

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

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15
16 **Abstract**

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

32
33 ***Keywords:*** *landfill, landfill gas, methane, solid waste, waste characterization.*

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37 **Introduction**

38 Landfilling is one of the most common ways of municipal solid waste (MSW) disposal.
39 MSW is made up of different organic and inorganic fractions like food, vegetables, paper, wood,
40 plastics, glass, metal and other inert materials. In cities it is collected by respective municipalities
41 and transported to designated disposal sites. The insanitary methods adopted for disposal of waste
42 cause serious health and environmental problems. The poorly maintained landfill sites are prone
43 to groundwater contamination because of leachate percolation (Mor et al., 2006a). Further they
44 cause bad odors and risks of explosion of methane gas that can accumulate at the landfill site
45 (Tchobanoglous et al., 1993). Typically the landfill gas consists of 50-60 vol% of methane and
46 30-40 vol% carbon dioxide with numerous chemical compounds such as aromatics, chlorinated
47 organic compounds and sulfur compounds (Khalil, 1999).

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

58 The objective of the present study was to characterize the MSW in order to assess the
59 methane generation potential of the Gazipur landfill site. The estimate of the amount of methane

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

66 **Material and Methods**

67 **Site Specification**

68 Delhi, with a population approaching to 14 million is estimated to generate about 7000
69 metric tons of garbage daily. The per capita generation of solid waste in Delhi ranges from 150 g
70 to 600 g day depending upon the economic status of the community involved and it mainly
71 includes waste from households, industry and medical establishments (Devi and Satyanarayan,
72 2001).

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

77 The Gazipur landfill site covers an area of 73 acres ($3.0 \times 10^5 \text{ m}^2$) and is operational since
78 1983 (Fig 2). The average waste depth is estimated around 12 m and it mainly comprises of the
79 waste from slaughterhouse, hospital, municipal, residential, construction and demolition waste,
80 and dairy industry. A computerized scale of 25 metric ton weighs all the vehicles transporting the
81 waste to the site.

82 **Collection of Samples**

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

91 **Analytical Methods**

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

106 **Landfill Gas Production Modeling**

107 ***First Order Decay Model***

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

112 Landfill gas is formed as a result of biodegradation of the organic carbon in the waste: per
113 kg of organic carbon that degrades, about 1.87 m³ of landfill gas normalized to 1 atm and 0°C is
114 produced (Oonk et al., 1994). The gas formation on a landfill at some moment in time α_t is
115 proportional to the decay of organic material at that time:

$$116 \quad \alpha_t = -1.87 A \frac{dC}{dt} \quad (1)$$

117 Where α_t is the landfill gas formation at a certain time (m³/year), A is amount of waste
118 deposited (ton) and $\frac{dC}{dt}$ is rate of carbon degradation; where C (kg/ton) is the amount of organic
119 carbon which can be converted into gas per ton of waste.

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

$$123 \quad -\frac{dC}{dt} = k_1 \cdot C^n \quad (2)$$

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

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

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

$$140 \quad \alpha_t = \zeta 1.87 A C_0 k_1 e^{-k_1 t} \quad (3)$$

141 Where α_t is the landfill gas formation at a certain time (m^3 per year), ζ is the formation
142 factor, k_1 is the degradation rate constant (year^{-1}), A is the amount of waste deposited (ton), C_0 is
143 the amount of degradable organic carbon in the waste (kg/ton) at the time of deposition, t is time
144 elapsed in years since deposition (year), and the factor 1.87 has the dimension $\text{m}^3 \text{kg}^{-1}$. The Hoeks
145 (1983) and US EPA (1994) models are also basically the same as the model outlined above.

146 ***Modified Triangular Model (MTM)***

147 The gas generation rate can also be estimated with the triangular model (Kumar et al. 2004).
148 This model assumes that the degradation takes place in two phases. The first phase starts after 1
149 year of deposition and the rate increases linearly from zero at 1 year after deposition to a

150 maximum value at 6 years after deposition and then decreases linearly to zero at 16 years after
151 deposition. The total gas generation (G) during the period $t + 1$ to $t + 16$, with t the year of waste
152 deposition is given by:

$$153 \quad G = \zeta 1.87 A_t C_0 \quad (4)$$

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

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

159 **Results and Discussion**

160 **Waste Characterization**

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

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

173 %. The increase in moisture content in deeper layer may be related to the leachate accumulation
174 and it provide the basis for the hydrolysis of organic materials. Once the organic matter is
175 hydrolyzed and dissolved in water, landfill gas forms quickly (Tchobanoglous et al., 1993).

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

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

190 Volatile solids also play an important role in landfill gas formation and their content at
191 Gazipur landfill varies from 24.6 to 31.6 % with an average value of 28.2 ± 2.5 % on wet weight
192 basis, whereas the average ash content of the waste was 71.8 ± 2.5 %. The presence of carbon
193 content is also essential for landfill gas formation. The lesser the carbon content the lower will be
194 the gas formation. The carbon content of MSW at Gazipur varied from 5 to 11 %, with an
195 average value of 8.35 ± 1.6 %. Following carbon, the nitrogen and phosphorus in particular are
196 also essential for microbial activity in a landfill. The anaerobic ecosystem assimilates only a

197 small part of the substrate into the new cells and therefore requires much less nitrogen and
198 phosphorus, than the aerobic system. The average nitrogen content in the sample was 0.94 ± 0.13
199 %, while phosphorus content was 0.62 ± 0.1 % on dry weight basis.

200 ***Recommendations for MSW Management in Delhi***

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

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

218 If we are able to use a landfill in an optimal way, it will not only help to operate it in
219 economical way but also we can also use it for a long duration. Land price has increased
220 significantly during last decades and it is increasingly difficult to find a suitable place for a

221 landfill. Further to this some campaign should also be organized by the respective municipalities
222 to create general awareness among people for the proper disposal of waste.

223 **Estimation of Methane Production at Gazipur Landfill Site**

224 *First-Order Decay Model Estimation*

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

231 In the present study the first order kinetic model has been used to estimate the methane
232 generation and has been compared with the triangular model. The estimation of methane
233 generation was calculated based on the amount of waste dumped at Gazipur landfill site. The
234 waste contains an average moisture content of 40 % (wet weight basis) and the carbon fraction of
235 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
236 value of 0.58 has been used in this study (Oonk et al., 1994), whereas $k_1 = 0.094 \text{ year}^{-1}$ was used
237 from Oonk et al., 1994, who have validated these values for the first order model.

238 The records of waste dumped at the Gazipur landfill site were available only for the years
239 1997-2001. The amount of waste dumped from year 1996 to 1983 were extrapolated assuming
240 that the waste dumped in 1983 was zero, as the start year for this landfill site was 1984, and
241 increased linearly between 1983 and 1996. The estimated total landfill gas emission is 42.76×10^6
242 $\text{m}^3 \text{ year}^{-1}$, as can be seen in Table 3. As the Gazipur landfill site is spread over an area of 3×10^5
243 m^2 it will yield a landfill gas potential of $142.5 \text{ m}^3/\text{m}^2/\text{year}$. Typical methane fraction of landfill

244 gas is 50 %, implying that the landfill will produce $71.3 \text{ m}^3/\text{m}^2/\text{year}$ or $21.38 \times 10^6 \text{ m}^3/\text{year}$ or
245 $954.5 \times 10^6 \text{ mol/ year}$ or $15.3 \times 10^6 \text{ kg /year}$ of methane.

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

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

$$253 \quad C_0 = C/(1 - \zeta - \zeta \exp(-k_1 t)) \quad (5)$$

254 Thus different values of C_0 were obtained for each year of disposal. Using these values an
255 estimate of the 2001 landfill gas emission was calculated. The result was $52 \times 10^6 \text{ m}^3 \text{ year}^{-1}$ (or
256 $26 \times 10^6 \text{ m}^3/\text{year}$ of methane), about 20% than the calculation outlined in Table 3. We conclude
257 that the influence of scavengers and the influence of a changing carbon concentration on the
258 estimate cancel each other, and $21 \times 10^6 \text{ m}^3/\text{year}$ methane is the most realistic estimate.

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

262 However, we can see from Table 3 that the waste from the year 1996- 2001 contributes
263 nearly 63 % of the landfill gas or methane generated. As there is no historical record of the waste
264 dumped, waste deposited may have a nearly exponential increasing characteristic rather than a
265 linear increase one, we can assume that figures generated for 1984-1995 are an overestimate.
266 Assuming that no waste was deposited during this period, we can assume that our methane

267 generation can be lesser by a maximum of 37 %, i.e. the value could be as low as 44.9
268 $\text{m}^3/\text{m}^2/\text{year}$. But this is a limit assuming no garbage deposited during 1984-1995 and the actual
269 would be more than this and approximately will range between 44.9 and $71.3 \text{ m}^3/\text{m}^2/\text{year}$.

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

274 ***Modified Triangular Model (MTM) Estimation***

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

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

291 for given period of time, this can be used for design and feasibility studies for landfill gas
292 utilization systems.

293 ***Regional and Global Implication of Gazipur Methane Emission***

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

308 Based on these estimations it can be concluded that the maximum methane emission from
309 Gazipur landfill site is around 0.08 % of the global landfill methane emission. The contribution
310 of Gazipur landfill to waste disposal in Delhi has increased over the years and is roughly one
311 third at present of total waste. So it is reasonable to assume that roughly one fourth of the landfill
312 methane emissions in Delhi occur at Gazipur. Bearing that in mind, the estimate of Gurjar et al.
313 (2004) mentioned above is probably an overestimate. Our methane emission estimate for Gazipur

314 landfill represents 0.8 % of the landfill methane emission in India as estimated by Garg et al.
315 (2001), and 3 % of the landfill methane emission in India as estimated by Kumar et al. (2004).

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

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

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

338 Other approaches may include the reduction of the organic fraction (may be done by
339 increased combustion or separate collection and treatment of vegetable, fruits, garden waste,
340 paper and textile waste) and by increasing the oxidation capacity of the cover layer. Mor et al.
341 (2006b), for instance, have studied compost as cover material to increase the oxidation capacity
342 of the landfill cover. Such practice is realistic, when no other option is feasible for the mitigation
343 of greenhouse gas emission from landfills. Mor et al. (2006b) calculated that a compost layer of
344 28-55 cm can theoretically oxidize all methane emitted by the Gazipur landfill site.

345 **Conclusion**

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

361 formation and recovery was taken into account when the landfill was designed. To reduce the
362 greenhouse gas emission from the Gazipur landfill site, increasing the oxidizing capacity of the
363 top layer or collection of methane to flare it, are recommended.

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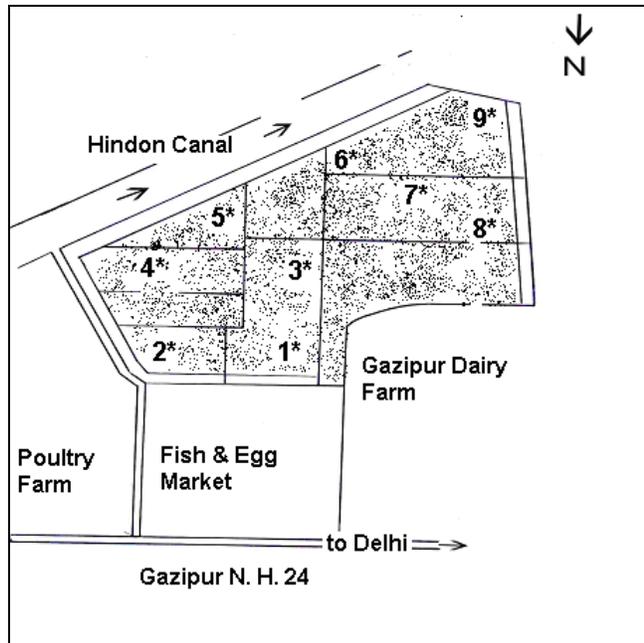
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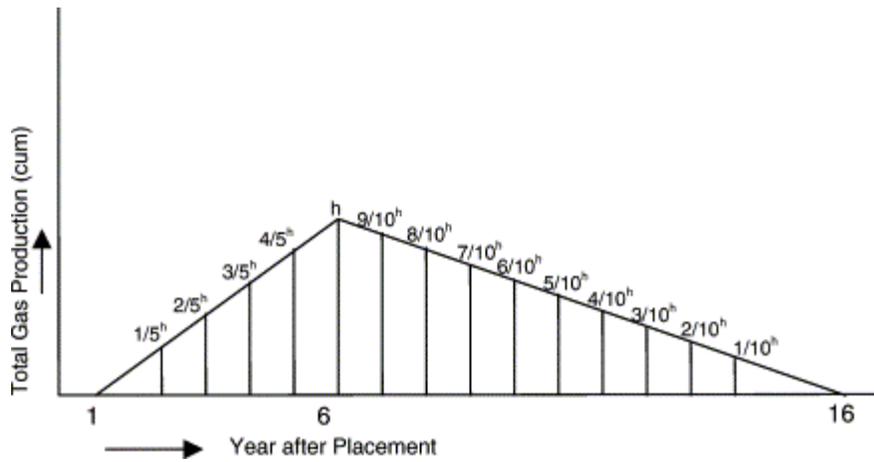
Fig. 1: Location of Gazipur and other landfill sites in Delhi.



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

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

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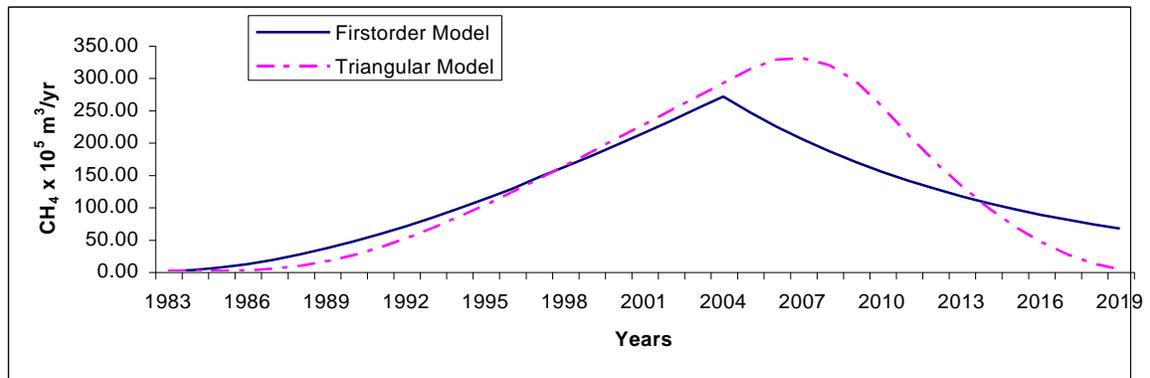
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Fig 4: Estimation of landfill gas formation over time at Gazipur landfill site.

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

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Borehole No.	Depth (m)	Plastic¹	Paper²	Cloth	Metal³	Stone⁴	Compostable⁵
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
ΣAverage		7.3±7.2	3.7±3.4	23.3±4.5	2.7±1.7	3.3±2.9	59.2±9.9

478 ¹ Plastic bags, plastic bottles, packaging material

479 ² Paper, wrapper, cardboard, packaging paper

480 ³ Cables, foils, ferrous and non- ferrous material

481 ⁴ Stones, bricks, construction material

482 ⁵ Vegetables, food, garden waste, wood

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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 to 3	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	-
ΣAverage		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	<i>t</i> (Year)	<i>A</i> (ton)	<i>A.C₀</i> (ton)	LFG (m³/yr)	CH₄ (m³/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 10⁴	66.04 x 10⁴	42.76 x 10⁶	21.38 x 10⁶