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Greenhouse gas emissions from municipal solid waste management in Indian mega-cities: A case study of Chennai landfill sites

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Abstract

Municipal solid waste generation rate is over-riding the population growth rate in all mega-cities in India. Greenhouse gas emission inventory from landfills of Chennai has been generated by measuring the site specific emission factors in conjunction with relevant activity data as well as using the IPCC methodologies for CH_4 inventory preparation. In Chennai, emission flux ranged from 1.0 to 23.5 mg CH_4 m^{-2} h^{-1}, 6 to 460 μg N_2O m^{-2} h^{-1} and 39 to 906 mg CO_2 m^2 h^{-1} at Kodungaiyur and 0.9 to 433 mg CH_4 m^{-2} h^{-1}, 2.7 to 1200 μg N_2O m^{-2} h^{-1} and 12.3 to 964.4 mg CO_2 m^{-2} h^{-1} at Perungudi. CH_4 emission estimates were found to be about 0.12 Gg in Chennai from municipal solid waste management for the year 2000 which is lower than the value computed using IPCC, 1996 [IPCC, 1996. Report of the 12th session of the intergovernmental panel of climate change, Mexico City, 1996] methodologies.

Keywords: Methane (CH_4); Carbon dioxide (CO_2); Nitrous oxide (N_2O); Landfill; Open dumping

1. Introduction

Municipal solid waste (MSW) generally includes degradable (paper, textiles, food waste, straw and yard waste), partially degradable (wood, disposable napkins and sludge) and non-degradable materials (leather, plastics, rubbers, metals, glass, ash from fuel burning like coal, briquettes or woods, dust and electronic waste). Generally MSW is managed as collection from streets and disposal at landfills. Anaerobic decomposition of MSW in landfills generates about 60% methane (CH_4) and 40% carbon dioxide (CO_2) together with other trace gases (Hegde et al., 2003). This percentage differs spatially due to waste composition, age, quantity, moisture content and ratio of hydrogen/oxygen availability at the time of decomposition (e.g. fat, hemicellulose, etc.).

Economic and demographic growth of cities, changing lifestyles of people, changing land use patterns and technological advancements led to increase in quantity and complexity of urban MSW generation and management. The nature of MSW varies with country, city, suburb and seasons. Biodegradable food materials and yard wastes normally dominate in MSW of developing countries while paper and hardboard dominate in developed countries (Joseph et al., 2003; Vishwanathan and Trakler, 2003). Solid waste generated in Indian cities increased from 6 Tg in 1947 to 48 Tg in 1997 (Pachauri and Sridharan, 1998) with per capita increase of 1–1.33% per year (Rao and Shantaram, 2003). About 0.5–0.7 kg $capita^{-1}$ day^{-1} MSW is generated in urban India (Kameswari et al., 2003) with volatile matter content of about 10–30% (Rao and Shantaram, 2003). About three-fourth of the MSW generated from urban India is collected and disposed off in non-scientifically managed dumping grounds. Almost 70–90% of landfills in India are open dumpsites (Joseph et al., 2003). Nation-wide data on MSW is still not available in India (Kumar et al., 2004b), however, most of the urban centres were surveyed by different agencies and national

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level data have been generated. In 1971, the urban population in India generated about 374 g capita^{-1} day^{-1} of solid waste. In another survey conducted by National Environmental Engineering Research Institute, Nagpur, India, the quantity of waste produced has been found to vary from 200 to 600 g capita^{-1} day^{-1} (NIUA, 1989). A survey in 1981 placed this figure to 432 g capita^{-1} day^{-1} and yet another survey in 1995 quoted this figure as 456 g capita^{-1} day^{-1}. Surveys conducted in 1989 projected MSW generation for 33 Indian cities to be about 14.93 Gg per day. The Environmental Protection Training and Research Institute estimates by the survey in 1995 for 23 Indian cities reported MSW generation as 11 Tg per year (MOEF, 2006). The survey conducted by Central Pollution Control Board (CPCB) estimated MSW generation from Class I and II cities to be about 18 Tg in 1997 (MOEF, 2006). Indian mega-cities (Delhi, Mumbai, Kolkata and Chennai) are top producer of MSW in India due to high density of residential and floating population, from households, offices, trade/commercial activities, industries and health care centres.

MSW in Indian mega-cities is mainly disposed in landfills by means of open dumping however; a small fraction is used for composting in Delhi and Mumbai. In Chennai and Kolkata, composting facility is implemented in pilot stage. All the four Indian mega-cities are upgrading their capabilities in MSW collection and disposal by technological advancements viz waste to energy plan, source segregation, increase in collection efficiency of wastes (up to 90% and more), etc. However, financial constraints are largely limiting this up-gradation process (NIUA, 1989).

In Chennai, MSW originates from residential (~68%), commercial (~14%), restaurant (~12%), industrial (~2%), etc. activities. Healthcare centres dispose their wastes separately. After collection, MSW is disposed at Kodungaiyur (KDG) and Perungudi (PGD) landfills. Out of ten zones in Chennai, waste collected from zones I to V is dumped at KDG and from zones VI to X is dumped at PGD. Structural features of both landfill sites are listed in Table 1. Due to large MSW dumping area, landfills have less height of MSW deposits even after longer period of continuous dumping. At KDG, area of land filled during the period 1980–1987 was covered with soil and is currently used for civic purposes. Significant greenhouse gas (GHG) emissions were not expected from such parts of land, as in hot and wet climate with shallow disposal sites, degradation might be rapid (Kumar et al., 2004a).

In developing countries such as India, inventory estimates of CH_4 from landfills have large uncertainties due to inadequate data availability on management and emissions. MSW sent to the landfill passes through various intermediate stages such as sorting of recyclable and compostable materials. This may change the quantity and properties of waste ultimately reaching the landfill sites, thereby influencing GHG emissions. Measurements of GHG emissions from landfill are, therefore, important to reduce uncertainties in the inventory estimates from this source. It is expected that the quantum and complexity of this source will grow in future and the contribution of GHG emission from India will become larger if current practices are to prevail especially in mega-cities. Field measurement of CH_4 emission was conducted in Chennai to identify key variables that influence GHG emissions as well as for comparing the resulting inventory estimates with that of IPCC recommended methodologies. N_2O and CO_2 were also measured to assess the nature of emission.

2. Materials and methods

Data on municipal solid waste were collected from the municipal corporation and other sources to quantify the changes in waste generation rate and decomposable matter in four Indian mega-cities viz Chennai, Delhi, Kolkata and Mumbai. CH_4 emission inventory from landfills of Chennai were prepared for the year 2000 using three approaches viz field measurements and empirical model equations as recommended in tier I (mass balance) and tier II (first order decay) methodologies of IPCC guidelines (IPCC, 1996). Inventory estimates of CO_2 and N_2O were also computed on the basis of field measurements.

2.1. CH_4, CO_2 and N_2O measurements

CH_4, CO_2 and N_2O emission measurements were carried out in December 2003 and September 2004 at KDG and

Table 1
Salient features of landfills in Chennai

Characteristics	Kodungaiyur (KDG)	Perungudi (PGD)
Shape and size	Rectangular, 263046 m^2	Rectangular, 220000 m^2
Land filling started	Year 1980	Year 1987
Mode of waste disposal	Open dumping	Open dumping
Types of soil	Clayey alluvial flatland	Silty clay alluvial flatland
Drainage	Towards Buckingham canal (east)	Towards Buckingham canal (north and south)
Elevation from sea level (m)	~6.2	~1.0
Height of MSW deposit	Average height ~5 m (uneven)	Average height ~3.2 m (relatively flat)
Land use pattern	Residential colonies and industrial units in close proximity	Residential colonies and industrial units in close proximity

Source: [ERM (1995), observation and personal communication].

PGD landfills of Chennai. Sampling points were decided on the basis of age (2–4 years) of MSW at surface layer and height of deposition (5–15 feet) at central and peripheral region of landfills. Chamber technique was used for gas sampling (IAEA, 1992; Parashar et al., 1996; Mitra et al., 2002; Gupta et al., 2007). Gas samples were collected at an interval of 15 min, at each location using 50 ml syringes, for 45 min. Ambient and MSW temperatures at the study sites were also recorded. MSW soil samples were taken to determine moisture contents. Gas samples were analyzed for CH_4 and CO_2 by gas chromatograph (GC; SRI, USA, Model 8610 C) – flame ionization detector, fitted with a methanizer. N_2O concentrations were quantified using GC-electron capture detector. During sample analyses, CH_4 (5.63 ppmv), CO_2 (500 ppmv) and N_2O (0.31 ppmv) calibration gas standards were used. Emission fluxes of these gases were calculated and multiplied with area of landfills to get annual emissions.

2.2. IPCC methodologies and required data

In this study, year 1988 was assumed as starting year for inventory preparation and IPCC 1996 methodology in conjunction with IPCC Good Practice Guidance, 1996 was followed to estimate CH_4 emission. MSW data record for both landfill sites (KDG and PGD) was available from 1996 and hence data from 1988 to 1996 were calculated considering average growth rate of MSW during 1996–2003, subtracting the amount of inert material (debris) and moisture. Compostable matter content and their fractional composition are important to calculate degradable organic carbon (DOC) content, which is a critical factor for CH_4 emission calculation. DOC and CH_4 generation potential (Lo; which is MCF $\times$ DOC $\times$ DOC_F $\times$ F $\times$ 16/12), were calculated for both landfill sites using waste composition data.

Default values of 0.4 for methane correction factor (MCF), 0.77 for fraction of degradable organic carbon dissimilated (DOC_F), and zero for oxidation factor (OX) and recovered methane (R) were used for computation in this study as per the IPCC Tier I method (IPCC, 1996; IPCC Good Practice Guidance, 1996; Kumar et al., 2004b). In our study, data was available for MSW land filled, and hence the amount of MSW land filled is equal to the total municipal solid waste (MSW_T) multiplied by fraction of MSW sent to landfill (MSW_F). Therefore, CH_4 emission is calculated by multiplying MSW land filled with Lo.

The ratio of total CH_4 emitted since the time of opening of the landfill to the amount of MSW dumped gives the emission factor (EF) as Gg CH_4 per Gg waste. This EF when applied to the amount of waste dumped (after subtracting moisture and inert) in specified year (year 2000 in the present case) gives the CH_4 emission for that year.

First order decay (FOD) method, as outlined in the IPCC tier II methodology, provides a time-dependent emission profile that reflects the true pattern of degradation process over a period of time. This method requires data on current, as well as historic waste quantities, composition and disposal practices over the decades (IPCC, 1996). We used IPCC default values for the unavailable data, of some parameters viz CH_4 generation rate constant (0.05) and fraction by volume of CH_4 in landfill gas (0.5). FOD equation for a particular landfill site is as follows (IPCC, 1996; IPCC Good Practice Guidance, 1996).

Equation $QCH_4 = L_0 \times R \times (e^{-kc} - e^{-kt})$

where t = time since start of MSW disposal and c = time since landfill was closed (in our case $c = 0$). This equation has been slightly modified to introduce the normalization factor in IPCC good practice guidance (IPCC Good Practice Guidance, 1996).

$$CH_4 \text{ generated in year 't'} = \sum_x \left[(A \times K \times MSW_T \times MSW_F \times Lo(X)) \times e^{-k(t-x)} \right]$$

where $A = (1 - e^{-k})/k$ = normalization factor, which corrects the summation and all other parameters have usual meaning as in IPCC, 1996.

3. Results and discussion

3.1. Municipal solid waste in Indian mega-cities

The general characteristics of four Indian mega-cities namely Chennai, Delhi, Kolkata and Mumbai and their solid waste management are given in Table 2. Population of Mumbai increased from 8.2 million in 1981, to 12.3 million in 1991, a growth of ~49%. However MSW generated, increased from 3.2 to 5.35 Gg per day during the same period, recording a growth of ~67%. In Chennai, the population increase was about 21% between 1991 and 2001, while waste generation increased by ~61% from 1996 to 2002 (Fig. 1). This indicates the rapid increase in municipal waste generation in the Indian mega-cities outpacing the population growth. High garbage pressure on available landfill also requires alternate arrangement of MSW management. Over the past few decades, composition of MSW in Indian mega-cities have recorded higher percentages of earth and inert materials (35–52%), varying degradable matter (35–84%) and lowest recyclable material (10–20%) as shown in Table 3. Plastic content in MSW had rapidly increased in past and stabilized thereafter due to growing awareness and recycling practices. Generation of electronic wastes is also on the rise, but is not included here. MSW containing plastics are prevalent in Kolkata while paper waste is more dominant in Chennai and Mumbai. Although the waste generation has increased yet the percentage of decomposable matter has been relatively stagnant (Table 3). Cumulatively recyclable materials are reduced throughout the decades in all mega-cities of India. Compostable matters vary among households of different income groups in all mega-cities. Hotspots of compostable matter generation are vegetable markets. Quantity of compostable matter in Delhi during the year 1995 was higher

Table 2
General characteristics of Indian mega-cities and their solid waste management

Parameter	Year	Mega-cities			
		Chennai	Delhi	Kolkata	Mumbai
Area (km^2)		174	1484	187.33	437.71
Population (million)	1971	2.47	4.07	3.15	5.97
	1981	4.28	6.22	4.13	8.23
	1991	5.42	8.42	11.02	12.6
	2001	6.56	12.87	13.20	16.43
Waste generation (kg $capita^{-1}$ d^{-1})	1971/73	0.32	0.21	0.5	0.49
	1994	0.66	0.48	0.32	0.44
	1999	0.61	1.1	0.545	0.52
Garbage pressure (tons km^{-2})		17.529	4.042	16.548	13.708
Pressure on landfill		3050	5000	2500	6000
Waste collection (Gg per day)	1999	3.124	5.327	3.692	6.0
Mode of disposal (%)	Landfilling	100	93	100	91
	Composting	–	7	–	9

(Source: CPCB (1999)), (–) data is not available.

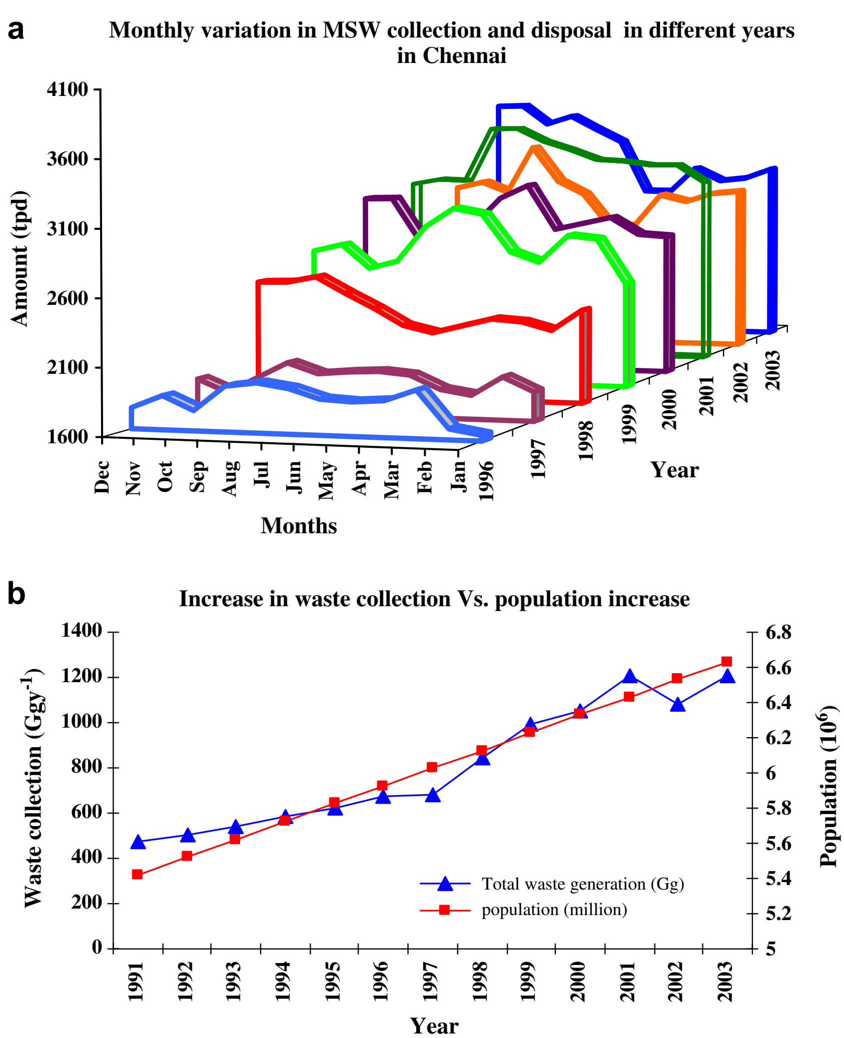

Fig. 1. (a) Variation in the daily MSW collection in different months from 1996–2003 in Chennai; (b) increase in MSW and population growth in Chennai.

compared to other years because the survey was carried out from households with a different income group that did not include street and market wastes. Larger fractions of wastes were inert originating from households, street sweeping and ash (Agrawal and Chaturvedi, 1997). Therefore, it may be said that the major driving force of increase

Table 3
Variation in MSW composition characteristics in mega-cities over past decades

MSW characteristics	City	% Composition variation over years				
		1971–1973[a]	1990–1993[c]	1995[a]	1997–1998[b,d]	2000–2002[b]
Compostable matter	Chennai	47.97	44	44	49.6	47.24
	Delhi	35.42		65–84	47.07	–[f]
	Kolkata	40.37	41	40	47	46.58[e]
	Mumbai	59.78		40	–	37.5
Rags	Chennai	4.85	4.27	5	4.5	–
	Delhi	4.7	4	4	–	–
	Kolkata	3.6	–	3	–	–
	Mumbai	2.48	–	3.6	–	–
Rags and textile	Chennai	4.85	4.59	10		3.14
	Delhi	–	8	8	–	0.52
	Kolkata	3.6	2.9	3	–	–
	Mumbai	–	–	7.2	–	–
Papers	Chennai	7.75	4.69	10	4.5	6.45
	Delhi	6.29		6.6	4.8–9	3.62
	Kolkata	3.18	5.2	10		
	Mumbai	4.89		10		15
Leather and rubber	Chennai	–	<1	5	1	1.45
	Delhi	–	–	0.6	–	1.83
	Kolkata	0.86	2	1	–	–
	Mumbai	–	–	0.2	–	–
Plastics	Chennai	0.88	<1	3	2.5	7.04
	Delhi	0.85	–	1.5	4.1–8.65	4.17
	Kolkata	0.65	3.5	8	0.65	1.54[e]
	Mumbai	2.92	–	2	–	–
Metals	Chennai	0.95	<1	<1	0.04	0.03
	Delhi	1.21	–	2.5	–	0.45
	Kolkata	0.66	–	<1	–	0.66[e]
	Mumbai	2.46	–	<1	–	0.8
Glass	Chennai	0.97	<1	<1	–	–
	Delhi	0.57	–	1.2	0.85–2.9	0.49
	Kolkata	0.38	–	3	0.66	0.24[e]
	Mumbai	0.72	–	0.2		0.4
Ash, fine earths and others	Chennai	–	33	33	38.9	34.65
	Delhi	36[d]	–	51.5	–	36.56
	Kolkata	51.18[d]	46.95	47	–	35[e]
	Mumbai	44.2[d]	–	44	–	35

[a] TEDDY (2001).
[b] Corporation of Chennai, personal communication, NSUI (<www.nsui.com/mumbai.htm>); <http://www.mcgm.gov.in/Departments/swmanage/stats.htm>; <www.nsui.com/mumbai.htm> and <http://www.pdc.org/PDCEMI/jsp/Wiki?Mumbai,India>.
[c] ERM (1995); Calcutta Municipal Corporation (1993).
[d] India Development report (1997).
[e] CPHEEO (2000).
[f] Data is not available.

in generation and change in composition of MSW are dependent on the economy and demography.

Annual and seasonal variations in the quantities of MSW disposed off in Chennai have also been observed (Fig. 1). Garbage contributes >90% (range: 84.9–96.4) of land-filled waste while rest is debris. Lifestyles of the city dwellers, commercial activities, recycling, etc. contribute to variations in waste composition. Although, the amount of MSW generated and collected is higher in rainy season, the fraction of garbage is lesser due to poor collection efficiency. Higher MSW generation in rainy season is mainly due to increasing debris and street sweeping wastes, higher household waste generation is due to dampening of materials and agglomeration of smaller waste materials besides other lifestyle related activities. Lesser organic carbon is due to solubility of organic matter and other wastes in rain water which ultimately goes to drainage system. Debris content is higher between June and August (summer). Debris or inert materials are generally used as landfill cover soil material. Composition of MSW in Chennai has changed considerably in recent years (1998–2002) due to increased utilization of papers, plastics, rubber and leather and decrease in other components like compostable matters, glass, metals, etc. KDG dumping ground receives about 45% MSW collected in Chennai and PGD dumping ground receives the remaining 55%. MSW dumped at KDG and PGD since January 1988 to December 2003 was 4.39 Tg and 5.29 Tg, respectively, resulting in about 3.2 and 3.86 Tg of dry garbage, respectively, after subtracting 27% for their moisture contents.

3.2. GHG emission fluxes and inventory estimation based on measurement

The GHG emission fluxes showed wide variations within each site and between the KDG and PGD dumping grounds (Fig. 2) although the composition of MSW was largely similar. This may be due to the heterogeneous nature of landfill and uneven height and compaction across the landfill areas. Other reasons for variation in fluxes at different points within a site (KDG or PGD) may be attributed to the changes in moisture content, compaction and age of the MSW. Maximum CH_4 flux was observed at the locations with 1.5–2.5 m of top layer containing wastes dumped over a period of 1–3 years. At KDG dumping ground, CH_4 flux ranged from 2.4 to 23.5 mg m^{-2} h^{-1} in December 2003 and 1.0 to 10.5 mg m^{-2} h^{-1} in September 2004 resulting in emission of 17.9 ± 9.9 tons (t) y^{-1} and 9.7 ± 3.6 t y^{-1}, respectively, with an annual average of 13.8 t y^{-1}. N_2O flux ranged from 142 to 384 μg m^{-2} h^{-1} in December 2003 and from 6 to 460 μg m^{-2} h^{-1} in September 2004 resulting in emissions of 0.65 ± 0.17 t y^{-1} and 0.32 ± 0.02 t y^{-1}, respectively, with an annual average of 0.49 t y^{-1}. CO_2 emission flux ranged from 39 to 906 mg m^{-2} h^{-1} in December 2003 and 106 to 242 mg m^{-2} h^{-1} in September 2004 resulting in an average emission of 0.924 ± 0.358 Gg y^{-1} and 0.33 ± 0.067 Gg y^{-1}, respectively, with an annual average of 0.627 Gg y^{-1}. At PGD, CH_4 flux varied from 0.90 to 9.94 mg m^{-2} h^{-1} in December 2003 and 1.8 to 433 mg m^{-2} h^{-1} in September 2004 resulting in an overall emission of 7.27 ± 2.7 and 196 ± 145.8 t y^{-1}, respectively, with annual average of 101.6 t y^{-1}. N_2O flux in the same location ranged from 15 to 155 μg m^{-2} h^{-1} in December 2003 and 2.7 to 1200 μg m^{-2} h^{-1} in September 2004, resulting in emission of 0.20 ± 0.05 and 0.78 ± 0.52 t y^{-1}, respectively, with annual average of 0.49 t y^{-1}. CO_2 emission flux ranged from 102 to 544 mg m^{-2} h^{-1} in December 2003 and from 12.3 to 964.4 mg m^{-2} h^{-1} in September 2004 resulting in emission of 0.506 ± 0.123 Gg y^{-1} and 0.560 ± 0.435 Gg y^{-1}, respectively, with an annual average of 0.533 Gg y^{-1}. Presence of N_2O and large fraction of CO_2 indicate that air is present inside the landfill column and some of the decomposition processes are aerobic. In these conditions, considerable fraction of CH_4 can get oxidized resulting in lower percentage of CH_4 in landfill gas (LFG). The site at KDG had low CH_4 emissions as compared to PGD. However it has higher emission of CO_2 probably due to the prevalence of more aerobic conditions at KDG.

During the study period, the ambient temperature in the study area ranged from 35 to 46 °C whereas the soil temperature below 15 cm from the surface layer ranged between 30 and 39 °C. We observed that the ambient and soil temperatures did not correlate with emission fluxes. CH_4 and N_2O fluxes obtained in this study were found to be in agreement with reported values in literature regarding similar type of landfills (Park and Shin, 2001; Hegde et al., 2003). Deviations in emission rates, if any, are due to the composition of waste. However emission fluxes were lower than those reported from sanitary landfills (Bogner et al., 1995; Borjesson and Svensson, 1997a; Rinne et al., 2005). Our results are also comparable with the observed emission flux from landfills, which were closed ten years ago (Borjesson and Svensson, 1997b). Therefore, it could be inferred that lesser organic matter is available for anaerobic degradation in open dumping grounds than in sanitary landfills.

Although the content of organic carbon and nitrogen are major factors influencing GHG emissions from landfills, these emissions are interactive and interdependent. Assuming CH_4, N_2O and CO_2 as simultaneous emissions, when each gas was made as a normalizing factor for the other two gases, it was found that highest correlation ($r^2 = 0.746$, correlation = 0.86) was obtained when CH_4 was the normalizing factor and N_2O was plotted against CO_2 (Fig. 2b). Available literature indicates that methanotrophs (methane oxidizing bacteria) are a source of N_2O (Mandernack et al., 2000; Knowles, 2005). Thus, besides nitrification and denitrification, N_2O generation and emission from landfills may also depend on CH_4 related phenomenon. Mineralization and increase in ammonium concentration inhibits methanotrophic activity. However, this may not be true for landfills because, when N_2O was kept as a constant, CO_2 and CH_4 were not well correlated ($r^2 = 0.3$). It may be said that methane generation and its oxidation perhaps also influence emissions of N_2O and CO_2 from landfills.

3.3. CH_4 emission estimates based on IPCC methodology

The IPCC Tier 1 methodology is empirical in nature and some of the empirical constants, which vary according to the composition of waste, management of the landfill and depth of landfill, were considered while developing this methodology. Moreover, the Tier I method assumption that total CH_4 is released in the same year from MSW dumped; is far from reality. However, in earlier Indian inventory, CH_4 emission was computed using tier I methodology and distributed the total amount of estimated CH_4 emission over 15 years considering 6th year as peak emission year based on triangular form of gas evolution (Kumar et al., 2004a; NATCOM, 2004).

The DOC content was found to vary from 11% to 13% in MSW of Chennai. Total amount of CH_4 generated during 1988–2003 as per IPCC Tier I methodology has been estimated to be 82.56 and 99.51 Gg at KDG and PGD, respectively, resulting in an emission factor (EF) of 0.026 Gg CH_4 per Gg waste, which is slightly higher than the values reported from landfills of Delhi (Kumar et al., 2004a). Approximately 314 and 379 Gg MSW has been disposed at KDG and PGD, respectively, during the year 2000. The consequent CH_4 emissions for the year 2000 have been estimated to be 8.1 Gg for KDG and 9.8 Gg for PGD. However, the Tier II methodology of IPCC 1996 guidelines yielded CH_4 emission estimate for the year 2000 to be about 2.49 Gg for KDG and 3 Gg for PGD.

Significant processes in a landfill include microbial and other oxidation of CH_4 within the landfill's surface layer, which has been estimated to be between 10% and 20% (Onk, 1996). Open burning practiced by rag pickers to get recyclable materials like metals leads to burning of rags, textiles, wood, decomposable matter, leather and rubber. This practice may burn up to 75% of combustible materials (Sinha, 1997). Burning of MSW by rag pickers at landfill sites was common in Chennai. In such cases, CH_4 emission estimates for KDG is 0.59 Gg, which may be further reduced to 0.53 Gg if we were to consider 10% CH_4 oxidation in topmost layer. Similarly the CH_4 estimate for the PGD dumping ground would be 0.72 and 0.64 Gg, respectively, for the year 2000. Inventory estimates based on field

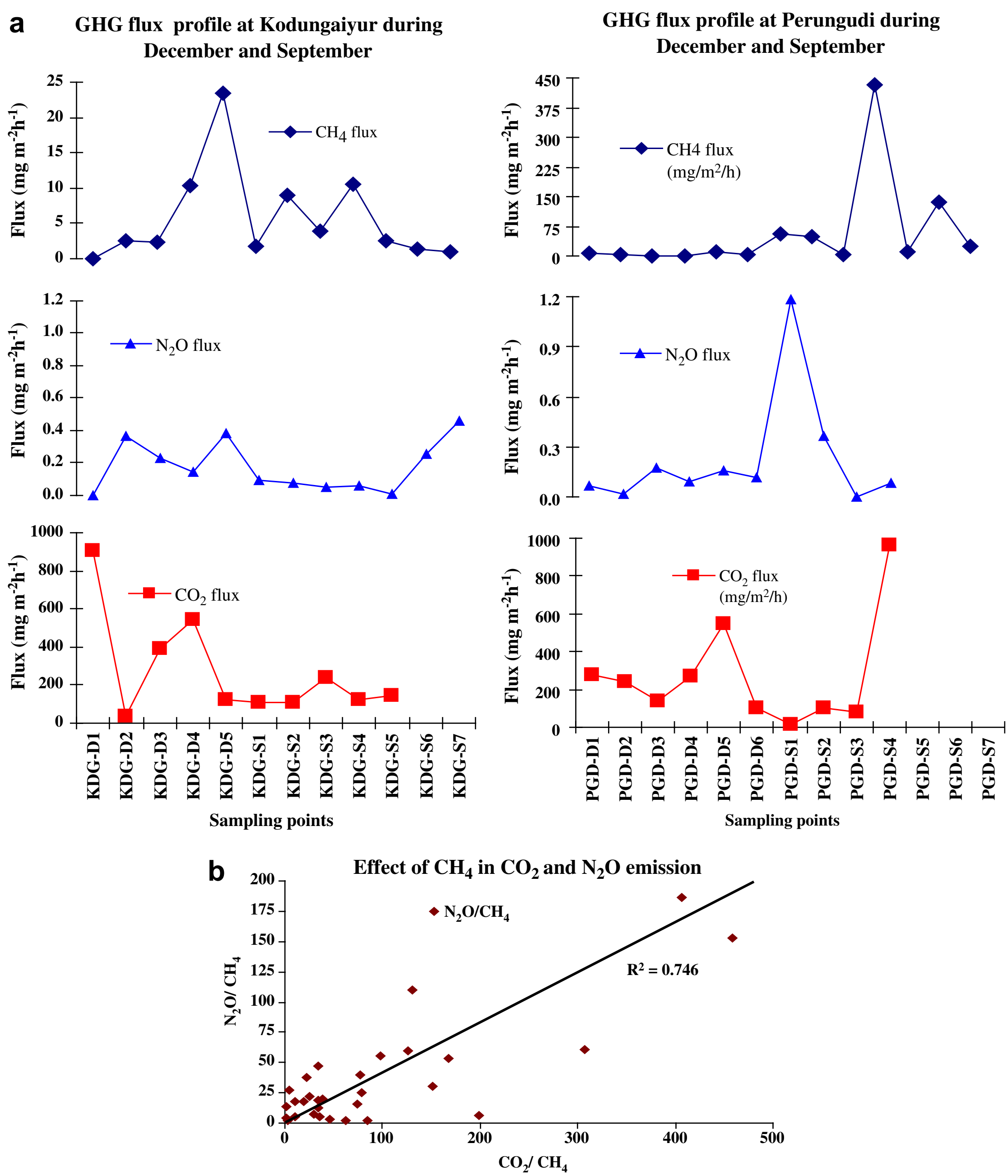

Fig. 2. Emission fluxes of gas and their interrelationship (a) Emission fluxes in landfills (PGD = Perungudi, KDG = Kodungaiyur, D = December, S = September); (b) effect of CH_4 on CO_2 and N_2O emissions.

measurements were lower than calculated estimates using Tier I and Tier II of the IPCC recommended methodologies.

The model equation outlined in IPCC Tier II methodology was designed to estimate CH_4 gas generation from landfills and not its emission to the atmosphere. Moreover, aerobic degradation of DOC in MSW of tropical regions such as Chennai may be higher due to higher temperature and moisture. Site condition also play important role, as significant organic carbon washed out during rain and may get eliminated from system since there is no leachete management for landfills in Chennai. In the early stages of MSW dumping, sewage water was discharged at the soil surface after primary treatment. This enabled ready degradation/washing (as leachete) of dumped MSW, which might have induced early stabilization of organic matter in waste. Besides these site and climate specific factors, default value for decay rate constant and fraction of degradable organic carbon dissimilated, contributes some of the differences in emission estimation of CH_4.

Uncertainties in methane emission measurements may be attributed to difficulty in determination of actual area of landfills and any bias in sampling and analysis. Standard error of mean is reflected as range due to wide variations in fluxes. We could not make uncertainty assessment with the activity data collected from the Corporation of Chennai due to unavailability of detailed data. Uncertainties in amount of waste reaching to landfill site, composition of waste, quantity of GHG generated, oxidation of methane in upper crust of landfill and net emission to the atmosphere are all the other factors contributing to the uncertainties in GHG emission estimation from landfills. Several model equations that predict the amount of methane generated such as mass balance, first order decay, multiphase model, etc., need precise data. Therefore, even a small variation in the DOC or methane generation rate constant may lead to large variations in CH_4 emission estimates.

4. Conclusions

MSW generation is over-riding the population growth in Indian mega-cities. Mumbai is the highest waste generating megacity followed by Delhi, Kolkata and Chennai. High garbage pressure requires alternate management options of MSW disposal apart from landfilling in topographic depressions. Physical composition of waste has not significantly changed in recent times. Compostable matter in MSW is approximately 40-50% with the same amount of inert materials. However, lower compostable matter content in Mumbai was mainly attributed to increasing amount of trade waste.

In Chennai, CH_4 emission has been found to be about 0.12 Gg y^{-1} whereas N_2O emission is about 1 t y^{-1}. Majority of organic material in waste is decomposed aerobically resulting in emission of about 1.16 Gg y^{-1} of CO_2. Lower emission of CH_4 is due to lower height of MSW deposits in the landfill area, uncontrolled leaching of organic matter, open burning of MSW in landfill and climatic conditions. Difference between CH_4 emission estimates of measurement and IPCC methodologies as well as uncertainties is mainly due to lack of certain site and region specific data as well as model equation assumptions. It is also important to study MSW reaching to landfills along with the generation and composition determination at source for CH_4 emission inventory as intermediate stages of waste handling also influence its quantity.

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References

Agrawal, R., Chaturvedi, B., 1997. Solid waste disposal and recycling in Delhi: a case study. In: Dutta, M. (Ed.), Waste Disposal in Engineering Landfill. Narosa Publishing House, New Delhi, pp. 221–236.

Bogner, J., Spokas, K., Burton, E., Sweeney, R., Corona, V., 1995. Landfills as atmospheric methane sources and sinks. Chemosphere 31 (9), 4119–4130.

Borjesson, G., Svensson, B.H., 1997a. Seasonal and diurnal methane emission from a landfill and their regulation by methane oxidation. Waste Management and Research 15, 33–54.

Borjesson, G., Svensson, B.H., 1997b. Effect of gas extraction interruption on emissions of CH_4 and CO_2 from a landfill, and on methane oxidation in the cover soil. Journal of Environmental Quality 26, 1182–1190.

Calcutta Municipal Corporation, 1993. Solid Waste Management of the City of Calcutta, Calcutta Municipal Corporation.

CPCB, 1999. Status of solid waste generation, collection and disposal in metro cities. Central Urban Pollution Series: cups/46/1999/2000 in 1999–2000. Central Pollution Control Board, New Delhi.

CPHEEO, 2000. Manual on MSW management, first ed. Central Public Health and Environmental Engineering Organisation, Ministry of Urban Development, Government of India.

ERM (Environmental Resource Management), 1995. Report of master plan of Chennai to Madras Metropolitan Development Authority, vol. 2.

Gupta, P.K., Jha, A.K., Koul, S., Sharma, P., Pradhan, V., Gupta, V., Sharma, C., Singh, N., 2007. Methane and nitrous oxide emission from bovine manure management practices in India. Environmental Pollution 146, 209–224.

Hegde, Ullas, Chang, Tsan-Chang, Yang, Shang-shyng, 2003. Methane and carbon dioxide emissions from Shan-ch-ku landfill site in northern Taiwan. Chemosphere 52, 1275–1285.

IAEA, 1992. Manual on measurement of methane and nitrous oxide emissions from agriculture, International Atomic Energy Agency, Vienna, Australia, pp. 45–67.

India Development report, 1997, India Development report, 1997 available from Ministry of Environment and Forest, Government of India, at <http:mospi.nic.in/comenv2000tab7.4.3.htm>.

IPCC, 1996. Report of the 12th session of the intergovernmental panel of climate change, Mexico City, 1996.

IPCC Good Practice Guidance, 1996. IPCC Good Practice Guidance and Uncertainties Management in National Greenhouse Gas Inventories.

Joseph, K., Viswanathan, C., Trakler, J., Basnayake, B.F.A., Zhou, G.M., 2003. Regional networking for sustainable landfill management in Asia. In: Proceedings of the Sustainable Landfill Management Workshop, 3–5 December 2003 Anna University, Chennai, 2003, pp. 39.

Kameswari, K.S.B., Ravindranath, E., Ramanujam, R.A., Rajamani, S., Ramasami, T., 2003. Bioreactor landfills for solid waste management. In: Proceedings of the Sustainable Landfill Management Workshop, 3–5 December 2003 Anna University, Chennai, 2003, pp. 39.

Knowles, R., 2005. Denitrifiers associated with methanotrophs and their potential impact on the nitrogen cycle. Ecological Engineering 24, 441–446.

Kumar, S., Mondal, A.N., Gaikwad, S.A., Devotta, S., Singh, R.N., 2004a. Qualitative assessment of methane emission inventory from municipal solid waste disposal sites: a case study. Atmospheric Environment 38, 4921–4929.

Kumar, S., Gaikwad, S.A., Shekdar, A.V., Kshirsagar, P.S., Singh, R.N., 2004b. Estimation method for national methane emission from solid waste landfills. Atmospheric Environment 38, 3481–3487.

Mandernack, K.W., Kinney, C.A., Coleman, D., Huang, Y.S., Freeman, K.H., Bogner, J., 2000. The biogeochemical controls of N_2O production and emission in landfill cover soils: the role of methanotrophs in the nitrogen cycle. Environmental Microbiology 2 (3), 298–309.

Mitra, A.P., Gupta, P.K., Sharma, C., 2002. Refinement in methodologies for methane budget estimation from rice paddies. Nutrient Cycling in Agroecosystem 64, 147–155.

MOEF, 2006. Hazardous waste: special reference to municipal solid waste management. Available from <http://envfor.nic.in/soer/2001/ind_waste.pdf> and <www.envfor.nic.in/divisions/cpoll/delpolln.html> (accessed 31.05.06).

NATCOM, 2004. India's initial national communication to the United Nations Framework Convention on Climate Change. Ministry of Environment and Forests, Government of India, p. 35.

NIUA, 1989. Upgrading Municipal Services: Norms and Financial Implications. National Institute of Urban Affairs, New Delhi.

Onk, H., 1996. Dutch abiogenic emissions of methane and nitrous oxide and options for emission reduction. Energy Conversion Management 37 (6–8), 985–989.

Pachauri, R.K., Sridharan, P.V., 1998. In: Pachauri, R.K., Batra, R.K. (Eds.), Directions, Innovations and Strategies for Harnessing Action for Sustainable Development. TERI, New Delhi.

Parashar, D.C. et al., 1996. Methane budget from paddy fields in India. Chemosphere 33, 737–757.

Park, J.W., Shin, H.C., 2001. Surface emission of landfill gas from waste landfill. Atmospheric Environment 35, 3445–3451.

Rao, J.K., Shantaram, M.V., 2003. Soil and water pollution due to open landfills. In: Proceedings of the Sustainable Landfill Management Workshop, 3–5 December 2003 Anna University, Chennai, 2003, pp. 27–38.

Rinne, J., Pihlatie, M., Lohila, A., Thum, T., Aurela, M., Tuovinen, J.P., Laurila, T., Vesala, T., 2005. Nitrous oxide emissions from a municipal landfill. Environmental Science and Technology 39 (20), 7790–7793.

Sinha, C., 1997. Open burning of municipal solid waste: State level Analysis. TERI Monitoring on Environmental Science 2 (2), 71–75.

TEDDY (Tata Energy data directory year book), 2001. Characteristics of municipal solid waste (%) on weight basis, Tata Energy Research Institute, New Delhi.

Vishwanathan, C., Trakler, J., 2003. Municipal solid waste management in Asia: A comparative analysis. In Proceedings of the Sustainable Landfill Management Workshop, 3–5 December Anna University, 2003, pp. 5, 40.