

Qualitative assessment of methane emission inventory from municipal solid waste disposal sites: a case study

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Abstract

In developing countries like India, urban solid waste (SW) generation is increasing enormously and most of the SWs are disposed off by land filling in low-lying areas, resulting into generation of large quantities of biogas. Methane, the major constituent gas is known to cause global warming due to green house gas (GHG) effect. There is a need to study the ever-increasing contribution of SW to the global GHG effect. To assess the impacts, estimation of GHG emission is must and to avoid misguidance by these emission-data, qualitative assessment of the estimated GHG is a must. In this paper, methane emission is estimated for a particular landfill site, using default methodology and modified triangular methodology. Total methane generation is same for both theoretical methodologies, but the modified triangular method has an upper hand as it provides a time-dependent emission profile that reflects the true pattern of the degradation process. To check the quality of calculated emission-data, extensive sampling is carried out for different seasons in a year. Field results show a different trend as compared to theoretical results, this compels for logical thinking. Each methane emission-data is backed up by the uncertainty associated with it, this further strengthens the quality check of these data. Uncertainty calculation is done using Monte Carlo simulation technique, recommended in IPCC Guideline. In the due course of qualitative assessment of methane emission-data, many site-specific sensitive parameters are discovered and are briefly discussed in this paper.

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1. Introduction

Globally, efforts are being made to control greenhouse gas (GHG) emission from various sources, waste sector is one of them. Methane gas liberating from landfill is a serious threat to our environment as its global warming potential is more than 20 times of that

of carbon dioxide (CO₂). Methane emission from landfill is estimated to account for 3–19% of the anthropogenic sources in the world (IPCC, 1996). But unfortunately solid waste (SW) management is much neglected and the maintenance of record in this respect is poor, in India.

To improve upon this pathetic condition, an attempt is made for qualitative assessment of the methane emission-data at Okhla landfill site in Delhi (India). This study also attempts to point out the shortcomings, in Indian Sanitary landfill management and record keeping. Three methods are employed to estimate the methane emission, two of them are theoretical (viz.

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default and triangular) and the third is field investigation. After determining emission with all three methods, uncertainty associated with methane estimation is also calculated as a part of qualitative assessment.

Scientists have been recognizing the importance of qualitative assessment for emission inventories. Quality assurance/quality control (QA/QC) and uncertainty estimation in national GHG emission inventories have become part of the IPCC good practice guidance (IPCC, 1996). Only few countries such as UK (Charles et al., 1998), Norway (Rypdal, 1999; Rypdal and Zhang, 2000), The Netherlands (van Amstel et al., 2000), USA (EIA, 1999) and Austria (Winiwarter and Rypdal, 2001) have prepared such uncertainty estimates at different levels. There exist only a handful of studies, which actually approach uncertainties in inventories (e.g. Winiwarter, 1993; Beck et al., 1995; Kuhlwein and Friedrich, 2000) or their impact to atmospheric models (Hanna et al., 1998).

2. SW management in India

In Indian urban centres, municipality is responsible for SW management and is a labour oriented activity due to financial constraints and lack of trained staff municipalities do not maintain proper records.

The waste quantity and composition varies quite often due to cultural practices, seasonal variations, food habit, methods and frequency of waste collection, ragpicker's activity, waste burning, etc. Majority of municipal agencies do not weigh their SW vehicles but estimate the quantities on the basis of the number of trips made by the vehicles. This is not at all reliable because of the change in density of the SW. Hence; it is difficult to deterministically estimate the quantity and composition of waste reaching disposal sites (Shekdar, 1989). At disposal site, uncontrolled dumping is observed and leveling and provision of earth cover are rarely provided. The ragpickers are further observed to be active at disposal site.

The methane emission from municipal SW landfills depends on quantity and composition of SW reaching landfill sites and other landfill details which municipality do not maintain, thereby leading to unreliable methane emission-data.

3. Generation of landfill gases (LFG)

The generation of LFG is found to occur in five, more or less sequential phases, namely initial adjustment phase, transition phase, acid phase, methane fermentation phase and maturation phase. In Phase-I, aerobic decomposition occurs and CO₂ is generated. As the oxygen (O₂) in the trapped air reduces, Phase-II, i.e.

transition phase starts and anaerobic condition developed. In Phase-III, the reaction is strictly anaerobic. At the end of Phase-III, methane formers come into existence and then it continues up to Phase-V. The principal gases produced are methane and CO₂. The oxidation/reduction potential in the range of –150 to –300 mV is an indicator of methane production. The rate of LFG generation diminishes significantly in Phase-V (maturation phase) because most of the available nutrients have been removed with the leachate during the previous phases, and the substrates that remain in the landfill are slowly biodegradable.

4. Factors affecting LFG generation

LFG is generated by degradation of biodegradable fraction and is influenced by physico-chemical composition of waste and environmental variables. The environmental variables affecting methane generation includes, pH, temperature, moisture, nutrient, etc. Most of the landfills are not provided with capping and compaction is not followed; due to this aerobic zone varies. The values of pH vary with the depth of filling, indicator of aerobic/anaerobic reaction. There is a lot of variation in the LFG emission due to hydrogeology of the site and the methods of landfill (i.e. open dumping or sanitary landfill).

Hence, it is necessary to account for the variables associated with the estimation of LFG emission at the site as compared to theoretical estimation. The knowledge of the biological process in the landfill is very important for proper choice of method for methane estimation (Shekdar, 1993).

5. Okhla landfill site

The site is well maintained as per Indian condition, having past data on SW quantity for some years. The area of Okhla landfill site is 14.95 ha (32 acre). The Okhla landfill site has been in operation since August 1994. The waste quantity handled by Okhla site during 1994–2001 is presented in Table 1. The waste for 1994–1996 is extrapolated. The inert material that does not produce gas is subtracted to get the total biodegradable waste i.e. 3311.867 Gg.

Methane emission will depend on the year wise generation of SW, manner in which these wastes are dumped and the structural features of the site. The structural features of the site are shown in Fig. 1 along with the sampling area. As inferred from the figure, the wastes are deposited at the extreme end of the landfill site (near cargo). The height of landfill above the ground level open to air is 15–18 m at the end and decreasing to 3–5 m at the entrance gate.

Table 1
Quantity of SW reaching Okhla landfill site

S. No.	Year	Domestic (Gg)	Inert (Gg)	Others (Gg)	Total (Gg) (excluding inert)	Total waste (Gg)
1	1994	152.040 ^a	21.786 ^a	24.228 ^a	176.268 ^a	198.054 ^a
2	1995	364.894 ^a	52.286 ^a	58.148 ^a	423.042 ^a	475.328 ^a
3	1996	374.344 ^a	57.250 ^a	56.044 ^a	430.388 ^a	487.638 ^a
4	1997	399.140	81.000	50.340	449.480	530.480
5	1998	392.000	65.352	95.975	487.975	553.327
6	1999	398.616	39.488	30.216	428.832	468.320
7	2000	395.448	60.480	59.202	454.650	515.130
8	2001	375.120	135.564	86.112	461.232	596.796
	Total	2851.602	513.206	460.265	3311.867	3825.073

^aExtrapolated from years 1997 to 2001.

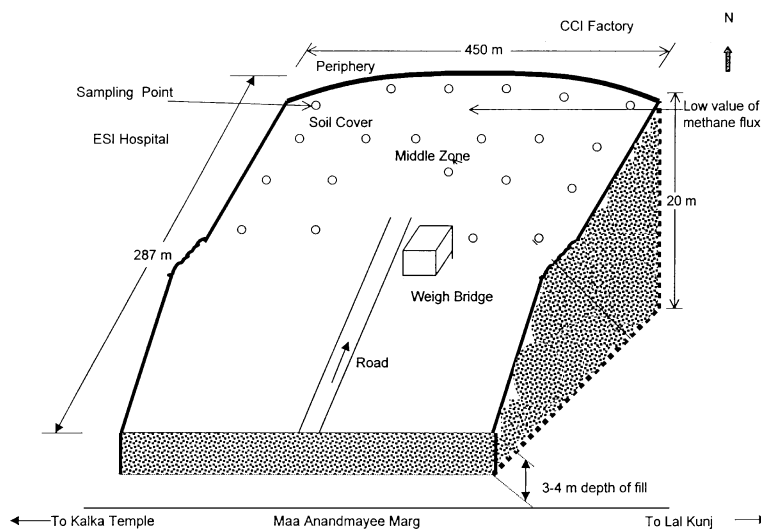


Fig. 1. Structural features highlighting sampling points of Okhla landfill site, Delhi.

6. Methods for methane quantification

The estimation of LFG has been consistently investigated by the various researchers across the globe. For estimating LFG, various models such as empirical models, stoichiometric models, biochemical models, etc. have been developed. Each of these models differs in kinetic expression and parameters. (NEERI, 2002)

There is a need of consistent and reliable data for estimation of LFG. In India, where such conditions do not prevail, it may be necessary to adopt empirical relationship coupled with scientific logic. According to IPCC (1996), on national level, two methods viz. default method (Tier 1; DM) and first order decay (Tier 2; FOD) methods are recommended for estimating LFG.

The methane emission could be better estimated by using the first-order decay (FOD) in two phases. In the first phase, the rate of generation keeps on increasing till the peak is reached; thereafter, it keeps on declining till the material is stabilized.

7. Default methodology (DM)

DM is basically an empirical model. A number of empirical constants have been considered while developing the DM. The empirical constants vary according to the composition of waste, management of the landfill site and depth of landfill. The total yield of methane gas for the total waste deposited up to the particular year is computed using Eq. (1) (IPCC, 1996). Though IPCC has claimed that DM provides reasonable annual estimate of actual emissions and this has been widely used in the situations where detailed data is not available (IPCC, 1996). But it may not provide realistic estimate as it is assumed that all potential methane is released in the year the waste is disposed off.

$$\text{Emission} = (\text{MSW}_T \times \text{MSW}_F \times \text{MCF} \times \text{DOC} \times \text{DOC}_F \times F \times 16/12 - R) \times (1 - \text{OX}) \quad (1)$$

Table 2
Methane emission calculation using MTM

S. No.	Year	MSW (Gg)	CH ₄ (Gg) [Col (3) * 0.0308]	CH ₄ (m ³) (mass * density)	Height of triangle 2* Col (5)/15
(1)	(2)	(3)	(4)	(5)	(6)
1	1994	176.268	5.429	7564518	1008602
2	1995	423.042	13.030	18154791	2420639
3	1996	430.388	13.256	18470044	2462673
4	1997	449.480	13.844	19289374	2571917
5	1998	487.975	15.030	20941382	2792184
6	1999	428.832	13.208	18403268	2453769
7	2000	454.650	14.003	19511244	2601499
8	2001	461.232	14.206	19793710	2639161
Total		3311.867	102.006		

Methane estimation based on DM for the year 2001 is done with the help of Eq. (1). Where, MSW_T is the total SW reaching in the year 2001, i.e. 461.232 Gg, MCF is taken as 0.4 for unmanaged shallow depth landfill site (less than 5 m), based on composition of waste for Delhi, DOC value is taken as 0.15. The default value for dissimilated organic fraction (DOC_F) and fraction of methane in LFG (F) is 77% and 50%, respectively. The value for methane recovery factor and oxidation factor is zero. The emission coefficients arrived in estimation of methane emission using DM is 0.0308. The total methane generation is calculated to 14.206 Gg (Table 2) in the year 2001. The total gas generated in the time span of 8 years from 1994 to 2001 is 102.006 Gg, for which total waste (excluding inert) deposited in the landfill up till 2001 is taken (i.e. 3311.867 Gg).

8. FOD method

FOD method provides a time-dependent emission profile that reflects the true pattern of the degradation process over a time period. The FOD method requires data on current, as well as historic waste quantities, composition and disposal practices for decades (IPCC, 1996). At present due to lack of data, this method cannot be used for estimation of methane emission. Therefore, a modified approach is proposed wherein the biogas is released in a triangular form, based on time-dependent profile like that of FOD.

9. Triangular method

In this method time-dependent release of GHG is based on the FOD. Under normal conditions, the rate of decomposition, as measured by gas production, reaches a peak within the first 3–6 year and then slowly tapers off, continuing for periods up to 25 years or more. The first part of the triangle is due to Phases I, II and III and

the second part of the triangle consists of Phases IV and V of the LFG generation process (George et al., 1993).

According to the triangular method, the organic fraction is divided into two classes viz. rapidly biodegradable waste (RBW) and slowly biodegradable waste (SBW). (George et al., 1993). Total yield of LFG for both categories is computed using mass balance equation (George et. al., 1993). To make the mass balance equation extensive characterization and quantification of the SW is required, which is not feasible practically. Hence, the modified triangular method (MTM) is used in the present study. The proposed model is useful in expressing the output of any landfill site within probable range and also to use production in two-phase triangular form as a first approximation, with finite decomposition time as shown in Fig. 2.

9.1. MTM

In absence of detailed data, it is assumed that volume of methane emission is same as of DM and degradation takes place in two phases. First phase starts after one year of deposition and rate of gas generation reaches the peak in 6th year and thereafter generation rate decreases to become zero in the 16th year in the second phase. Accordingly, the gas generated for yearly deposition is calculated, and the combined effect is taken to get the values of emission for a particular year.

Calculations of MTM for Okhla site, is shown in Table 2. Methane emission (Col-4) is calculated by multiplying municipal SW quantity and EF of DM. Methane generated is converted into volume (Col-5) using density (i.e. 0.1776 kg m^{-3}) and is equated to total area of the triangle, having base of 15 years. Height of the triangle (Col-6) represents methane emission in 6th year. Each triangle formed represents time-dependent emission profile for respective yearly deposition of SW. Fig. 3 shows the combined yearly emission. Area under the curve is equal to 102.006 Gg of methane and the curve represents the emission profile.

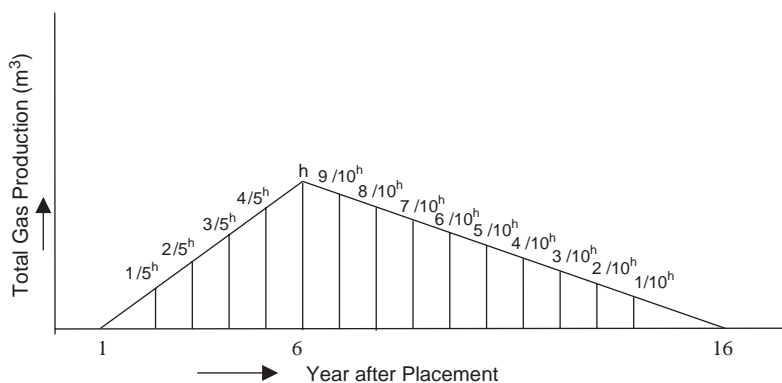


Fig. 2. Triangular form for gas production.

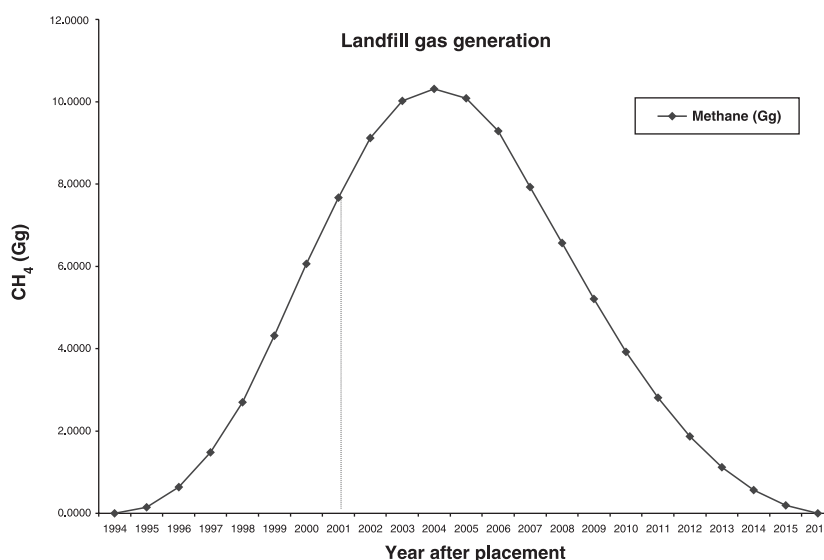


Fig. 3. Emission profile LFG.

The maximum and minimum methane generation is 10.313 Gg and 0.06374 Gg respectively (Fig. 3). The respective EF is calculated by dividing these emissions with their respective waste and the values are 0.02236 and 0.00148. The emission and EF for the study year 2001 is 7.667 and 0.01662, which is very low as compared to the values of DM. The only difference is the emission profile.

10. Field sampling

Emission rate is obtained by field sampling from the Okhla landfill site. Sampling is carried out by static box method. The rectangular box (31 cm × 52 cm × 70 cm) is made of perspex sheet and is mounted on a base with channel to hold water. The water channel would isolated the inside air from outside atmosphere. A septum is

fixed on the top of the box for taking sample and a necessary arrangement is also made to measure inside box temperature. Sample is collected using fixed volume syringes and are analysed by gas chromatograph (GC).

Sampling is carried out for different season with day and night samples as well. The first set of field sampling is done in October 2002. In this set 55 samples are collected well distributed over landfill area. In March 2003 second set of 28 field samples are taken and the sampling points are selected within the central region of dumping area.

The average methane gas estimated by field sampling at Okhla landfill site is 0.326079 Ggyr⁻¹. The average methane gas generated in the central region at Okhla landfill site is 1.776 Ggyr⁻¹. Mean Emission Factor from the field is 0.003852 and the standard deviation for emission factor is 0.0003722 (Table 5).

11. Analysis of the field samples

It is observed that the methane flux indicated very low value for the samples taken at the edges or the periphery of the site as compared to the samples taken at the central region of the site. This may be due to air intrusion at periphery as no soil cover was provided. So, in the next set, sampling point is concentrated on the central region, where the methane flux is more. The samples, taken at night are showing little higher values for methane flux, than the samples at daytime.

12. Uncertainty determination

Measurement of any quantity is based on how it is defined. So, the first step for the determination of uncertainty is to finalize its definition. Uncertainty can be defined by the terms vagueness and ambiguity (Morgan et al., 1984).

Emission inventories are a compilation of a large number of input parameters. The way these parameters have been processed to yield the final result, i.e. the total emission, depends on the emission model used. In general, however, most emission sectors are estimated by multiplying an EF with the activity data (A), statistical parameters for the respective source. In an emission inventory, none of the input parameters (EF or A) is known exactly and the value of parameter is determined as “best estimates”.

According to the current study, the choice of method for the estimation of uncertainties is based on the IPCC good practice guidance (IPCC, 1996). The IPCC guidelines have suggested Error propagation equation (Tier I) and Monte Carlo simulation (Tier II) approach for the calculation of uncertainties in the estimation of GHG emission.

12.1. Monte Carlo analysis

This is a Tier II approach for detailed analysis of uncertainties. The core of Monte Carlo analysis is to vary the input parameters A, i.e. waste quantity and EF, according to the probability distribution function (PDF)

within likewise pre-defined ranges (max and min) of input parameters. For each random set of input, total emission is calculated. Performing a large number of emission calculations using such random sets leads to many different output values, which again can be expressed as a PDF (IPCC, 1996). IPCC recommends normal distribution function. Standard deviations and the mean is required for defining distribution curve. For the present analysis, Monte Carlo simulation software is developed in Turbo C++ language.

12.2. Uncertainty associated with methane emission

IPCC has documented the uncertainties of empirical constants (Table 3, 4), used in DM. Using this percentage of uncertainty; value range of these empirical constants is calculated. The mean value for total SW and emission is 3311.867 Gg and 102, respectively, for the years 1994–2001. After simulation, mean emission value and the associated standard deviation is 101.743 and 16.854 respectively (Table 5). The PDF formed by emission data is also normal. The value of uncertainty for the default emission worked out to be 33.13%.

In MTM, volume of gas released each year is depicted in Fig. 3. Waste quantity for the study year 2001 is 461.232 Gg and the emission is 7.667. After simulation, the mean value for the emission and the associated standard deviation is 7.676 and 1.373, respectively. The value of uncertainty for the emission worked out to be 35.77%.

The field data on emission rate is obtained by using static box method. The waste quantity for the study year 2001 is 461.232 Gg, the emission is 1.776 Gg. Range of EF is the maximum and minimum values taken from the set of data collected in the field. Mean emission and standard deviation of emission after simulation is 1.78 and 0.24, respectively. The value of uncertainty of the emission for the normal PDF is 26.96%. The low uncertainty proved that the field sampling represents the correct gas emission from the top surface, but under the assumed condition (Article: 13.0 Sensitive parameter). The other factors like, aerobic zones, leachate formation and its drainage, lateral surface emissions etc. were not taken into account.

Table 3
Uncertainties associated with the default parameters according to IPCC

Parameter	Uncertainty range	Value range
Degradable organic carbon (DOC)=0.21 (maximal default value)	–50%, +20%	0.105–0.252
Fraction of degradable organic carbon dissimilated (DOC _F)=0.77	–30%, +0%	0.539–0.770
Methane correction factor (MCF=0.4)	–30%, +30%	0.280–0.520
Fraction of CH ₄ in landfill gas (F)=0.5	–0%, +20%	0.500–0.600

Table 4
Bacteriological analysis of soil sample collected from Okhla landfill site, Delhi

Sr. No.	Date of sample collection	Sampling point	Sample collected at depth (in m)	Total coliform g ⁻¹ dry wt.	Faecal coliform g ⁻¹ dry wt	Faecal streptococci g ⁻¹ dry wt	Total bacterial count g ⁻¹ dry wt
1.	4.2.03	SW landfill was covered with soil in 2002	0.5	29 × 10 ³	36 × 10 ²	31 × 10 ²	37 × 10 ⁵
			1.0	26 × 10 ³	33 × 10 ²	241 × 10 ³	31 × 10 ⁵
			1.5	49 × 10 ³	10 × 10 ³	29 × 10 ²	22 × 10 ⁵
2.	4.2.03	Recently covered landfill with soil	0.5	54 × 10 ⁴	26 × 10 ⁴	58 × 10 ³	78 × 10 ⁵
			1.0	52 × 10 ³	40 × 10 ²	58 × 10 ³	56 × 10 ⁵
			1.5	29 × 10 ³	27 × 10 ³	57 × 10 ²	25 × 10 ⁵
3.	5.2.03	SW landfill was covered in 1998 (3 year)	0.5	20 × 10 ²	66 × 10 ¹	36 × 10 ²	60 × 10 ³
			1.0	14 × 10 ³	28 × 10 ²	27 × 10 ³	2 × 10 ⁶
			1.5	75 × 10 ⁴	36 × 10 ⁴	74 × 10 ²	46 × 10 ⁴
4.	5.2.03	SW landfill was covered in 1999 (21/2 year)	0.5	18 × 10 ²	11 × 10 ²	62 × 10 ¹	11 × 10 ⁴
			1.0	57 × 10 ²	31 × 10 ²	18 × 10 ²	15 × 10 ⁵
			1.5	73 × 10 ³	34 × 10 ³	18 × 10 ²	46 × 10 ⁴
5.	5.2.03	SW landfill was covered in 1997 (5 year)	0.5	11 × 10 ²	15 × 10 ¹	17 × 10 ²	16 × 10 ⁵
			1.0	13 × 10 ²	16 × 10 ¹	20 × 10 ¹	90 × 10 ⁴
			1.5	18 × 10 ²	12 × 10 ²	50 × 10 ¹	25 × 10 ⁴

13. Sensitive parameters

Emission-data of all three methods and their assumptions are tested in the light of, biological degradation process, location of site and its topographic feature. Although, biological process is the most important factor influencing the result, but location of landfill site, its structural features, leachate generation and migration of gas are equally important.

A suitable environment is needed for the growth of methanogenous bacteria. Parameters such as pH, temperature, moisture, nutrient etc. affects their growth. Few parameters such as potential difference (–150 to –300 mV), pH (<7.0), etc. are indicators of active anaerobic degradation. Tests are conducted at different depths for measuring potential difference and identifying anaerobic bacteria in the landfill site. Results given in Table 4 supports the presence of anaerobic bacteria after a depth of 1.5 m. The waste on the surface and on the lateral side up to this depth, is not contributing to methane generation. This loss in the organic matter is to be considered in the theoretical estimation of the methane.

Migration of gas in the landfill is a very important factor. Sampling points are selected on the top surface of landfill, assuming same migrating rate, through all the surfaces. The gas will take the least resistive paths for its escape, and it may take any direction. Actually, on the top surface, soil cover is placed and compacted by the bulldozers. Moist soil gets compacted to much high degree than the organic matter. Thus, the least resistive path for the gas shall be towards lateral surface. It is reflected in the trend of field sampling also. Peripheral

samples, shows very-very low flux as compared to the middle zone. This fact is also proved from the smoke in the site. Methane escaping from the sides is supporting the fire. According to our perception, the amount of gas escaping from the lateral surface shall be relatively more than the top surface.

In the absence of leachate collection and its treatment facility, leachates during get collected in the nearby pits and some amount of it enter into the nearby drain. The samples from these pits are tested for BOD and COD. The results indicated a high BOD of about 2200 mg lit⁻¹ and COD equals to 3100 mg lit⁻¹. These leachates indicated loss in the organic matter, which may contribute to the methane generation if it was recycled.

14. Conclusion

In the present study qualitative assessment of different methane emission-data was performed. Field emission-data varied widely from the estimated values and also within the estimated values there was variation. Methane emission estimated using DM was 14.206 Gg, whereas MTM gives 7.667 Gg for the study year (2001). Although the total emission for both methods is same, MTM's value is almost half of the default value. The difference in their prediction is attributed to the difference in the assumption of emission profile, as mentioned in section "7.0 Default Method".

Field measurements for the study year were found to be 1.776 Gg, which is far lower than the values estimated by either of the methods. Although field values were expected to be lower than estimated values, the present

Table 5
Uncertainty calculation

Method	Year	Emission (Gg)		Activity data (Gg)		Emission factor			Emission after stimulation (Gg)		Uncertainty (%)
		Mean	Standard deviation	Mean	Standard deviation	Mean	Range	Standard deviation.	Mean	Standard deviation	
Default	1994–2004	102		3311.867	Expert judgment	0.0308	0.011319–0.06054	Expert judgment	101.743	16.854	33.13
Modified triangular	2001	7.667		461.232	Expert judgment	0.016628	0.00148–0.022359	Expert judgment	7.676	1.373	35.77
Field samples	2001	1.776		461.232	Expert judgment	0.003850	1.41E-04–4.415E-03	3.722E-04	1.78	0.24	26.96

study finds vast difference between them. It is imperative that many emission paths and emission potentials go unaccounted during field measurement. There is certain amount of uncertainty associated with sampling also.

MTM was found to be more representative of field conditions. Lack of availability of data required, leads to assumptions and consequently negative impact on the comparability. Although there is variation among the estimation methods presented, the study brought out the parameters and assumptions to be assessed critically for future research studies. Only the continual study and regular data maintenance can improve the reliability of GHG emission-data, in developing countries like India.

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