Municipal Solid Waste Characterization and its Assessment for Potential Methane Generation: A Case Study

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Abstract

There has been a significant increase in municipal solid waste (MSW) generation in India during the last few decades and its management has become a major issue because the poor waste management practices affect the health and amenity of the cities. In the present study various physico-chemical parameters of the MSW were analyzed to characterize the waste dumped at Gazipur landfill site in Delhi, India, which shows that it contains a high fraction of degradable organic components. The decomposition of organic components produces methane, a significant contributor to global warming. Based on the waste composition, waste age and the amount of total MSW dumped, a first order decay model (FOD) was applied to estimate the methane generation potential of Gazipur landfill site, which yields a maximum value of 15.3 Gg per year. This value accounts about 1-3 % of the Indian landfill methane emission. Further a comparison of FOD with a recently proposed triangular model was also performed and it shows that both models can be used for the estimation of methane generation. However the decrease of the emission after closure is more gradual in the case of the first order model, leading to larger gas production prediction after more than ten years of closure. The regional and global implications of national landfill methane emission were also discussed.

***Keywords**: landfill, landfill gas, methane, solid waste, waste characterization.*

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Introduction

Landfilling is one of the most common ways of municipal solid waste (MSW) disposal. MSW is made up of different organic and inorganic fractions like food, vegetables, paper, wood, plastics, glass, metal and other inert materials. In cities it is collected by respective municipalities and transported to designated disposal sites. The insanitary methods adopted for disposal of waste cause serious health and environmental problems. The poorly maintained landfill sites are prone to groundwater contamination because of leachate percolation (Mor et al., 2006a). Further they cause bad odors and risks of explosion of methane gas that can accumulate at the landfill site (Tchobanoglous et al., 1993). Typically the landfill gas consists of 50-60 vol% of methane and 30-40 vol% carbon dioxide with numerous chemical compounds such as aromatics, chlorinated organic compounds and sulfur compounds (Khalil, 1999).

Landfills comprise the principal source of anthropogenic methane emission and are estimated to account for 3-19% of anthropogenic emission globally (US EPA, 1994). Recent estimates are in the range of 19-40 Tg yr^{-1} (Bogner and Matthews, 2003). There is an increasing concern for methane, because it is a very potent greenhouse gas and accont about 23 times more powerful than carbon dioxide on a 100-year time horizon (Crutzen, 1991, IPCC, 2001). The methane emissions from municipal solid waste landfills depend on the quantity and composition of the solid waste dumped at the site (Hoeks, 1983; US EPA, 1994) and a significant amount of landfill gas eventually makes its way to the atmosphere (Mor et al., 2006b).. The composition of the waste deposited at the landfill site should, therefore, be ascertained for the estimation of gas emission potential of the landfill site.

The objective of the present study was to characterize the MSW in order to assess the methane generation potential of the Gazipur landfill site. The estimate of the amount of methane produced from this landfill site may provide an aid to potential use of methane as an alternative source of energy, hazard control and/ or for the contribution to the global climate change. Further on the basis of waste composition, waste age and the amount of total waste dumped, a first order decay model (FOD) was applied to estimate the amount of methane produced from the Gazipur landfill site. The results obtained from the FOD model have been compared with predictions of the recently proposed modified triangular model (MTM) by Kumar et al., 2004.

Material and Methods

Site Specification

Delhi, with a population approaching to 14 million is estimated to generate about 7000 metric tons of garbage daily. The per capita generation of solid waste in Delhi ranges from 150 g to 600 g day depending upon the economic status of the community involved and it mainly includes waste from households, industry and medical establishments (Devi and Satyanarayan, 2001).

The earliest landfill was started in 1975 in Delhi near Ring road. In 1978 two other landfills were started at Timarpur and Kailash Nagar. To date 17 landfill sites have been filled and closed. At present there are three large functioning landfill sites at Ghazipur, Okhla and Bhalswa (Fig. 1). These sites are spread over an area of about 1.5 x 10^6 m^2.

The Gazipur landfill site covers an area of 73 acres (3.0×10^5 m^2) and is operational since 1983 (Fig 2). The average waste depth is estimated around 12 m and it mainly comprises of the waste from slaughterhouse, hospital, municipal, residential, construction and demolition waste, and dairy industry. A computerized scale of 25 metric ton weighs all the vehicles transporting the waste to the site.

Collection of Samples

The samples were collected using augers/drillers from 9 boreholes at different locations (Fig 2). The landfill drilling makes it possible to collect samples at various depths and hence from each location 4 samples were collected for each depth-slab. The samples from same location but from different borehole with a similar depth slab were mixed to make one representative sample hence in total 25 samples were collected from different depths to get a representative profile (both horizontally and vertically) of the MSW. The collected samples were passed through a 15 mm sieve as an aid to physical segregation of MSW into different inorganic and organic components.

Analytical Methods

The collected samples were transferred to the laboratory on the day of sampling for their physico-chemical analysis. The moisture content and total solids were determined gravimetrically. For this purpose the samples were oven dried for 48 hours at 105 °C. One of the fractions obtained in the segregation process was a mixture of Kitchen/ food waste, plants and soil, and will be referred as compostable matter in this paper. The dried biodegradable fraction of MSW was analysed for pH, volatile solids, potassium, phosphorus, sulfur, oxygen, carbon, hydrogen and nitrogen. pH was analyzed by shaking 50 g of waste in 250 ml of water for 24 hours and analyzing by pH meter. Organic matter, volatile solids and ash content were determined by weight loss on ignition methods. In this 25 g of dry waste was ignited at 360^{o}C for evaluating the organic matter and at 550°C for 24 hours to determining the quantity of volatile solids and ash content (US EPA, 2001). Further, flame photometry was used for potassium analysis while phosphorus and sulfur were determined by gravimetric methods. The fraction of carbon, hydrogen, nitrogen and oxygen were determined by CHN/O analyser (2400 Perkin Elmer).

Landfill Gas Production Modeling

First Order Decay Model

Several methods have been described for modeling landfill gas formation. (Augenstein and Pacey, 1991; Popov and Power, 1999). In general, landfill gas formation models are not based on microbiological or biochemical principles, but more on a practical description of formation, as observed in laboratory experiments or in full-scale recovery projects.

Landfill gas is formed as a result of biodegradation of the organic carbon in the waste: per kg of organic carbon that degrades, about 1.87 m^3 of landfill gas normalized to 1 atm and 0°C is produced (Oonk et al., 1994). The gas formation on a landfill at some moment in time α_t is proportional to the decay of organic material at that time:

$$\alpha_t = -1.87 A \frac{dC}{dt} \qquad (1)$$

Where α_t is the landfill gas formation at a certain time (m^3/year), A is amount of waste deposited (ton) and $\frac{dC}{dt}$ is rate of carbon degradation; where C (kg/ton) is the amount of organic carbon which can be converted into gas per ton of waste.

The effect of age is accounted for in the first order decay model. The organic carbon in a certain amount of waste is assumed to decay exponentially with time. The degradation of organic material can be described as an n^{th} order reaction equation:

$$-\frac{dC}{dt} = k_1 . C^n \qquad (2)$$

For a first order model, n = 1 and k_1 is the rate of degradation per year. Equation 2 states that the rate of loss of the decomposable matter is proportional to the amount of decomposable matter.

The model assumes that the factor limiting the rate of methane production at a landfill is the amount of material remaining in the landfill that will ultimately form methane. It assumes that other variables and factors affecting the decomposition process are not limiting the rate of methane production. However, it has already been seen that certain other factors certainly have an impact on methane formation in a landfill. This indicates that the rate of gas production is lower than that determined on the availability of substrate alone (Christensen et al., 1989). To eliminate this uncertainty into the model a formation factor or generation factor (ζ) is added due to the heterogeneity of the waste composition as shown in equation 3. Anaerobic decomposition can be hindered in specific microenvironments due to unsuitable environmental conditions; the formation factor takes that into account.

Assuming that a certain fraction (ζ) of the waste is converted into landfill gas, and subsequently solving the differential equation (2), results in a description of C as a function of C_0 and time. Substitution of these solutions of relation (2) in (1), results in the first order model-

$$\alpha_t = \zeta 1.87 A C_0 k_1 e^{-k_1 t} \tag{3}$$

Where α_t is the landfill gas formation at a certain time (m^3 per year), ζ is the formation factor, k_1 is the degradation rate constant ($year^{-1}$), A is the amount of waste deposited (ton), C_0 is the amount of degradable organic carbon in the waste (kg/ton) at the time of deposition, t is time elapsed in years since deposition (year), and the factor 1.87 has the dimension $m^3\,kg^{-1}$. The Hoeks (1983) and US EPA (1994) models are also basically the same as the model outlined above.

Modified Triangular Model (MTM)

The gas generation rate can also be estimated with the triangular model (Kumar et al. 2004). This model assumes that the degradation takes place in two phases. The first phase starts after 1 year of deposition and the rate increases linearly from zero at 1 year after deposition to a maximum value at 6 years after deposition and then decreases linearly to zero at 16 years after deposition. The total gas generation (G) during the period t +1 to t +16, with t the year of waste deposition is given by:

$$G = \zeta 1.87 A_t C_0 \quad (4)$$

Where A_t is the amount of waste deposited in year t.

The gas production pattern assumed in this model has a triangular shape, as illustrated in Fig. 3 of Kumar et al. (2004). By equating the area of the triangle to the total gas generation, the gas generation in each of years t + 1 to t + 16 can be calculated. Estimates of landfill gas generation based on both methods will be presented in the next section.

Results and Discussion

Waste Characterization

Physical and chemical analysis of the waste is important to characterize and classify the municipal solid waste for its proper management and for accurate estimation of the amount of landfill gas produced from the municipal solid waste. The physical survey of Gazipur landfill site shows that the non-degradable fraction dumped at the site includes ferrous and non-ferrous metals, earthenware, stones and brickbats, plastics, glass and ceramics etc. The organic fraction includes paper/cardboard, rubber/leather and compostable matter. Table 1 shows the physical properties of Gazipur MSW on wet weight basis, whereas chemical composition of MSW at various depths is depicted in Table 2.

The compostable material forms a major fraction of MSW and is found to increase with depth. The chemical parameters do not show significant variations with depth except for the moisture content, which increases from an average value of 30 % in the top 3 meter to 45 % in the bottom 3 meter of the waste (Table 2), whereas the average total soild content was 59.4 ±13.6

%. The increase in moisture content in deeper layer may be related to the leachate accumulation and it provide the basis for the hydrolysis of organic materials. Once the organic matter is hydrolyzed and dissolved in water, landfill gas forms quickly (Tchobanoglous et al., 1993).

The variation of the moisture content of MSW is also dependent on the composition of the waste and the climatic conditions. Moisture content in the landfill is very important, if sufficient moisture is not available then gas formation will not proceed and in some cases will not start at all. Thus methane production rate is very dependent on the moisture content of the waste. Dach et al., 1995 have also reported that water content is the most important parameter for kinetics of degradation. Reduced biodegradation or no biodegradation takes place when moisture content is below 25%.

The optimum pH for landfill gas production has been reported to be near 7.0 and gas production ceased at a pH of 5.5 (Farquhar and Rovers, 1973). During the methane fermentation phase of decomposition acids and hydrogen gas are converted to methane and carbon dioxide; and pH rises to a more neutrals value. In the present study all the samples had a slightly alkaline pH in the range of 7.4 - 8.4 and a shift toward more alkaline pH (from low pH to high pH) was observed in the samples withdrawn at suitable distance from surface to bottom, indicating the presence of methane fermentation phase.

Volatile solids also play an important role in landfill gas formation and their content at Gazipur landfill varies from 24.6 to 31.6 % with an average value of 28.2 ±2.5 % on wet weight basis, whereas the average ash content of the waste was 71.8 ±2.5 %. The presence of carbon content is also essential for landfill gas formation. The lesser the carbon content the lower will be the gas formation. The carbon content of MSW at Gazipur varied from 5 to 11 %, with an average value of 8.35 ±1.6 %. Following carbon, the nitrogen and phosphorus in particular are also essential for microbial activity in a landfill. The anaerobic ecosystem assimilates only a small part of the substrate into the new cells and therefore requires much less nitrogen and phosphorus, than the aerobic system. The average nitrogen content in the sample was 0.94 ±0.13 %, while phosphorus content was 0.62 ±0.1 % on dry weight basis.

Recommendations for MSW Management in Delhi

Based on the waste characteristics at Gazipur landfill site, the following recommendations are made for the proper management of MSW in Delhi, which of course follow the rule of reduce, reuse and recycle.

a.) Segregation of waste at the source is always a best practice as waste characteristics show that plastic (7.3±7 %), paper (3.7±3 %), cloths (23.3±4.5 %) and metal (2.7±1.7 %) form a significant fraction of the MSW and this fraction can be recycled. Frequent movement of scavengers and rag-pickers can be seen at the landfill site. However, the figures above are based on measurements of the buried waste, after such scavenging activity, which shows that a significant amount of recyclable waste remains dumped at the landfill. Furthermore with this strategy, the quality of compost will be much better b.) Construction and demolition waste can also be recycled. We suggest reuse of such material in construction activity and as raw material for the formation of roads and highways. Considering that lots of construction activities are going in and around Delhi the reuse of such material should not be a problem. c.) On the basis of type of waste different categories of waste should be landfilled separately at the sites e.g compostable waste. d.) The use of biodegradable material as compost is recommended as MSW in Delhi contains a significant amount of compostable waste (59.2±10 %). This will not only help the municipalities in an economical way but also will reduce the dependence on synthetic fertilizers.

If we are able to use a landfill in an optimal way, it will not only help to operate it in economical way but also we can also use it for a long duration. Land price has increased significantly during last decades and it is increasingly difficult to find a suitable place for a landfill. Further to this some campaign should also be organized by the respective municipalities to create general awareness among people for the proper disposal of waste.

Estimation of Methane Production at Gazipur Landfill Site

First-Order Decay Model Estimation

The first order decay model is most widely used for the prediction of landfill gas because it accounts for the effect of age (Hoeks, 1983; Van Amstel et al., 1993; Oonk and Boom, 1995). Oonk et al (1994) have validated the landfill gas formation model. Nine landfill sites in The Netherlands were included for the verification and the predicted values of gas formation by the first order model were compared with the observed ones. A majority of the results showed relative errors of less than 22%.

In the present study the first order kinetic model has been used to estimate the methane generation and has been compared with the triangular model. The estimation of methane generation was calculated based on the amount of waste dumped at Gazipur landfill site. The waste contains an average moisture content of 40 % (wet weight basis) and the carbon fraction of the waste is 8.35 % on dry weight basis (Table 2). ζ is typically of the order of 0.5 to 0.6 and the value of 0.58 has been used in this study (Oonk et al., 1994), whereas $k_1 = 0.094$ year^{-1} was used from Oonk et al., 1994, who have validated these values for the first order model.

The records of waste dumped at the Gazipur landfill site were available only for the years 1997-2001. The amount of waste dumped from year 1996 to 1983 were extrapolated assuming that the waste dumped in 1983 was zero, as the start year for this landfill site was 1984, and increased linearly between 1983 and 1996. The estimated total landfill gas emission is 42.76×10^6 m^3 year^{-1}, as can be seen in Table 3. As the Gazipur landfill site is spread over an area of 3×10^5 m^2 it will yield a landfill gas potential of 142.5 m^3/m^2/year. Typical methane fraction of landfill gas is 50 %, implying that the landfill will produce 71.3 m^3/m^2/year or 21.38 *x* 10^6 m^3/year or 954.5 *x* 10^6 mol/ year or 15.3 *x* 10^6 kg /year of methane.

However, frequently scavengers remove some of the waste deposited. This can reduce the garbage by around 20 % (Agarwal et al., 2005). Since the carbon percentage was calculated as a percent of the waste in its final form, the amount of carbon and hence the amount of methane generated will also be lesser by approximately 20 % i.e. 57 m^3/m^2/year.

On the other hand, our calculation underestimates the actual methane emission because the current carbon content of the landfill was used in equation (3) instead of C_0, the carbon content at the time of disposal. As an alternative calculation we estimated C_0 as:

$$C_0 = C/(1 - \zeta - \zeta \exp(-k_1\, t)) \quad (5)$$

Thus different values of C_0 were obtained for each year of disposal. Using these values an estimate of the 2001 landfill gas emission was calculated. The result was 52 *x* 10^6 m^3 $year^{-1}$ (or 26 *x* 10^6 m^3/year of methane), about 20% than the calculation outlined in Table 3. We conclude that the influence of scavengers and the influence of a changing carbon concentration on the estimate cancel each other, and 21 *x* 10^6 m^3/year methane is the most realistic estimate.

Further, we only have recorded waste dumped data for the year 1996 to 2001 and have extrapolated this to obtain the data for the years 1984-1995; this could also lead to an error in the estimate.

However, we can see from Table 3 that the waste from the year 1996- 2001 contributes nearly 63 % of the landfill gas or methane generated. As there is no historical record of the waste dumped, waste deposited may have a nearly exponential increasing characteristic rather than a linear increase one, we can assume that figures generated for 1984-1995 are an overestimate. Assuming that no waste was deposited during this period, we can assume that our methane generation can be lesser by a maximum of 37 %, i.e. the value could be as low as 44.9 m^3/m^2/year. But this is a limit assuming no garbage deposited during 1984-1995 and the actual would be more than this and approximately will range between 44.9 and 71.3 m^3/m^2/year.

The scarcity of historical data may mislead the estimation of methane, which is very important for methane emission inventories with relation to global warming. Our study provides an aid for the estimation of methane and reduces the uncertainty of the estimation of methane emissions.

Modified Triangular Model (MTM) Estimation

The gas generation between years 1983 and 2019 is computed for every year of deposition. The methane emission estimated using equation 4 is equated to the area of the triangle. The peak value (h) of methane emission shown in Fig. 3 of Kumar et al. (2004) is calculated knowing the volume of gas and the base of the triangle (15 years). Using the peak value, other ordinates were calculated. This procedure is applied for every year from 1983 to 2019 and the gas emission values for consecutive years are added up to get the volume of methane emission for every year. The value obtained for 2001 was 75.57 m^3/m^2/year, very similar to the value obtained with the first-order model.

Gazipur landfill site has almost reached its maximum capacity for waste dumped, so it is expected that there will be no waste deposited after 2005. Fig. 4 shows the methane production of the landfill, as calculated from the first order model and the triangular model. Total methane generation is the same for both models and they give similar predictions during the active phase of the landfill. After closure the first order model predicts an immediate decrease of the landfill gas production rate, whereas the triangular model predicts maximum production three years later. However, the decrease is more gradual in the case of the first order model, leading to larger gas production prediction after more than ten years of closure. If the rate of gas production is known for given period of time, this can be used for design and feasibility studies for landfill gas utilization systems.

Regional and Global Implication of Gazipur Methane Emission

The global maximum landfill methane emission ranges from 19 to 40 Tg per year, with value towards the lower end of this range being most realistic (Bogner and Matthews, 2003). India figures among the top ten contributors to the greenhouse gas emissions, although the current gross emissions per capita in India are only one sixth of the world average (ADB, 1994). Garg et al. (2001) has estimated that methane emission in India contributed 27 % to carbon dioxide equivalent greenhouse gases in 2000 and it amounted to approximately 18.63 Tg of methane in 2000, while MSW contribute 10 % to this. Kumar et al. (2004) found considerably lower values. They estimated national methane emission from solid waste disposal sites using the IPCC default methodology, and found values increasing from 263 Gg in year 1980 to 502 Gg in year 1999, less than a third of the Garg et al. (2001) estimate. Gurjar et al. (2004) estimates that total methane emission for Delhi have increased over by about 40 % from 133 Gg in 1990 to 192 Gg in 2000, the solid waste disposal being the main source of methane in Delhi, contributing to about 80 % of the emission. Based on our practical evaluation of MSW at Gazipur landfill, the maximum methane emission was estimated at 15.3 Gg per year.

Based on these estimations it can be concluded that the maximum methane emission from Gazipur landfill site is around 0.08 % of the global landfill methane emission. The contribution of Gazipur landfill to waste disposal in Delhi has increased over the years and is roughly one third at present of total waste. So it is reasonable to assume that roughly one fourth of the landfill methane emissions in Delhi occur at Gazipur. Bearing that in mind, the estimate of Gurjar et al. (2004) mentioned above is probably an overestimate. Our methane emission estimate for Gazipur landfill represents 0.8 % of the landfill methane emission in India as estimated by Garg et al. (2001), and 3 % of the landfill methane emission in India as estimated by Kumar et al. (2004).

Waste disposal in Gazipur represents an urban population of 3-4 million people, which is approximately 1-1.4% of the urban population in India. Given the pronounced influence of economical status on waste generation, it can be expected that the contribution of Gazipur landfill to the landfill methane emission in India is somewhat more than 1-1.4%. At present the Indian population is around 1027 million and the urban population form 27.78 % of it (http://www.censusindia.net/results/). Considering Gazipur landfill emission as representative, our estimation yields a value of 1.25 Tg of methane per year from Indian MSW. This value lies in between the estimate of Garg et al. (2001) and Kumar et al. (2004), with more close to Garg et al., 2001. Further, it has to be noticed that with the increase in economical and social status of small towns and cities, an increase in total MSW is expected and thus in future the methane emission form MSW will increase. It demands for safe disposal of MSW and abatement of methane emission.

As the Gazipur landfill site is not planned and it has no collection system for methane recovery, the landfill gas is emitted to the atmosphere. Considering the impact of methane in global warming it is necessary to take some action to reduce methane emission from landfill sites. The collection of landfill gas as a potential source of energy can be applied to reduce such emissions but it requires proper design and planning for a landfill.

Optimization of this integral efficiency implies that landfill gas recovery should be started as soon as possible. High efficiency landfill gas recovery is possible and will be economical, if one takes landfill gas formation and recovery into consideration when the landfill is designed. Recovery is best done in a combination of compartment-wise landfilling and construction of well systems.

Other approaches may include the reduction of the organic fraction (may be done by increased combustion or separate collection and treatment of vegetable, fruits, garden waste, paper and textile waste) and by increasing the oxidation capacity of the cover layer. Mor et al. (2006b), for instance, have studied compost as cover material to increase the oxidation capacity of the landfill cover. Such practice is realistic, when no other option is feasible for the mitigation of greenhouse gas emission from landfills. Mor et al. (2006b) calculated that a compost layer of 28-55 cm can theoretically oxidize all methane emitted by the Gazipur landfill site.

Conclusion

Physical and chemical characterization of Gazipur MSW shows that it contains a high proportion of degradable organic matter, which likely indicate that there is a vital scope for the development of landfill gas technology in India. At present there is no planned landfill in India with collection system for methane recovery and hence it is eventually emitted to the atmosphere, contributing to the global warming. Based on waste characteristics and amount of waste dumped, the application of FOD and MTM was applied for the estimation of methane emission from Gazipur MSW. Both models yield very similar values and can be used for the estimation of methane emission, where a scarcity of historical data exist. These estimations amount to a maximum value of 15.3 Gg of methane per year from Gazipur landfill. Considering the Gazipur as a case, we also tested if the existing inventories for total national methane emission are realistic. As our study is based on the characterization of waste in an actual landfill, it is more reliable than other estimate, and the total projected emission falls in between the other inventories and hence limits the uncertainties. Further, the estimates of methane emission by these models shows that the Gazipur landfill site significantly contributes to the atmospheric methane emission, although it could be reduced if the site was systematically planned and the landfill gas formation and recovery was taken into account when the landfill was designed. To reduce the greenhouse gas emission from the Gazipur landfill site, increasing the oxidizing capacity of the top layer or collection of methane to flare it, are recommended.

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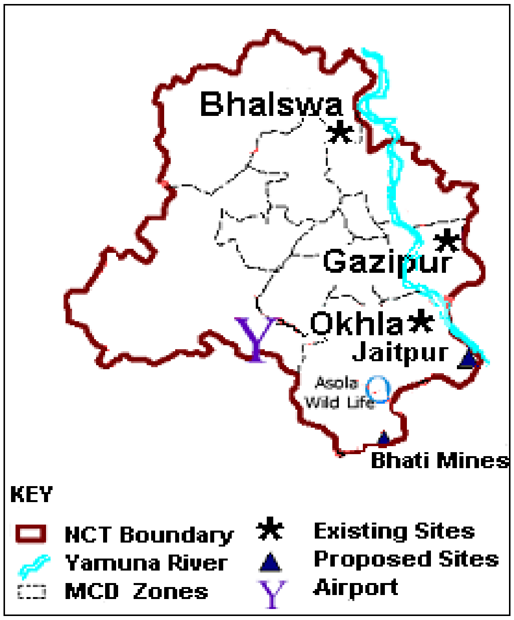

Fig. 1: Location of Gazipur and other landfill sites in Delhi.

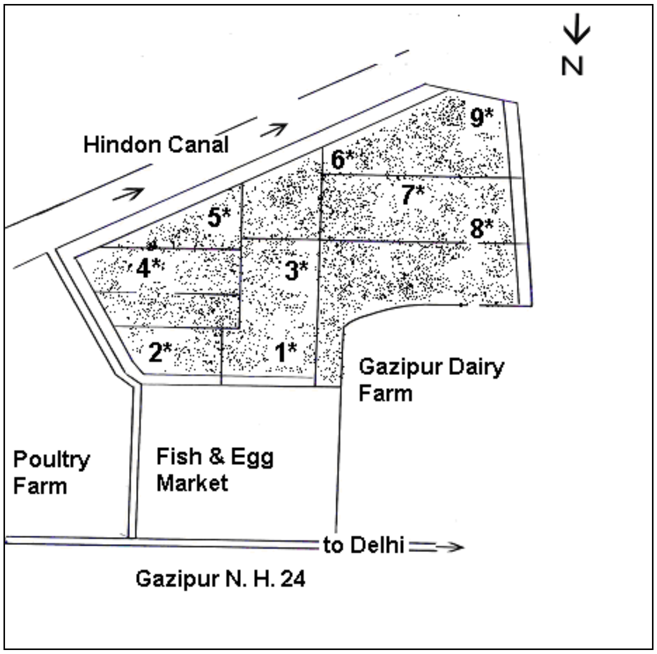

Fig. 2: Sketch map of sampling sites near and around Gazipur landfill site.

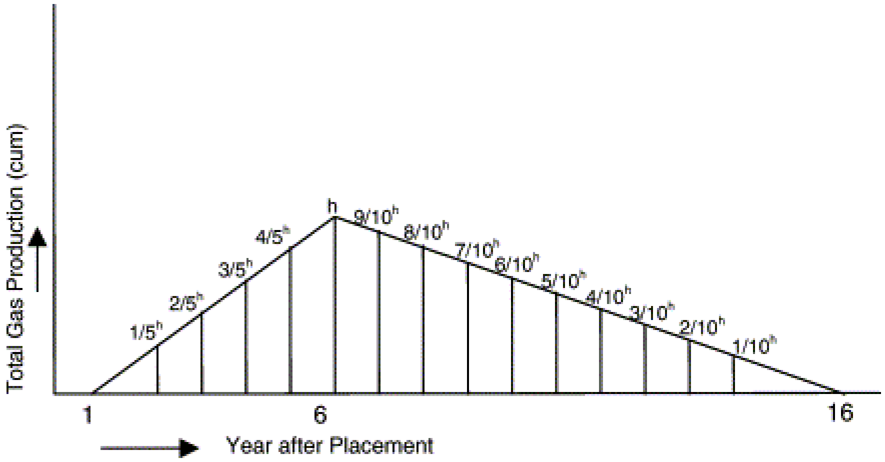

Fig. 3: Triangular form for gas production (from Kumar et al., 2004).

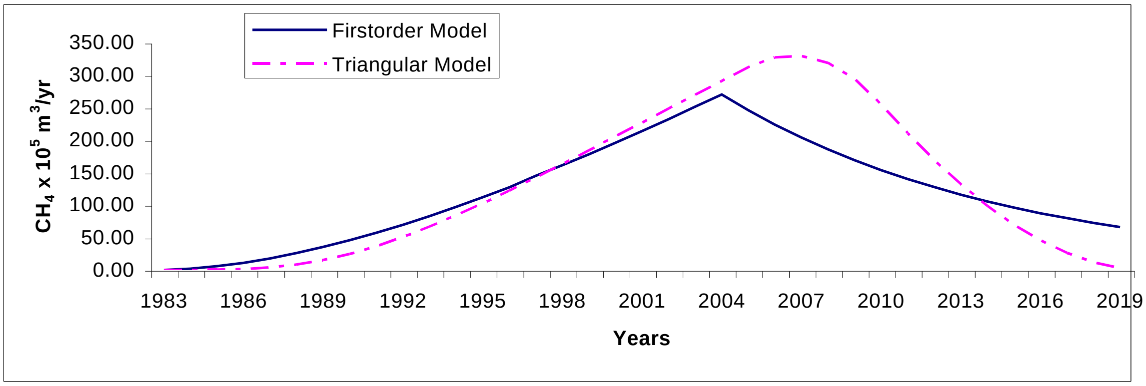

Fig 4: Estimation of landfill gas formation over time at Gazipur landfill site.

Table 1: Physical composition of Gazipur landfill MSW at various depth (% on a wet weight basis).

Borehole No.	**Depth (m)**	**Plastic[1]**	**Paper[2]**	**Cloth**	**Metal[3]**	**Stone[4]**	**Compostable[5]**
1	0 to 3	8.7	14.1	21.4	0	8.5	47.3
1	3 to 6	7.6	14.5	13.6	6	0	53.9
1	6 to 9	0	5.2	7.5	0	8.2	79.1
2	0 to 3	35.1	5.8	32.2	0	0	16.9
3	0 to 3	5.2	2.1	17.7	2.9	0	72.1
3	3 to 6	0	0	9	0	15.4	76.6
3	6 to 9	0	0	20.1	0	0	79.9
4	0 to 3	6.4	6.4	11.1	4.2	0	71.9
4	3 to 6	5.2	0	16.4	13.2	6.6	58.2
4	6 to 9	0	0	20.7	4.6	0	74.7
5	0 to 3	29.7	12	34.8	1.9	0.9	20.7
5	3 to 6	38.4	5.8	14.7	17.9	0	23.2
5	6 to 9	0	0	32.7	0	0	67.3
6	0 to 3	7	11.5	27.5	1.8	1.5	50.7
6	3 to 6	0	0	14.9	0	4.7	79.4
6	6 to 9	0	0	43	0	1	56
7	0 to 3	5	3.8	35.6	1.9	0	53.7
7	3 to 6	2.6	2.6	10.1	0	9.7	75
7	6 to 9	0	0	17.8	0	5.5	76.7
7	9 to 12	0	0	36.4	0	2.7	60.9
8	0 to 3	12.2	3.2	19.2	0	0.6	64.8
8	3 to 6	0	0	46.7	0	1.1	52.2
8	6 to 9	0	0	44.8	6.8	0	48.4
9	0 to 3	20.5	8.1	24.8	2.9	0.4	43.3
9	3 to 6	5	1.1	20	0	15.4	58.5
Average	0 to 3	***14.3±11.3***	***7.4±4.3***	***24.9±8.4***	***1.7±1.5***	***1.3±2.7***	***49±20***
	3 to 6	***7.4±12.9***	***3.0±5.1***	***18.2±12***	***4.6±7.2***	***6.6±6.4***	***59.6±18.3***
	6 to 9	***0±0***	***0.7±2***	***26.7±13.9***	***1.6±2.9***	***2.1±3.4***	***68.9±12.3***
∑Average		**7.3±7.2**	**3.7±3.4**	**23.3±4.5**	**2.7±1.7**	**3.3±2.9**	**59.2±9.9**

[1] Plastic bags, plastic bottles, packaging material

[2] Paper, wrapper, cardboard, packaging paper

[3] Cables, foils, ferrous and non- ferrous material

[4] Stones, bricks, construction material

[5] Vegetables, food, garden waste, wood

Table 2: Chemical composition of MSW at various depth at Gazipur landfill.

Borehole No.	**Depth (m)**	**pH**	**Moisture content***	**Volatile Solid***	**Organic matter***	**N***	**C***	**H***	**P***	**K***	**S***
1	0 to3	7.8	23.9	27.2	23.6	0.84	6.1	0.9	0.8	0.7	<0.01
1	3 to 6	8.2	30.3	31.6	27	0.79	7.6	0.96	0.7	0.5	<0.01
1	6 to 9	8.2	21.4	27	22.6	0.99	8.98	1.17	0.6	1	<0.01
2	0 to 3	7.9	27.2	31.6	26.7	0.74	6.02	0.84	0.7	1	<0.01
3	0 to 3	8.6	10.7	26.3	21.8	0.96	9.67	1.15	0.6	1.2	<0.01
3	3 to 6	8.4	51.2	26.9	22.1	0.97	9.32	1.22	0.5	1.2	<0.01
3	6 to 9	7.6	38.9	25.3	21.8	0.75	5.74	0.79	0.6	1.5	<0.01
4	0 to 3	7.8	40.5	31.1	26.4	0.78	5.89	0.87	0.8	1	<0.01
4	3 to 6	8.1	45.6	29.6	26.7	0.94	8.91	1.25	0.7	1	<0.01
4	6 to 9	8.1	53.2	30.1	27.1	1.20	9.37	1.35	0.7	0.7	<0.01
5	0 to 3	7.9	31.9	29.1	23.4	0.89	9.30	1.25	0.6	1	<0.01
5	3 to 6	8.6	42.6	27.1	23	0.83	8.36	1.04	0.8	0.5	<0.01
5	6 to 9	8.4	40.2	25.6	21.5	0.94	8.52	1.14	0.7	0.5	<0.01
6	0 to 3	8.2	37.1	30.8	25.9	1.05	8.85	1.25	0.6	1.2	<0.01
6	3 to 6	7.8	60.9	24.6	20.8	0.95	9.58	1.35	0.6	1	<0.01
6	6 to 9	8.1	52.6	26.9	21.1	0.84.	6.92	0.98	0.6	0.7	<0.01
7	0 to 3	8	27.2	24.6	20.8	1.11	10.63	1.55	0.5	0.7	<0.01
7	3 to 6	8.2	43.6	24.9	21	1.16	10.46	1.53	0.6	0.7	<0.01
7	6 to 9	8.4	54.5	31.6	27.9	0.99	7.38	1.11	0.6	1	<0.01
7	9 to 12	7.9	57.7	26.6	23.5	1.08	8.79	1.36	0.6	1	<0.01
8	0 to 3	8.1	30.2	24.9	20.5	0.97	8.39	1.32	0.4	1	<0.01
8	3 to 6	8.6	53.5	31.2	26.8	0.95	9.90	1.38	0.5	1.2	<0.01
8	6 to 9	8.4	54.3	28.9	23.1	1.02	10.8	1.40	0.5	1	<0.01
9	0 to 3	8.4	30.2	30.2	26.9	0.92	8.05	0.96	0.7	1.2	<0.01
9	3 to 6	8.2	43.8	31.4	28.2	0.78	5.00	0.83	0.6	1	<0.01
Average	0 to 3	***8.1±0.3***	***28.8±8.5***	***28.4±2.7***	***24±2.6***	***0.92±0.12***	***8.11±1.7***	***1.13±0.24***	***0.63±0.13***	***1.0±0.19***	-
	3 to 6	***8.3±0.3***	***46.4±9***	***28.4±2.9***	***24.5±3***	***0.92±0.12***	***8.66±1.7***	***1.2±0.23***	***0.62±0.1***	***0.89±0.29***	-
	6 to 9	***8.2±0.3***	***45±12.4***	***27.9±2.4***	***23.6±2.8***	***0.99±0.15***	***8.26±1.7***	***1.14±0.21***	***0.6±0.07***	***0.91±0.32***	-
∑Average		**8.2±0.3**	**40.1±12.9**	**28.2±2.5**	**24±2.6**	**0.94±0.13**	**8.35±1.6**	**1.16±0.22**	**0.62±0.1**	**0.94±0.25**	**-**

* on wet weight basis and recorded as percentage of total mass except for pH.

Table 3: Estimation of Methane generation at Gazipur Landfill Site, Delhi, for the year 2001 according to the first-order decay model.

Year of disposal	***t*** **(Year)**	***A*** **(ton)**	**$A.C_0$ (ton)**	**LFG (m^3/yr)**	**CH_4 (m^3/yr)**
2001	0	83.85 x 10^4	7.01 x 10^4	7.14 x 10^6	3.57 x 10^6
2000	1	78.64 x 10^4	6.57 x 10^4	6.10 x 10^6	3.05 x 10^6
1999	2	74.12 x 10^4	6.19 x 10^4	5.23 x 10^6	2.62 x 10^6
1998	3	68.67 x 10^4	5.74 x 10^4	4.41 x 10^6	2.21 x 10^6
1997	4	68.17 x 10^4	5.70 x 10^4	3.99 x 10^6	1.99 x 10^6
1996	5	59.52 x 10^4	4.97 x 10^4	3.17 x 10^6	1.58 x 10^6
1995	6	54.94 x 10^4	4.59 x 10^4	2.66 x 10^6	1.33 x 10^6
1994	7	50.36 x 10^4	4.21 x 10^4	2.22 x 10^6	1.11 x 10^6
1993	8	45.78 x 10^4	3.83 x 10^4	1.84 x 10^6	0.92 x 10^6
1992	9	41.20 x 10^4	3.44 x 10^4	1.51 x 10^6	0.75 x 10^6
1991	10	36.63 x 10^4	3.06 x 10^4	1.22 x 10^6	0.61 x 10^6
1990	11	32.05 x 10^4	2.68 x 10^4	0.97 x 10^6	0.49 x 10^6
1989	12	27.47 x 10^4	2.30 x 10^4	0.76 x 10^6	0.38 x 10^6
1988	13	22.89 x 10^4	1.91 x 10^4	0.57 x 10^6	0.29 x 10^6
1987	14	18.31 x 10^4	1.53 x 10^4	0.42 x 10^6	0.21 x 10^6
1986	15	13.73 x 10^4	1.15 x 10^4	0.29 x 10^6	0.14 x 10^6
1985	16	9.16 x 10^4	0.77 x 10^4	0.17 x 10^6	0.09 x 10^6
1984	17	4.58 x 10^4	0.38 x 10^4	0.08 x 10^6	0.04 x 10^6
Total:	**-**	***790.06 x*** 10^4	***66.04 x*** 10^4	***42.76 x*** 10^6	***21.38 x*** 10^6