products of hydrolysis into organic acids and alcohols.
III. Acidogenesis/acetogenesis: Using an anaerobic process, bacteria convert organic acids created by aerobic bacteria into acetic, lactic, and formic acids, alcohols (methanol and ethanol), hydrogen and carbon dioxide.
IV. Methanogenesis: The products of acidogenesis/acetogenesis are converted into acetic acid, hydrogen and carbon dioxide. In the anaerobic stage, a large amount of landfill gas is generated by anaerobic degradation of organic substances, primarily methane and carbon dioxide, as well as other trace gases like H_2S, N_2O and CO.
V. Oxidation: Aerobic condition occurs where aerobic microorganisms convert the methane in the last phase to carbon dioxide and water.

Gas production in landfills begins after 6 – 12 months of waste placement, rises to a maximum shortly after and gradually declines over a period of 30 – 50 years (Falzon, 1997). One ton of municipal solid waste can produce up to 300 m^3 of LFG (Qin *et al*., 2001).

The factors that influence LFG generation are landfill waste composition and availability of readily biodegradable organic matter, the age of the waste, moisture content, pH, temperature, presence and distribution of (Kumar *et al*., 2004; Machado *et al*., 2009). Different environmental factors, such as wind and atmospheric pressure, on LFG emissions and their diffusion into the atmosphere have been investigated (Czepiel *et al*., 2003) as well as the influence of rain in making the dump top-layer less permeable (Aronica *et al*., 2009). The three processes that lead to the formation of landfill gas are bacterial decomposition, volatilization, and chemical reactions (ATSDR, 2001).

The general chemical reaction for anaerobic decomposition of solid waste is given as (Tchobanoglous *et al.*, 1993):

$$\underset{\text{(solid waste)}}{\text{Organic matter}} + H_2O \xrightarrow{bacteria} \text{biodegraded organic matter} + CH_4 + CO_2 + \text{other gases} \quad (1)$$

For complete conversion of the biodegradable organic matter to CO_2 and CH_4, the total volume of gas is estimated by the relation (Tchobanoglous *et al.*, 1993).

$$C_aH_bO_cN_d + \left(\frac{4a-b-2c-3d}{4}\right)H_2O \rightarrow \left(\frac{4a-b-2c-3d}{8}\right)CH_4 + \left(\frac{4a-b-2c+3d}{8}\right)CO_2 + dNH_3 \quad (2)$$

Greenhouse gases (GHGs) emissions are becoming significant energy and environmental issues relating to municipal solid waste (MSW) deposited in landfills in Malaysia. Malaysia is a subtropical nation with a total area of 329,847 km^2 and a population of around 28 million. There are currently 290 landfills in Malaysia of which 176 are active and the remaining 114 are not yet in operation (JPSPN, 2010). The largest of them is the Bukit Tagar Sanitary Landfill in Hutu Selangor (700 acres) and is designed to handle 3,000 tonnes but currently handles about 2,500 – 2,800 tonnes of municipal solid waste daily (approximately 1 million tonnes per year) with a leachate treatment capacity of 1,000m^3 per day. It has a potential capacity of 120 million tonnes of waste and will serve the major population base of Kuala Lumpur City and the Klang Valley.

The landfill under investigation is located in an industrial area in Johor State with total area of 50 acres. It consists of two cells each having an area of 13 acres. This landfill started operations in April 2002 and the first cell was closed in 2007. The second cell began operation in October 2007 and is expected to be full by October 2012. The landfill receives 300 – 350 tonnes of municipal and industrial waste daily. It has a leachate treatment system consisting of three ponds for anaerobic, aerobic, and settling activities. Currently there are no gas recovery facilities at the site.

Many methods and models have been developed to project potential generation of biogas from landfills. Two of these methods for estimating biogas have been recommended (IPCC 1996, IPCC 2006) in the establishment of national greenhouse gases inventories. They are the default methodology (Tier 1), adapted from theoretical methodology developed by (Bingemer and Crutzen, 1987), and is based on the premise that all the potential of landfill gases are released in the same year that the waste is deposited. This method is recommended for regions in which detailed data on solid waste is not available. The second and more complex method corresponds to the first order kinetic approach (Tier 2) and this provides a time-dependent emission profile that gives a true degradation pattern with time. Tier 2 model also depends on current and past waste quantities as well as their composition.

MATERIALS AND METHODS

The characterization of the waste sample was obtained from JPSPN (National Solid Waste Management Department) and was compared with actual field sampling analysis carried out by the authors and were found to be in close agreement. Hence the JPSPN data was used for this model. Because of lack of data on current and past waste quantities as well as their composition the authors have used the triangular approach which is a time-dependent method like the FOD model

(Tchobanoglous *et al.*, 1993). The degradation of the waste is assumed to occur in two stages with the degradable components of the waste being divided into two types: rapidly biodegradable waste (RBW) and slowly biodegradable waste (SBW). The total for both types are summed up to get the yield of landfill gas. Gas emission from the RBW peaks in the second year after waste deposition and tapers off till the sixth year when it becomes zero. For the SBW, gas generation starts in the second year, peaks after six years of waste deposition and slowly decreases for another ten years to become zero after the sixteenth year. The schematics of these two scenarios are shown in Figs. 1 and 2.

The volume of landfill gas emitted is equated to the total area of the triangle having a base of 5 years for RBW with the height of the triangle representing the peak emission at the end of the second year and decreasing gradually to zero at the end of the sixth year (Fig. 1). For SBW the volume of landfill gas emitted is equated to the total area of the triangle having a base of 15 years with the height of the triangle representing the peak emission at the end of the sixth year and decreasing gradually to zero at the end of the sixteenth year (Fig. 2)

The peak value of LFG emission, '*h*' is calculated based on the knowledge of the volume of the gases and base of the triangle. The area of the triangle is equal to half the base length x the altitude, hence, the total amount of gas produced is equal to

Total gas produced = ½ (base, year) x (altitude, peak rate of gas production, m^3*/year)* (3)

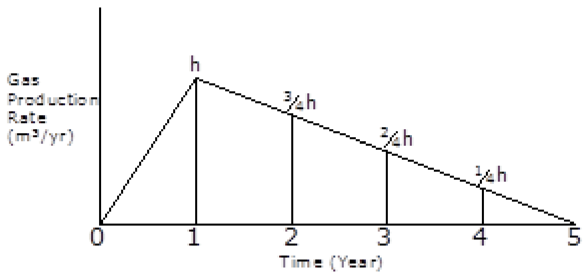

Fig. 1. Triangular gas production model for rapidly biodegradable waste

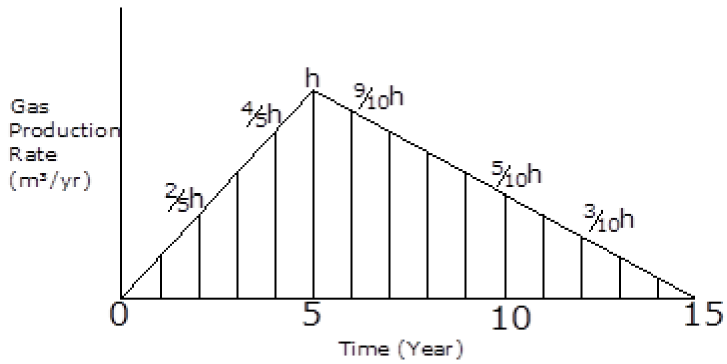

Fig. 2. Triangular gas production model for slowly biodegradable waste

For this model, what is required is the average waste composition for a particular landfill and the daily or annual amount of waste that is deposited into it.

RESULTS AND DISCUSSION

Table 1 shows the computation for the percentage distribution of the major organic elements. The first column is the waste composition as obtained from JPSPN. Column 2 is the calculated dry weight while the other columns show the elemental distribution in the waste. The amounts of carbon, hydrogen and oxygen in both the rapidly biodegradable waste and slowly biodegradable waste were very high for RBW and SBW respectively. These are so because the organic components of MSW have very high food components that are very rich in carbon hydrogen and oxygen. Elemental analysis is important because it shows the biodegradability by microorganisms and also allows the forecasting of potential biogas production (de Brauer, Achour et al. 2005). From this an appropriate chemical formulae without sulphur were determined as follows:

Rapidly decomposable: $C_{39.17}H_{62.26}O_{26.80}N$ ($C_{39}H_{62}O_{27}N$)

Slowly decomposable: $C_{36.39}H_{56.08}O_{19.80}N$ ($C_{36}H_{56}O_{20}N$)

These then yielded the reaction equations as

a) Rapidly decomposable

$$8C_{39}H_{62}O_{27}N + 86H_2O \rightarrow 161CH_4 + 151CO_2 + 8NH_3 \quad (4)$$

Table 1. Percentage distribution of the major organic elements

	Wet weight (kg)	Dry weight (kg)	Composition (kg)					
			C	H	O	N	S	Ash (misc)
Rapidly decomposable organic constituents								
Food waste	37.43	11.23	5.39	0.72	4.22	0.29	0.04	0.56
Paper/board	16.36	15.38	6.68	0.89	6.81	0.05	0.03	0.92
Yard*	1.91	0.77	0.35	0.05	0.29	0.03	0.002	0.05
Total	55.70	27.38	12.42	1.66	11.32	0.37	0.072	1.03
Slowly decomposable organic constituents								
Textiles	8.48	7.63	3.66	0.49	3.05	0.17	0.02	0.24
Rubber	1.32	1.23	0.86	0.11	-	-	0.02	0.25
Leather	-	-	-	-	-	-	-	-
Wood	3.78	3.02	1.50	0.18	1.29	0.01	0.008	0.01
Yard**	1.27	0.51	0.28	0.03	0.19	0.02	0.002	0.03
Total	14.86	12.39	6.25	0.81	4.53	0.20	0.05	0.53

Assuming 60% of yard waste will decompose rapidly.
* = 3.18 x 0.60 = 1.91
** = 3.18 – 1.91 = 1.27

b) Slowly decomposable

$$C_{36}H_{56}O_{20}N + 102H_2O \rightarrow 157CH_4 + 131CO_2 + 8NH_3 \quad (5)$$

Equations (4) and (5) are in agreement with the general equation given in equation (2). From the calculated formula and using the specific weights of methane (0.7183 kg/m^3) and carbon dioxide (1.9801 kg/m^3) respectively (Tchobanoglous *et al.*, 1993), the volume of methane and carbon dioxide produced were found to be

i) Rapidly decomposable

$$Methane = 12.60\, m^3 at\, STP$$

$$Carbon\, dioxide = 11.76\, m^3 at\, STP$$

ii) Slowly decomposable

$$Methane = 6.60\, m^3 at\, STP$$

$$Carbon\, dioxide = 5.48\, m^3 at\, STP$$

The total theoretical amounts of gas generated per unit dry weight of organic matter destroyed were $0.89\, m^3/kg$ for rapidly decomposable waste and

$0.975\ m^3/kg$ for slowly decomposable waste. These are the maximum amounts of gas expected to be evolved under optimum conditions from the biodegradable organic waste destroyed.

To estimate yearly landfill gas distribution, a landfill life span of 15 years was assumed. The waste was also assumed to be composed in the following manner:

Organic 86.25% - rapidly biodegradable

Inert: 13.75% - slowly biodegradable

It was also assumed that 75% of the rapidly biodegradable waste and 50% of the slowly biodegradable waste are available for degradation. This is because some organic materials will be in plastic containers and may not be degraded while some will be too dry and will not support biological activity. The time periods for total decomposition of rapidly biodegradable and slowly biodegradable organic matter are 5 and 15 years respectively.

The yearly rate of decomposition for rapidly biodegradable and slowly biodegradable organic matter was based on the triangular gas production model in which the peak rate of gas production occurred 2 and 6 years respectively, after gas production starts. Gas production was assumed to start at the end of the first full year of operation.

The rate and amount of gas produced at the end of each year from one kilogram (1kg) of the rapidly biodegradable and slowly biodegradable organic matter organic waste as they decomposed over a 6– and 16– year period are shown in Figs. 3 and 4 respectively.

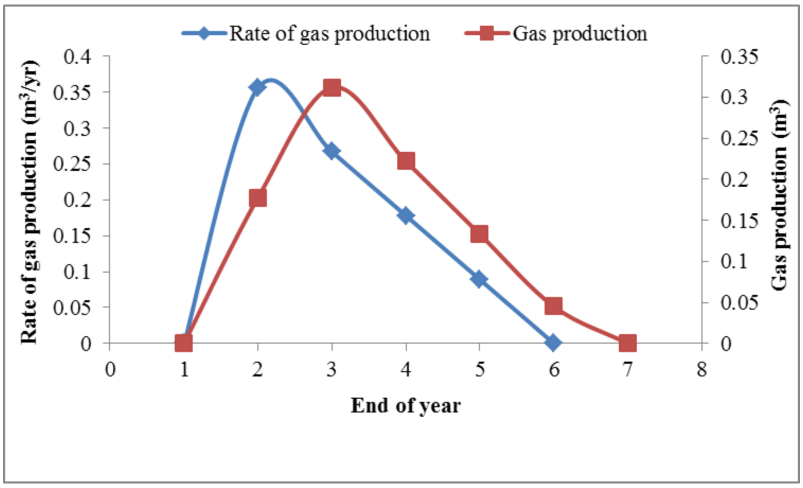

Fig. 3. Rate and amount of gas produced from rapidly biodegradable waste

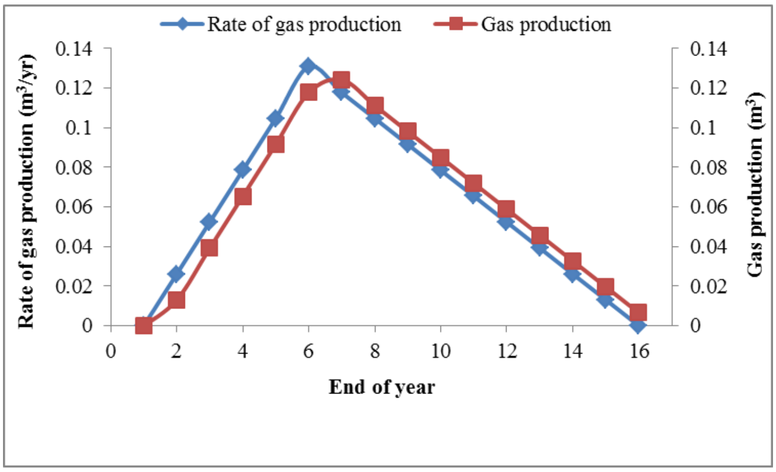

Fig. 4. Rate and amount of gas produced from rapidly biodegradable waste

The distribution of gas produced from rapidly biodegradable and slowly biodegradable organic material per kilogram of total waste deposited are computed on the assumption that 75% of RBW and 50% of SBW are available for degradation respectively based on dry weight. Hence, fraction of the total waste that is rapidly biodegradable is (0.274) (0.75) = 0.2055 kg RBW/kg total waste and the total amount of gas produced per kilogram of RBW is 0.183m^3/kg. Fraction of the total waste that is slowly biodegradable is (0.124) (0.50) = 0.062kg SBW/kg total waste and the total amount of gas produced per kilogram of RBW is 0.061m^3/kg. Landfill gas produced per year from RBW and SBW based on total weight is shown in the spreadsheet (Table 2).

Gas production peaked in the second year after waste deposition (2004) for rapidly biodegradable waste to 0.0641m^3/kg and then slowly tapers off to 0.00 m^3/kg by 2008. Gas production can continue for 25 years or more for RBW and for more than 50 years for SBW (Tchobanoglous, Theisen et al. 1993, Falzon 1997). For slowly biodegradable organic waste the highest production occurred in 2008 at 0.0077 m^3/kg and will reduce to 0.00 m^3/kg by 2018. When taken together it was observed that maximum gas production occurred in 2005 at 0.0665 m^3/kg. Production of gas is strongly dependent on the addition of moisture to the waste if it is well compacted, else the waste could remain in their original form after deposition, although in this instance, the landfill under investigation enjoys abundant rainfall because of its location.

After the initial adjustment period following waste deposition in the landfill, microbial decomposition began with an initial aerobic reaction because of the presence of some quantity of air in the landfill. The soil cover material supplied the aerobic and anaerobic microorganisms. The transition phase set in after the depletion of the oxygen and anaerobic conditions developed.

This work also precludes the existence of trace gases that may be brought with the incoming waste or from those that may be produced by biotic and abiotic reactions that occur in landfills. This is because landfill gas produced from waste with high carbohydrate percentage is said to be 505 methane and 50% carbon dioxide (Scharff and Afvalzorg, 2005).

The total landfill gas production rate and the average cumulative gas production for waste deposited in the landfill only in 2002 are shown in Fig 5. For the cumulative gas production, the upper and lower limits are also displayed. The evolution of landfill gas peaked in 2008 when the gas emission rate was 0.2829 Gg/yr with an average cumulative emission of 0.3142 Gg. By the year 2014, more than 95% of the landfill gas from this particular organic waste would have been emitted. The cumulative trend showed a steady increase till 2015 when there will be a massive reduction in gas emission. The emission characteristics displayed are for average values for a waste deposition of 300 – 350 tonnes per day.

Figure 6 shows the trend for a five-year continuous waste deposit in the closed landfill assuming equal amounts of waste are deposited in each of the five years. The maximum landfill gas production rate occurred in 2010 at 1.2804 Gg/year with an average cumulative gas emission of 1.5679 Gg. By 2024 this average cumulative gas emission will reach its peak 0f 3.30Gg and will be followed by a gradual decline. By the year 2029 this cumulative gas emission would have dropped to 0.5 Gg. This knowledge will be of much practical value in the design of landfill gas recovery system.

Table 2. Gas production from RBW and SBW based on total weight

End of year	Rapidly biodegradable waste		Slowly biodegradable waste		Total (RBW + SBW)	
	Rate of generation (m^3/yr)	Volume of gas (m^3)	Rate of generation (m^3/yr)	Volume of gas (m^3)	Rate of generation (m^3/yr)	Volume of gas (m^3)
2002	0.0000				0.0000	
		0.0000		0.0000		0.0000
2003	0.0000		0.0000		0.0000	
		0.0366		0.0008		0.0374
2004	0.0732		0.0016		0.0764	
		0.0641		0.0024		0.0665
2005	0.0549		0.0032		0.0598	
		0.0456		0.0041		0.0497
2006	0.0366		0.0049		0.0431	
		0.0273		0.0057		0.0330
2007	0.0183		0.0065		0.0264	
		0.0093		0.0073		0.0165
2008	0.0000		0.0081		0.0081	
		-		0.0077		0.0077
2009	-		0.0073		0.0073	
		-		0.0069		0.0069
2010	-		0.0065		0.0065	
		-		0.0061		0.0061
2011	-		0.0057		0.0057	
		-		0.0053		0.0053
2012	-		0.0045		0.0045	
		-		0.0045		0.0045
2013	-		0.0041		0.0041	
		-		0.0037		0.0037
2014	-		0.0032		0.0032	
		-		0.0028		0.0028
2015	-		0.0024		0.0024	
		-		0.0020		0.0020
2016	-		0.0016		0.0016	
		-		0.0012		0.0012
2017	-		0.0008		0.0008	
		-		0.0004		0.0004
2018	-		0.0000		0.0000	

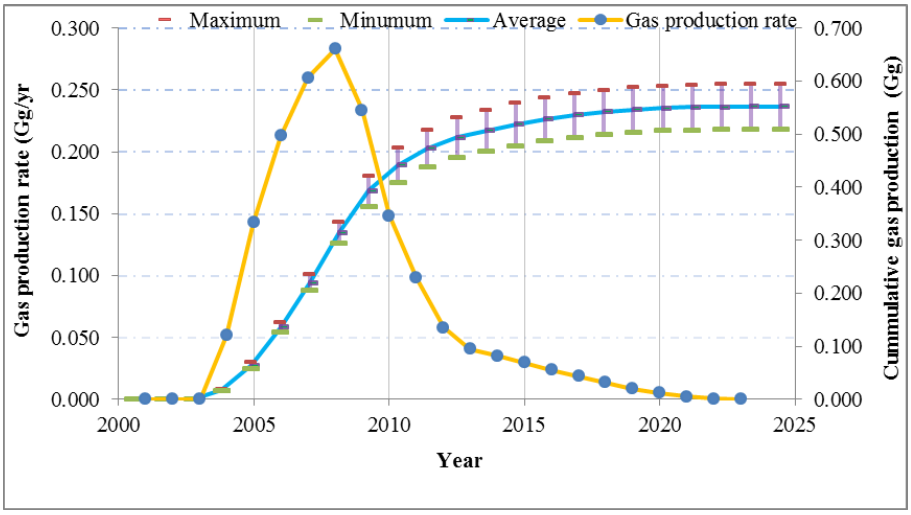

Fig. 5. Yearly and cummulative gas production rates

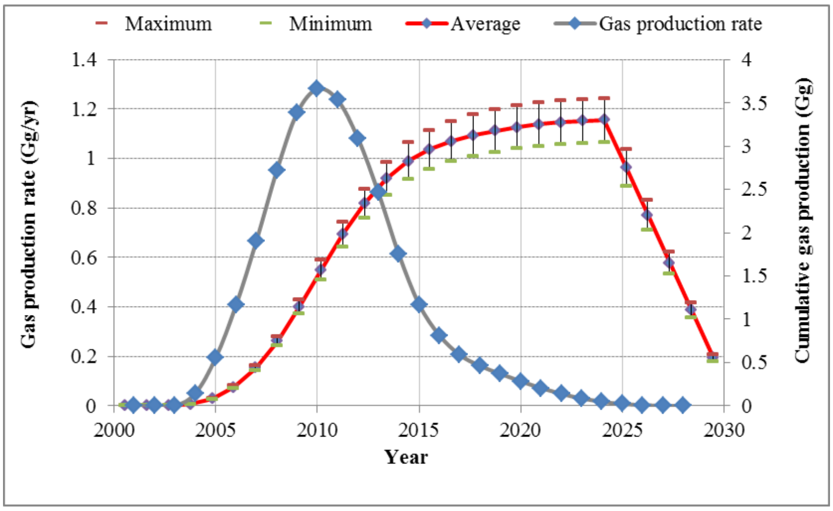

Fig. 6. Cumulative gas production

CONCLUSION

The triangular model has been used in this investigation to model the amount of landfill gas that could be emitted from the landfill. The values obtained are only for municipal solid waste deposited in the closed cell from 2002 to 2007. Since one of the assumptions was that equal amount of waste is deposited in the landfill we can extrapolate the yearly quantities of landfill gas that could be emitted. Because of the division of biodegradable organic waste into two – rapidly biodegradable waste (3 months – 5 years) and slowly biodegradable waste (up to 50 years), emission of landfill gases will continue for as long as waste continues to be deposited. Since methane is the primary component of natural gas and is therefore a rich energy source. This shows the potential of economic benefit if methane emission from municipal solid waste sites is reduced. The shorter atmospheric life of 11 years compared to 120 years for carbon dioxide (IPCC 1992) as well as its high potency gives the stabilisation of methane an immediate impact on climate change.

The high proportion of biodegradable organic matter increases the scope for the development of landfill gas collection system. Appropriate landfill gas utilisation programme based on the model will guide planners in the design of such a facility. It will be one of the measures to avoid the emission of these gases to the atmosphere.

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