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Gas Management and Energy Recovery from Municipal Solid Waste Landfill

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Abstract- Proper estimation of methane emission from municipal solid waste (MSW) landfill is essential for gas management. For developing countries where organic and inert portion in MSW are high, appropriate combination of the three models is proposed for estimation of landfill gas where Kolkata has been considered for case study. In Triangular model, 75% biodegradable portion of rapidly biodegradable waste and 50% biodegradable portion of slowly biodegradable waste is recommended. In IPCC model, degradable organic carbon and methane generation rate constant (*k*) in food waste are highly sensitive in total methane generation and recovery due to its higher percentage. In LandGem, suggested values of *k* is 0.1 y^{-1}; and methane generation potential (L_0) is 70 m^3 t^{-1}. Considering strength and weakness 40% weightage to Triangular and 30% each for IPCC and LandGEM is recommended as methane generation in these models is 5.06% less; 32.29% less and 37.35% more respectively from their average value (1,83,136 t) during year 2012-2021. For existing site flaring of methane is the suitable option. In case of proposed engineered landfill site, recovered methane and energy would be 5,53,410 t and 3.5×10^{10} MJ during 2022 to 2041 and 10 MW power plant could be supported for 20 years.

Index Terms- Municipal solid waste landfill; Methane recovery; LandGEM model; IPCC model; Energy recovery

1. INTRODUCTION

Solid waste placed in the landfills undergoes a number of simultaneous and interrelated biological, chemical and physical changes. Organic waste decomposition leads to the production of landfill gas (LFG) mainly consisting of methane (CH_4) and carbon dioxide (CO_2). According to Falzon, 1997 [1], methane production in landfills typically begins 6 to 12 months after waste placement, then rises to a maximum shortly after landfill closure and finally gradually declines over a period of 30-50 years. Now, it is of common understanding that LFG should be considered either as a significant source of pollution and risk if migrating uncontrollably to the air and ground, or as a potential environment-friendly renewable power source [2] . One ton of household waste has a methane gas production potential of 180 to 250 cubic meters over a period of 15 to 20 years [3-5]. There are two possible solutions for dealing with LFG emissions. In case of low methane ratios, LFG should be extracted and flared or oxidized in biofilters. On the other hand, in case of high methane content, LFG evidently becomes a valuable energy source, as it can be used to fuel engines producing electricity or generate thermal energy. More specifically, it can be used as a supplementary or primary fuel to increase the production of electricity, as a pipeline quality gas and vehicle fuel, or even for supply of heat and carbon dioxide for greenhouses and various industrial processes. Reported technologies that utilize LFG include internal combustion (IC) engines, gas turbines, fuel cells and boiler systems [6]. However, use of landfill gas may not be practical in all situations because of (i) high impurities: H_2S in landfill gas, cause corrosion in IC engine, (ii) low gas production rate from landfills, (iii) less organic content in landfills, (iv) high investment cost, (v) lack of skilled labour.

Clean development mechanism (CDM) is a project-based mechanism for promoting technology transfer and investment from developed countries to the developing countries to reduce the greenhouse gas (GHG) emissions [7]. Global warming is a worldwide problem that will affect both the developed and the less developed nations. Following energy and agriculture, landfill is the third biggest emission source of GHGs [8]. Landfills are estimated to account for around 13% of the total global anthropogenic methane emission which is equivalent to around 818 million metric tons of CO_2 ($MMtCO_{2}$-eq) [9]. According to the estimates from the GHG emission inventory in India in 1998, LFG generated a waste disposal site in India accounts for about 7 to 8% of the

GHG emission, being estimated to be 69 $MMtCO_2$.eq [10]. In addition to GHG reductions, the capture and use of landfill gas provides the ancillary benefits of limiting odors, controlling damage to vegetation, risk from explosions, fires and asphyxiation, and smog while providing a potential source of revenue and profit [11]. Despite these many benefits, landfill gas recovery is essentially an 'end of pipe' solution, which does not actively tackle the root cause of waste generation, unlike composting.

In developing countries, there are few cases where LFG is collected and treated because such projects require additional costs and have not been technically spread within the country [10]. Methane escaping from landfill sites will react with other pollutants in strong sunlight to produce ground level ozone and thereby contribute to photochemical smog [8]. Methane is explosive within the range of 5% to 15% concentration in air [9]. In previous decades, the United States environmental protection agency (USEPA) documented at least 40 explosions or fires caused by migrating landfill gas, including 10 accidents causing injuries or deaths. More recent accidents are less common due to better landfill gas management [12]. More importantly, this methane can travel through porous ground or layers of trash, appearing up to one kilometer away [13].

A landfill methane model is a tool that can be used to estimate methane generation rate, methane oxidation rate and total methane emission from landfill. Methods and models for predicting LFG generation first appeared in the early 1970's. In most of the developing countries the dominant disposal method is open dumping compared to the wide use of engineered landfills (ELF) in the western countries due to lack of finances of the Government, rapid population growth, and increasing urbanization [14-15]. In India approximately 90% of the generated waste in municipalities and urban areas are dumped in landfills, which have environmental impacts in the form of pollution to soil, ground water, air and contribution to global warming [16]. Nature of waste and management approach is almost similar throughout the developing countries therefore, Kolkata has been considered as a study area where MSW are disposed at Dhapa open dump site in ward number 58 under borough VII of Kolkata Municipal Corporation area. There is no gas recovery and controlling system and no detailed study has been carried out to know the amount of different gases generated from landfill. If landfill generated gases could be collected or flared it would have positive impact on the environment [17]. Purpose of this study is to suggest a proper approach for the estimation of methane generation, annual entrapment and its recovery that can be produced from existing open dump site and also from engineered landfill with phase wise closure facilities in developing countries. Proper estimation of methane considering waste characteristics and management in developing countries helps to find out an alternative renewable source of energy through the systematic recovery and utilization of municipal solid waste (MSW) landfill or generation of potential environment-friendly renewable power.

2. LANDFILL GAS GENERATION

Gas production is a function of many variables including physico-chemical composition of waste, environmental variables like pH, temperature, moisture content, nutrients, climate etc, and landfill methodologies. There are two stages in a landfill, its active stage, where MSW is being disposed of and other is its post closure period. The usual composition of landfill gas (% by volume) consists of about 47.7% methane, about 47.7% carbon dioxide, 0.1% carbon monoxide, 0.01% hydrogen sulphide, 0.5% trace components, 3.1% nitrogen, 0.8% oxygen and 0.1% hydrogen [18-19]. According to the EPA, methane is 21 to 25 times more efficient at trapping heat than carbon dioxide (CO_2). Nitrous oxide (N_2O) is 310 times more efficient than CO_2. Per fluorocarbons (PFCs) and hydro fluorocarbons (HFCs) have anywhere from around 1,000 to 10,000 times more potential than CO_2 [20].

In many landfills, the available moisture is insufficient to allow for the complete conversion of the biodegradable organic constituents in the MSW. The optimum moisture content for the conversion of the biodegradable organic matter in MSW is of the order 50 to 60%. Also in many landfills, the moisture that is present is not uniformly distributed. When the moisture content of the landfill is limited, the gas production curve is more flat and extends over a longer period of time. The production of landfill gas over extended periods of time is of great importance with respect to the management strategy to be adopted for post closure maintenance [19]. The variation in the rate of gas production from the anaerobic decomposition of the rapidly (five years or less – some highly biodegradable wastes are decomposed within days of being placed in a landfill) and slowly (5 to 50 years) biodegradable organic materials in MSW is shown in Fig.1. Following closure, a landfill continues to emit GHG, possibly for several hundreds of years [21]. Since in India, MSW contains more rapidly bio-degradable waste (RBW) and high moisture (~50%), therefore, after closure, effective gas generation period between 15 to 50 years is considered.

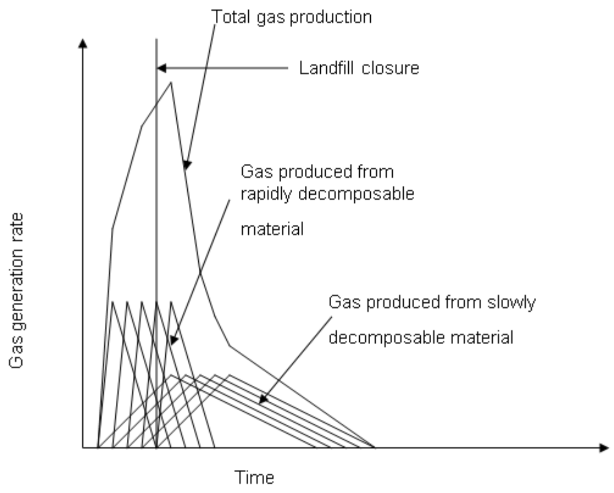

Fig. 1. Typical landfill gas generation rate from the rapidly and slowly decomposable organic materials

Landfill operators, energy recovery project owners and energy users need to assess the volume of gas produced and recovered over time from a landfill. Recovery and energy equipment sizing, project economics, and potential energy uses depend on the peak and cumulative landfill gas yield. The composition of the gas (percent methane, moisture content) is also important to energy producers and users. Proper landfill management can enhance both yield and quality of gas.

3. ANDFILL GAS LATERAL-MIGRATION AND RECOVERY

Lateral landfill gas migration through soil depends on various factors such as composition of waste, construction of landfills, climate, temperature, permeability and water content of the surrounding unsaturated zone and geological properties of surrounding strata. The methane oxidation is also an important factor. There have been some studies on landfill gas migration in soil and methane oxidation, but most were in temperate zone [22]. Boeckx and Cleemput, 1996 [23] examined the influences of moisture contents and soil temperature on the methane uptake capacity of the neutral landfill cover soil. Soil moisture contents of 10 to 25% w/w gave a maximum CH_4 oxidation rate. In wet condition, CH_4 consumption is slower because of limited gas diffusion. It is difficult to predict the gas migrating distance as it depends on many factors. Although distances greater than 1,500 m. have been observed, these are exceptional. More typically migration plumes extend for about 150 m.

Collection efficiency is a measure of the ability of the gas collection system to capture generated landfill gas. Since the gas generation rate from landfill cannot be measured directly, therefore it is estimated by mathematical models. Flare station records indicate that approximately 1% of the recovered gas is vented during routine and unscheduled maintenance annually [24]. Gas collection efficiency depends on type of disposal facility, collection system design, extent of collection system covers to waste volume, waste characteristics, collection system operation etc. Several practical factors influence the possibility of capturing the quantity of LFG generated. The most important are (i) LFG losses to the atmosphere through the surface or through lateral gas migration (ii) Pre-closure loss due to decomposition of organic material (iii) Boundary effects causing incomplete anaerobic decomposition of the near surface layer (e.g., air intrusion due to gas extraction) (iv) Other losses such as washout of organic carbon via leachate [25]. Achievable collection efficiencies for engineered landfill sites and open and controlled dumpsites are ~60-90% and ~30-60% respectively [26].

Most developed countries have policies that will constrain and potentially reduce future growth in methane emissions from landfills, such as expanded recycling and composting programmes, increased regulatory requirements to capture and combust LFG and improved LFG recovery technologies [27]. However, developing regions in Asia and Eastern Europe are projected to experience steady growth in landfill methane generation because of expanding populations, combined with a trend away from unmanaged open dumps to sanitary landfills with increased anaerobic conditions conducive to methane production [28].
Energy needs to be conserved to protect the environment from drastic changes, to save the depleting resources for future generations. Countries all over the world have started to ponder over a new energy policy with a possibility of having no or limited impact. Power generation from renewable energy sources results low carbon emissions but it needs high capital cost for setting up a plant. Non-renewable energy sources are available in nature only in limited amount in the form of fossil fuels, natural gas, oil and coal. These are apparently cheap, easy to use but can not be reproduced i.e. leads to resource depletion. These also cause global warming and serious health effect. Out of many forms of renewable energy, landfill gas to energy (LFGE) projects are win-win opportunities that create partnerships within the community, by involving citizens, non profit organizations, local governments and industry in sustainable community planning. These projects go hand-in-hand with community and corporate communities and lead to cleaner air, increased use of renewable energy, economic development, improved public welfare and safety, and reductions in GHGs [8].

4. STUDY AREA OF SOLID WASTE DISPOSAL SITE

Kolkata, capital of the state of West Bengal, is one of the four metropolitan cities in India. The city is centered on latitude 22^o 34' North and longitude 88^o 24' East. The city is approximately 30 km from the Bay of Bengal and river tides at Kolkata range over 4 m. Urbanization and industrialization influence the production of large quantity of city solid waste. Other cities in India, like Mumbai top the list with a population of 13.8 millions and daily MSW generation of 8000 t, Delhi 10 million and 6000 t, Chennai 5.8 million and 4000 t, Hyderabad 4.2 million and 2200 t [16].
Kolkata of about 187.33 sq.km Kolkata municipal corporation (KMC) area comprising of 15 boroughs and 141 electoral wards, has 9.1 million total population including floating population [29]. The total MSW generation is about 3000 t d^{-1}. Census by the Institute of Local Government and Urban Studies, report the decennial growth of population of Kolkata city from 1981 to 1991 as 6.61% and from 1991 to 2001 as 4.00% [30]. In case of floating population the increment considered is 2.15% per year. MSW acceptance from 2001 to 2011 is taken from computerized record of KMC and from 1987 to 2000 the same was calculated on the above basis. KMC operates two disposal sites, without having liner and leachate collection facilities that handle the city’s MSW. The existing Dhapa landfill site owned and operated by KMC is a 31.5 ha fill site in ward 58 of Borough VII. The site has been divided into an eastern disposal area (8.1 ha) which receives waste from KMC’s own vehicles, and a western disposal area (23.4 ha) which receives waste from KMC authorized private vehicles. Waste is deposited in an uncontrolled manner that has resulted in steep, unstable slopes, huge leachate accumulation within the waste mass and leachate runoff into nearby water bodies. Such

Table 1. Average physical composition of municipal solid waste [33]

	Recyclables				Others including inert						
Total Compos-tables	Paper	Plastic	Glass	Metal	Inert	Rubber and leather	Rags	Wooden matter	Coconut	Bones	Total
50.56	6.07	4.88	0.34	0.19	29.60	0.68	1.87	1.15	4.50	0.16	100.00
50.56	11.48				37.96						100.00

(All values are expressed in percentage on wet weight basis)

conditions limit both LFG generation and the potential for efficient LFG extraction. This facility receives more than 98% of the city's MSW. A small disposal site in Garden reach receives less than 2% of the city's waste where there is also no gas recovery and leachate collection system [17,31].

4.1. *Composition of municipal solid waste of Kolkata*

The physical and chemical compositions of MSW are shown in Table 1 and Table 2 [32-33].

Table 2. Characteristics and chemical composition of MSW at Kolkata during 2005 [33]

Sl. No.	Parameters	2005
1	Moisture	46
2	pH	0.3 – 8.07
3	Loss on ignition	38.53
4	Carbon	22.35
5	Nitrogen as N	0.76
6	Phosphorous as P_2O_5	0.77
7	Potassium as K_2O	0.52
8	C/N Ratio	31.81
9	Calorific value kJ kg^{-1}	5028

Biodegradable portion i.e., organic content is very high, recyclable portions are comparatively less and it has considerable quantity of inert materials which leads to overall low energy content [34].

In the existing system, major portion of recyclable materials (~9% of the total waste) are recovered by the informal sector of rag-pickers and the remaining portion is deposited in the landfill.

Deposited waste composition is considered for landfill gas generation. The composition of organic components (cellulose, proteins and lipids) affects the degradation of waste and as a result affects gas generation process. Presence of easily degradable organic carbon sources generates higher CH_4. Cellulose-to-lignin ratio (CLR) has an effect on CH_4 production and it has also a negative relation with age of solid waste samples which indicate that the older samples are methanogenically active [35]. Waste contains high amount of moisture which helps in higher rate of CH_4 production.

5. METHODOLOGY OF GAS EMISSION ESTIMATION

Several models to predict methane emissions originating from landfills have been proposed or are recommended by national governments. Landfill gas models can be broadly classified into zero-order, first-order, second-order, multiphase, or a combination of orders. The most common type of models use single-phase or multiphase first order kinetics that describe the decay of biodegradable waste and the production of methane. Most methane production models are based on MSW. They are therefore not much suitable for situations with lower amounts of organic waste. Emission model validation along with assumptions for extraction efficiency and methane oxidation has been carried out using LFG extraction field-data in most cases. Only two studies [36-37] have validated models using whole site methane emission measurements. Major uncertainties were introduced due to the differences between the default waste categories in the model and the actual data. The definitions of waste categories can differ between countries. A specific problem with former landfills is that very often the data on waste amounts and waste composition are not available. In that case assumptions have to be made that obviously increases the uncertainty of the estimate.

The EPER Germany, SWANA are zero order models in which CH_4 production rate is assumed to be constant against time. This assumption causes a vivid inaccuracy in the results [38,39]. First order models have a linear relation with maximum potential of CH_4 production per unit weight of waste as well as exponential relation with decay rate and time. In 1994, a study [40] was performed at several landfills in the Netherlands. Both first order and multi-phase models showed low mean relative errors in contrast to zero order models. On the basis of this study the Dutch government used the single-phase first order model to calculate national methane emissions from landfills. The Anglo-Welsh Environment Agency prefers Gas Sim, a first order multiphase model, LFG estimation [41]. Afvalzorg is also a first order multiphase model and based on Netherlands waste characteristics. LandGEM is recommended by the USEPA and the model is based on US waste composition, inert material and other non-hazardous wastes. It is user friendly in spreadsheet environment [42]. Complex mathematical models like Halvadakis [43] which follows the carbon in methane production chain from solid carbon to aqueous carbon, acidogenic and methanogenic biomass carbons, acetate carbon, carbon in CO_2 and then carbon in methane. Model is too difficult to be calibrated and used.

Landfill air emission estimation model [44], based on first order decay (FOD) reaction, is probably the most widely used model. Output of the model is compare reasonably well with more complex models and recommended by intergovernmental panel on climate change (IPCC) for calculating methane emissions from landfills [45]. Here, three models with their parameter characteristics and the default values are described individually.

5.1. ***Triangular model***

In this model, organic materials present in MSW of Kolkata (Table 1) is divided into two parts (1) rapidly bio-degradable materials (RBW) and (2) slowly bio-degradable materials (SBW) [46]. The annual rates of degradation for fast and slowly biodegradable materials are based on a Triangular model. The degradation rate for RBW usually reaches the maximum within the first two years and continues for around 5 years whereas SBW reaches its peak within 7 to 8 years and continues up to 15 years [19]. The biogas production is assumed to begin at the end of the first complete year of the landfill operation. LFG release is estimated based on the combination of the triangular forms of RBW and SBW and the area under the release curve would represent the gas released over the period (Fig. 1).

5.1.1. *Analysis of rapidly and slowly biodegradable waste*

Typical values of ultimate analysis [19] for RBW are shown in Table 3.

Table 3. Typical values of ultimate analysis of RBW

Component	Percentage (%)					
	C	H	O	N	S	Ash
Food waste	48.6	6.4	37.6	2.0	0.4	5.0
Paper	43.5	6	44	0.3	0.2	6

Table 4 shows chemical composition for the same. Chemical formula for rapidly biodegradable waste (RBW) is $C_{29.95}H_{47.03}O_{17.72}N\,S_{0.09}$.

Typical values of ultimate analysis and chemical composition of slowly biodegradable wastes (SBW) are shown in Table 5 and Table 6 respectively.
Chemical formula for slowly biodegradable waste (SBW) is $C_{34.62}H_{50.22}O_{18.78}N\,S_{0.03}$.

Table 5. Typical values of ultimate analysis of SBW

Component	Percentage (%)					
	C	H	O	N	S	Ash
Rubber and Leather	69	9	5.8	6	0.2	10
Wooden Matter	49.5	6	42.7	0.2	0.1	1.5
Coconut	49.6	6.1	43.2	0.1	0.1	0.9
Rags	55	6.6	31.2	4.6	0.15	2.5

Table 4. Analysis of weights and chemical composition of RBW (based on 100 kg MSW)

Component	Moisture Content (%)	Weight (kg)		Composition (kg)					
		Wet	Dry	C	H	O	N	S	Ash
Food Waste	72.50	50.56	13.904	6.757	0.890	5.228	0.278	0.056	0.695
Paper	6.00	1.07	1.006	0.438	0.060	0.443	0.003	0.002	0.060
Total		51.63	14.91	7.195	0.95	5.671	0.281	0.058	0.755

5.1.2. *Results of overall gas generation and CH_4 recovery*

The estimated gas production for rapidly and slowly biodegradable organic materials is shown in Table 7. This is based on considering the 75% biodegradable portion of RBW and the rest are not at all degradable

Table 6. Analysis of weights and chemical composition of SBW

Component	Moisture Content (%)	Weight (kg)		Composition (kg)					
		Wet	Dry	C	H	O	N	S	Ash
Rubber and Leather	5.0	0.27	0.256	0.177	0.0230	0.015	0.015	0.000	0.026
Wooden Matter	25.0	1.15	0.862	0.427	0.051	0.368	0.002	0.001	0.013
Coconut	40.0	4.5	2.700	1.339	0.165	1.166	0.003	0.003	0.024
Rags	10	1.87	1.683	0.926	0.111	0.525	0.077	0.002	0.042
Total		7.79	5.501	2.869	0.350	2.074	0.097	0.006	0.105

or very slowly degradable due to presence of non-biodegradable matter (lignin etc.). Due to the same reason, biodegradable portion for SBW is considered to be 50%. At the end of 15 years, total gas generation will be 0.150 $m^3 kg^{-1}$ of mixed waste (as discarded).

To estimate the total landfill gas production, waste deposited material from 1987 to 2011 is taken. Year 1987 is the landfill starting year and the landfill is assumed to be closed in 2011. One year is required to provide top cover and installation of gas extraction facilities so, gas entrapment starts from 2012. The effective extraction period for 10 years after the closure of the landfill is used in estimating methane generation and recovery. This is based on the fact that the majority of gas generation is in the first 10 years of total 15 years of effective gas production period.

Table 7. Gas production rate of RBW and SBW

End of year	Gas production in $m^3 kg^{-1}$ of dry weight in 1 year	
	RBW	SBW
0	0	0
1	0.214	0.0148
2	0.3745	0.0444
3	0.2675	0.074
4	0.1605	0.1036
5	0.0535	0.1332
6	0	0.1406
7	0	0.1258
8	0	0.1110
9	0	0.0962
10	0	0.0814
11	0	0.0666
12	0	0.0518
13	0	0.0370
14	0	0.0222
15	0	0.0074
Total	1.07	1.11

Same time period for waste deposition (1987-2011) and recovery (2012-2021) is considered for other models. From Fig. 2 it is observed that total CH_4 generation from 1987 to 2021 is 12,27,014 t and total methane entrapment will be 1,73,871 t.

Considering 50% recovery for open dump site, total 86,936 t methane can be recovered up to 2021 i.e. 10 years after closure and amount of GHG reduction likely to be 18,25,656 tCO_2.eq.

5.1.3. *Sensitivity analysis*

A sensitivity analysis is performed to estimate the total gas production by changes in biodegradable fraction in RBW and SBW. If 70% biodegradable waste in RBW and 40% biodegradable waste in SBW is considered, then the total gas generation for 15 years period is 0.135 $m^3 kg^{-1}$ of mixed waste (as discarded). In case of 80% biodegradable in RBW and 60% biodegradable waste in SBW, the same generation will be 0.163 $m^3 kg^{-1}$.

5.2. *IPCC model*

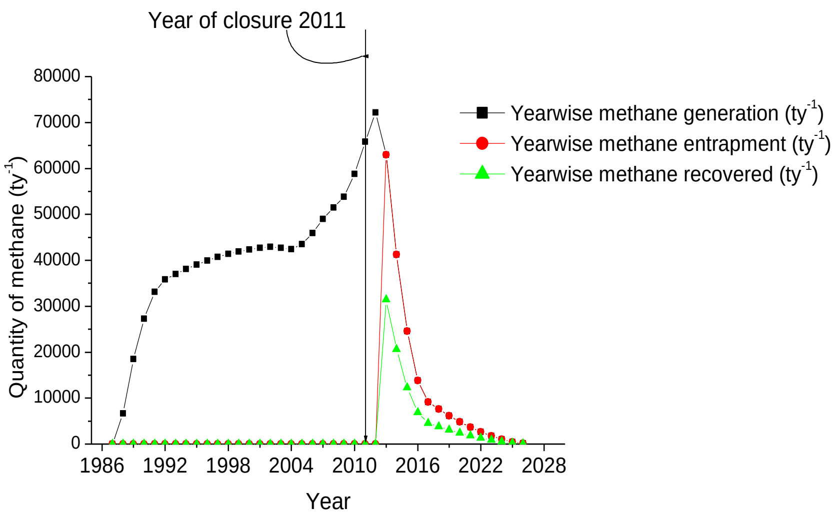

Fig. 2. Year wise methane generation, entrapment and recovery from existing Dhapa landfill site following Triangular model

The amount of methane generated at the landfill is estimated, using FOD model in spreadsheet, presented in the IPCC guideline [47]. The estimation formula of FOD model is described below. FOD model calculates the amount of methane generated with assumption that the rate of generation is proportional to the amount of reactant remaining, in this case the mass of degradable organic carbon decomposable under anaerobic conditions. In FOD model, at the end of the year *T* at the landfill, the mass of organic carbon remaining and the mass of degradable organic carbon is worked out. In addition, the amounts of accumulation and decomposition of decomposable degradable organic carbon each year is calculated. Based on these, the decomposable degradable organic carbon (DDOC) entering the solid waste disposal site is calculated in accordance to each category of waste (e.g. food waste, paper/cardboard, park and garden waste and wood). The amount of methane generated from the decomposable degradable organic carbon is calculated by the following equation:

$$\mathbf{CH_4\ generated_T} = \mathbf{DDOC_{m \cdot decomp_T}} \times \mathbf{F} \times \left(\frac{\mathbf{16}}{\mathbf{12}}\right)$$

Where,
$CH_4\ generated_T =$ amount of CH_4 generated from $DDOC_m$ decomposed in year T ($DDOC_{m \cdot decomp_T}$) in Gg;
$F =$ fraction of CH_4 by volume, in generated landfill gas;
$\left(\frac{16}{12}\right) =$ molecular weight ratio of $\left(\frac{CH_4}{C}\right)$

disposal site, and then CH_4 oxidized to carbon dioxide in the cover layer.

$$\mathbf{CH_4\ emitted_T} = \left(\sum \mathbf{x} \,.\, \mathbf{CH_4\ generated_T} - \mathbf{R_T}\right).\ (\mathbf{1} - \mathbf{OX_T});$$

Where,
$CH_4\ emitted_T = CH_4$ emitted in year T, in Gg;
$x =$ waste type/material or waste category;
$R_T =$ recovered in year T , in Gg;
$OX_T =$ Oxidation factor in year T (fraction).

5.2.1. *Selection of parameters*

Since the mean annual temperature is above 20^0 C and mean annual precipitation is more than 1000 mm in Kolkata city, therefore, the parameters applicable to moist and wet tropical climate presented in the IPCC Guidelines are considered. In this case the fraction of degradable organic carbon is considered as food waste: 0.15; paper: 0.4; wood and straw: 0.43; textiles: 0.24 and the methane generation rate constant (*k* in y^{-1}) are set as food waste: 0.4; paper: 0.07; wood and straw: 0.035; textiles: 0.07. Methane content in landfill gas is assumed as 50%. Delay time 6 months, conversion factor, C to CH_4 1.33, and the fraction of methane gas oxidized to carbon dioxide are not taken into account due to absence of daily or intermediate cover.

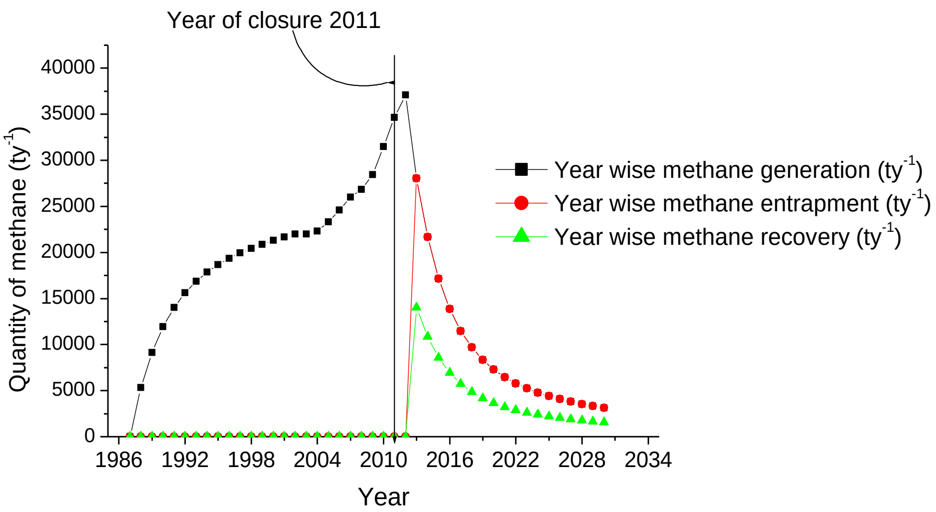

Fig. 3. Year wise methane generation, entrapment and recovery from existing open dump site following IPCC method

The CH_4 generated by each category of waste disposed is added to get total CH_4 generated in each year. Finally, emissions of CH_4 are calculated by subtracting first the CH_4 gas recovered from the

5.2.2. *Results of overall gas generation and CH4 recovery*

As per IPCC method, the estimated methane generation from 1987 to 2021 is found 6,56,000 t; methane entrapment and recovery for the period 2012 to 2021 are 1,24,000 t and 62,000 t respectively as shown in Fig. 3. GHG reduction will be 13,02,000 tCO_2-eq and for existing system total emission of CH_4 up to 2021 will be 1,24,74,000 tCO_2-eq.

5.2.3. *Sensitivity analysis*

A sensitivity analysis is conducted by means of certain variations of degradable organic carbon (DOC) in respect of default values of DOC: 0.15 for food waste, DOC: 0.40 for paper and DOC: 0.43 for wood, to find out the effect of methane gas generation and recovery from individual waste category and to the total gas generation and recovery. If DOC for food waste is considered 0.08, methane generation and recovery of food waste reduces by ~47% and total methane generation and recovery reduces by ~27% and ~17% respectively with respect to the default value. For DOC value of 0.2, individual methane generation and recovery increases by ~34%, total methane generation and recovery increases by ~19% and ~12% respectively. So effect in totality is significant due to higher percentage of rapidly degradable food waste. In case of variation of DOC in paper at 0.36 and 0.45, individual methane generation and recovery reduces by ~10% for the earlier and increases by ~12.5% for the later. However, there are no significant changes of variation in total methane generation and recovery (± 0.3% to ± 0.6%) because of lesser of paper percentage in waste composition. For wood, if DOC value is taken at 0.39, individual methane generation and recovery decreases by ~9.3% and if it is 0.46 then the value increases to 7%. However, total methane generation and recovery differs with less than 2% but higher than paper as its degradation rate is slower than the paper.

A sensitivity analysis is also carried out by means of certain differences of methane generation rate constant (k) i.e. k = 0.17 y^{-1} (half life durations: 4 years); k = 0.7 y^{-1} (half life durations: 1 year) in respect to default value of k = 0.4 y^{-1} (half life durations: 1.75 years) for food waste, similarly k = 0.06 y^{-1} (half life durations: 12 years); k = 0.085 y^{-1} (half life durations: 8 years) in respect to default value of k = 0.07 y^{-1} (half life durations: 10 years) for paper, likewise k = 0.03 y^{-1} (half life durations: 25 years); k = 0.05 y^{-1} (half life durations: 15 years), in respect of default value of k = 0.035 y^{-1} (half life durations: 20 years) for wood to evaluate the outcome in individual and overall methane generation and recovery. Half-life of the materials is related to the reaction rate (k) of the model through the equation: $\boldsymbol{k = t_{1/2}^{-1}.\ln 2}$.

According to the results, for methane generation rate constant variations of k = 0.17 y^{-1} and 0.7 y^{-1} for food waste, individual and total methane generation decreases by ~5.2% and ~3% for the first and increases by ~0.3% and ~0.2% for the later. But methane recovery from individual and total food waste significantly increases by ~77% and ~28% for the first along with decreased in recovery by ~46% (individual) and ~17% (total) with respect to the default value (k = 0.7 y^{-1}). Significant quantity of food waste is found in total waste. It is a rapidly biodegradable waste but if its half life increases i.e., degradation rate decreases, then remaining substantial amount of food waste in the landfill site are responsible for increased gas generation even after closure.

Regarding paper, individual and total methane generation decreases by ~7% and ~0.2% and recovery decreases by ~3% and ~0.2% for k = 0.06 y^{-1} with respect to the default value (k = 0.07 y^{-1}). Similarly for k = 0.09 y^{-1}, individual and total methane generation increases by ~10.5% and ~0.3% whereas recovery increases by ~2% and ~0.1%. The effect on methane recovery is very less as the amount of paper is small in comparison to the other materials. For k = 0.05 y^{-1} methane generation from wood only and total increases to 18.6% and 2.3% along with methane recovery increases by 13.2% (individual) and 3.2%

Table 8. Effect of composition variation on methane generation and recovery

% variation w.r.t. total waste	Individual changes in methane generation and recovery	Changes in total methane generation	Changes in total methane recovery
Food waste (± 1%)	± 2.3%	± 1.4%	± 0.85%
Wood (± 1%)	± 15.9%	± 1.9%	± 3.9%
Paper (± 1%)	± 84.0%	± 2.7%	± 4.5%

(total) respectively. Shorter half life of wood, i.e. 15 years instead of 20 years, contributes more methane in 10 years recovery period. Similarly for k = 0.03 y^{-1}, methane generation decreases by 14.3% for wood with respect to default value and 1.73% in total, along with methane recovery decreases to 11.7% (individual) and 2.8% (total).

Sensitivity analysis is also done by means of certain variations (in %) in composition of food waste, wood, and paper as shown in Table 8. In composition, food waste is too high (~50%) but it has low DOC (0.15). Due to its rapid biodegradability, methane generation is initially high for first five years from the deposition of waste but less amount of methane can be captured or recovered if the active period is more. Wood and paper are slowly biodegradable wastes with high DOC values (0.43) and (0.40), so, degradation rate is slow and significant methane generation will last for many years. Individual changes of methane generation and recovery is high because of higher percentage of carbon i.e., high DOC value but there is no major changes in total methane recovery as its quantity is very less in MSW.

5.3. *LandGEM model*

USEPA landfill gas emission model (LandGEM) is widely used for the estimation of methane from degradation of solid wastes in the waste disposal site with time. LandGEM model can be used as screening tool with clean air act (CAA) default values to calculate expected minimum emissions for the purpose of determining the applicability of regulations to a landfill. The model is based on first-order decay reaction in waste biodegradation and methane generation as shown in equation: $\mathbf{Q = L_0 . R . (e^{-kc} - e^{-kt})}$;

where Q =methane generated in current year (m^3 y^{-1}), L_0 =methane generation potential (m^3 t^{-1} waste), R =average annual waste acceptance rate during active life (t y^{-1}), k = methane generation rate constant (y^{-1}), c = time since MSW landfill closure (y), t = time since MSW landfill opened (y) [35].

5.3.1. *Selection of parameters*

Methane generation potentials (L_o) of 103.7, 121.4 and 60.7 m^3 t^{-1} of waste were determined experimentally and used for Bangkok, other municipalities in case of landfill site and open dump site respectively [48] as those were determined experimentally. The first-order decay rate constant k, 0.05 y^{-1} was recommended for developing countries [44]. The CAA default methane generation rate constant k value is 0.05 y^{-1} which corresponds to a half-life of about 14 years and default L_0 is 170 m^3 t^{-1}. However, the model can also be used with user-defined parameters based on site-specific data and waste composition [49]. A higher k value (0.1 y^{-1} for 7 year half-life) is applicable for high moisture conditions and rapidly degradable materials such as food waste consistent with Kolkata conditions and MSW characteristics. The methane generation capacity (L_0 = 70 m^3 t^{-1}) should be reduced for Kolkata waste having high inert and moisture content and less wood and paper [31,50].

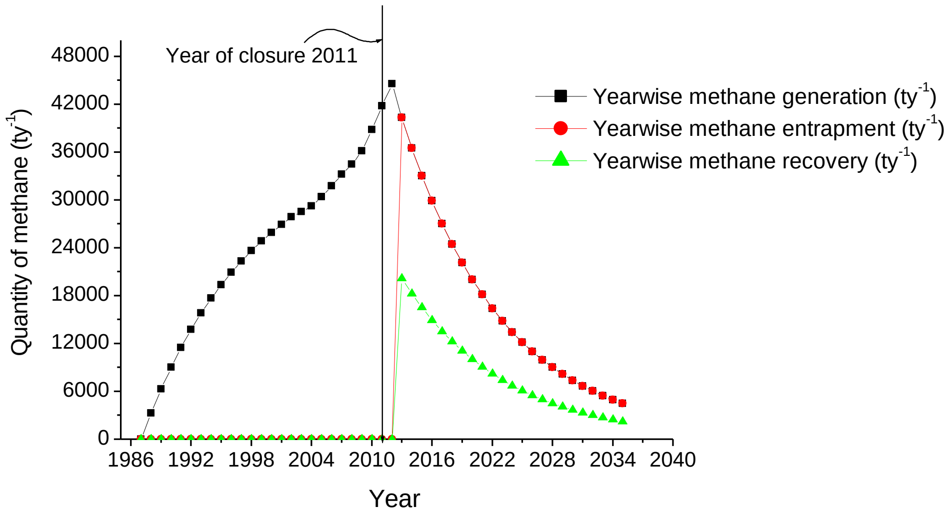

Fig. 4. Year wise methane generation, entrapment and recovery from open dump site Dhapa following LandGEM method

5.3.2. *Results of overall gas generation and CH_4 recovery*

As per LandGEM model, estimated methane generation, entrapment, recovery and emission from existing open dump site, Dhapa are shown in Fig. 4. Considering k = 0.1 $y^{-1}$and L_0 = 70 m^3 t^{-1}, quantity of CH_4 generation (1987-2021); CH_4 entrapment and recovery for the period of 10 years (2012-2021) are estimated as 8,69,570 t; 2,51,537 t and 1,25,769 t respectively. Compare to other models in LandGEM, CH_4 generation will continue for some more time after closure; however after 15 years of closure methane generation will have decreased. If recovery period is increased to 15 years, ~27% more methane recovery can be achieved. Quantity of GHG reduction would be 26,41,149 tCO_2-eq. For existing system 1,56,19,821 tCO_2-eq will be emitted from open dump site Dhapa and contribute to the climate warming.

5.3.3. *Sensitivity analysis*

Keeping the same methane generation rate constant, if L_0 is varied from 68 to 72 m^3 t^{-1} then the amount of CH_4 generation and CH_4 recovery varies between 2% to 3%. If k = 0.05 y^{-1} and L_0 = 70 m^3 t^{-1} are taken for CH_4 estimation then its generation will be on an average ~26% less and also its recovery will be reduced by ~10% compared to assumed values (k = 0.1 y^{-1}; L_0 = 70 m^3 t^{-1}) due to lower degradation rate. A disadvantage of LandGEM is that it can not differentiate the various types of organic matter as well as inert materials. Since the gas generation in LandGEM model is very much dependent on L_0 and k, therefore, these values should be considered based on the MSW characteristics and site conditions.

5.4. ***Power generation and CDM benefit***

Triangular, IPCC and LandGEM models are compared; average value of methane generation after closure from year 2012 to 2021 is found 1,83,136 t. It is observed that, methane generation in Triangular, IPCC and LandGEM model is 5.06% less, 32.29% less and 37.35% more from average value respectively. As Triangular model is considered based on site specific RBW and SBW composition of MSW, therefore it results close to the average value. IPCC is widely used model for methane generation for CDM benefit. As it is a conservative model to ensure the profit from CDM benefit it possibly predicts a lower value. LandGEM is also equally used for calculation of the gas generation but it is much sensitive to L_0 and k values. Absence of site specific L_0 value may lead to large gas generation deviation. So, the gas generation from MSW in the developing country like India, where bio-degradable and inert wastes are high, 40% weightage to Triangular model and 30% each for IPCC and LandGEM model is recommended. Considering the said combination of the three models, estimate of total CH_4 generation (1987-2021), CH_4 entrapment (2012-2021) and CH_4 recovery (50% for open dump site) will be ~9,48,477 t; ~1,82,210 t; and ~91,105 t respectively and if it is flared then the certified emission reduction (CER) will be 19,13,205 tCO_2-eq.

5.4.1. *Benefit from existing open dump site*

Two technical options, power generation and flaring, are compared. Electrical power generation with IC engines or gas turbines is the most common practice for landfill gas-to-energy application. Projects are set up according to the perceived electrical power

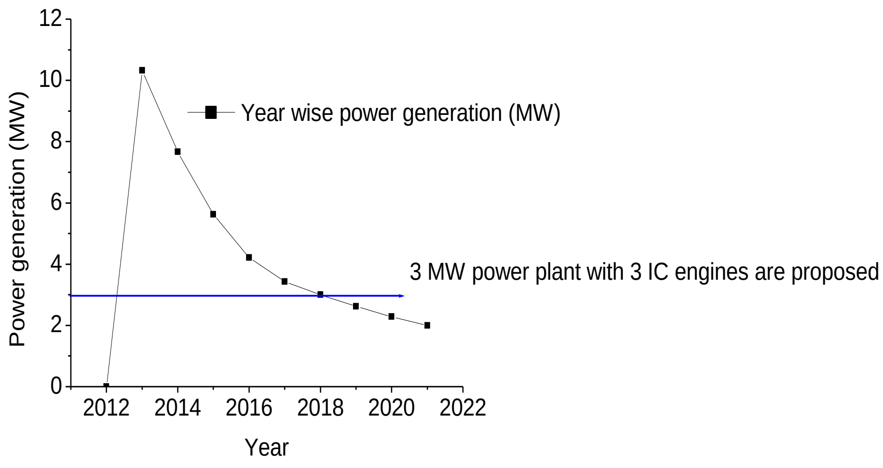

Fig. 5. Proposed power generation from existing open dump site, Dhapa

generation capacity and the number of generating units. If landfill gas production is insufficient to support at least one MW of power generation, it is generally deemed economically unsuitable. IC engines are typically used at sites capable of producing less than 3 MW [27] and three to five engines are usually employed per project. However, one or two turbine units are preferred at landfills, where gas quantity can support more than 3 MW [50].

It is calculated, after scientific closure of the existing Dhapa disposal site, 5×10^9 MJ energy can be recovered and utilized within the specified period of 10 years. For calculation of power generation from existing system, energy content of methane as 55.7 kJg^{-1}, heat rate for IC engines as 12,000 BTU per kWh and 90% annual capacity factor are considered [27]. As methane generation from the waste disposal site could rapidly decrease, it is not appropriate to install a generator with large capacity; hence installed capacity will be limited to 3 MW (Fig. 5).

In consideration of techno economical viability in Kolkata, earlier study [10] showed that cost of power generation in this range is not a profitable option. Therefore, as a CDM project, methane combustion by a flare system is preferred. In the case of flaring system, economic profits are summarized in Table 9 for the project crediting period of 10 years.

The estimated engineering, procurement and construction (EPC) costs (assuming 20% escalation cost for 5 years on the estimated cost of 2007) [10] include (i) engineering, legal, commercial, accounting and professional services; (ii) well field installation cost; (iii) flare station installation etc. Estimated annual costs of operation, maintenance and monitoring (O&M cost) includes (i) well field maintenance @ 3% of well field cost; (ii) flare station maintenance @ 2% of flare station cost; (iii) electricity (0.02 kWh per cubic meter of landfill bio-gas); (iv) operating labor and security; (v) management and administration; (vi) testing and instrument maintenance and calibration; (vii) insurance, licenses and fees; (viii) professional services etc. [51]. Average market price of CER through the project period is assumed \$7. Project profit of KMC is estimated according to its 50% investment of the EPC cost. The project profit of KMC, apart from environmental benefit, is around 10.2 crores for 10 years.

5.4.2. *Benefit from proposed ELF*

For future case, it is considered that if the existing open dumping system with one phase is modified as an engineered landfill (ELF) site in two phases, of which first phase will be closed after first 10 years (2012-2021) and the second phase will be used for the next 10 years (2022-2031), then methane recovery percentage will increase compared to open dumping system. In case of proposed engineering landfill site, same combination of three models is also applied to estimate year wise generation, entrapment and recovery of methane as shown in Fig. 6.

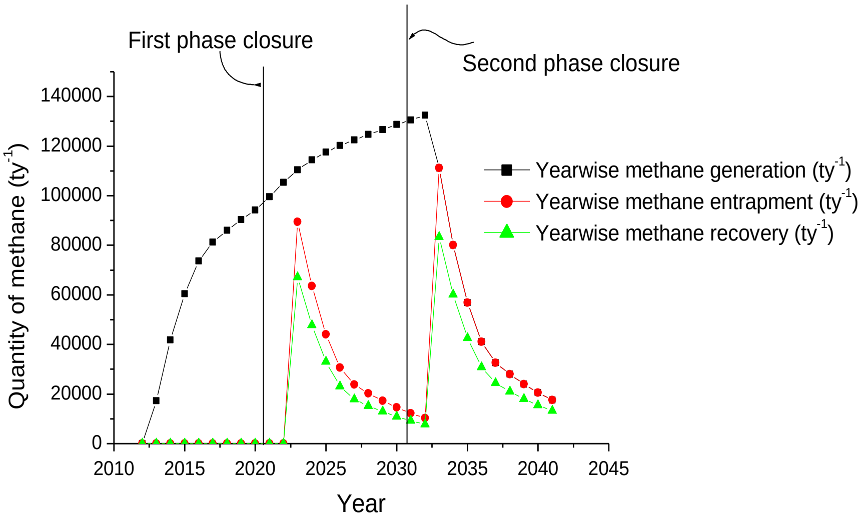

Fig. 6. Year wise generation, entrapment and recovery of methane from proposed engineered landfill site

Table 9. Summary of KMC profit for 10 years from existing site Dhapa

Project Income	Total CER (tCO_2-eq)	19,13,205
	Market price (INR/ tCO_2-eq)	364
	Total income	6,96,407
Project Expenditure	Capital cost (EPC cost + CDM set up cost)	2,26,842
	O&M cost	1,19,290
	Total expenditure	3,46,132
Project Profit	Profit before tax	3,50,275
	Tax (41.82%)	-1,46,485
	Profit after tax	2,03,790
KMC Income	Project profit 50%	1,01,895

Unit: in thousand INR except otherwise mentioned (1 US $=INR 52)

Year wise capture of gas in first ten years will be nil, then initiation of gas recovery will be started from first phase and continue. It will also be done from the second phase after closure, i.e. end of 20 years. Thereafter, it gradually diminishes with time elapsed. For the 1st 10 years (2022-2031) CH_4 recovery will be 2,36,880 t from the 1st phase and after closure of the 2nd phase recovery will be 3,16,530 t for the next 10 years (2032-2041). If phase wise system is not adopted then CH_4 recovery from the 1st phase will not be possible and additional 49,74,480 tCO_2-eq likely to be emitted in the environment which contributes to global warming. Since 75% gas recovery is considered for proposed ELF site, therefore, 5,53,410 t methane (year 2022 to 2041) can be captured and 3.5×10^{10} MJ energy would be available from it.

As this is a future project having phase wise closure facilities of engineered landfill site and greater methane capture rate achieves higher CER value (1,16,21,610 tCO_2-eq for 20 years) and higher energy generation.

Average possible power generation for 20 years will be 12.5 MW, therefore considering its techno economical viability, 10 MW power can be recommended.

6. CONCLUSION

Triangular, IPCC and LandGEM, landfill gas emission models are used for the estimation of the landfill gas emission rates from existing open dumping system and also from proposed ELF with phase wise closure facilities. The success of a LFG-to energy project is highly dependent to an accurate and timely estimation of the produced LFG, as an overestimation may lead to its failure. This estimation depends on the accuracy of the selected model, the quality of available data and the selection of correct coefficients. So for developing countries, where organic and inert portion in MSW are high, appropriate combination of the three models is proposed for estimation of landfill gas. Sensitivity analysis is conducted to examine and specify the effect of the selected coefficients to be arrived at more representative assessed landfill gas generation. In Triangular model, 75% biodegradable portion of RBW and 50% biodegradable portion of SBW is recommended. In IPCC model, DOC and k value in food waste are highly sensitive in total methane generation and recovery due to its higher percentage. In LandGem model, suggested values of k and L_0 are 0.1 y^{-1} and 70 m^3 t^{-1} respectively.

Site specific composition of MSW for Triangular model results close to the average value. As IPCC is a conservative model to ensure the profit from CDM benefit, it usually gives lower value. LandGEM is very much sensitive to L_0 and k values and compare to other models, CH_4 generation will continue for some more time after closure, which predicts higher recovery. So, the gas generation from MSW in the developing countries, where bio-degradable and inert wastes are high, 40% weightage to Triangular model and 30% each for IPCC and LandGEM model is recommended. This approach can also be adopted to find out suitable combination of different models for appropriate estimation of CH_4 generation and energy recovery in developed countries according to their waste characteristics and management.

For existing system, 5×10^9 MJ energy can be recovered for 10 years period after scientific closure of the existing open dump site, Dhapa, and installed plant capacity would be limited to 3 MW. So, for developing countries, flaring of methane is the suitable option because of its economic and commercial viability. Introduction of the engineered landfill with phase wise closure facilities for proposed project results 75% gas recovery efficiency and ~75% more methane recovery. If phase wise operation and closure is not adopted then additional 49,74,456 tCO_2-eq is likely to be emitted in the environment which contributes to global warming. From proposed ELF having CER value of 1,16,21,610 tCO_2-eq, 3.5×10^{10} MJ energy likely to be available and 10MW power plants could be supported for 20 years (year 2022 to 2041). Local benefits of this project include better managed landfill sites through reduced odors and explosion risks, employment opportunities and increased electricity supply, and reduced GHG emissions.

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