Economic Analysis and Life Cycle Impact Assessment of Municipal Solid Waste (MSW) Disposal: A Case Study of Mumbai, India

Supplementary information

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S1. Municipal solid waste generation data

Table S1. Annual waste acceptance rates at dumpsite/landfill

Year	MSW dumped (tonnes)
2016	1505187
2017	1513211
2018	1521278
2019	1529387
2020	1537540
2021	1545736
2022	1553976
2023	1562260
2024	1570588
2025	1578961
2026	1587378
2027	1595840
2028	1604347
2029	1612899
2030	1621497
2031	1630141
2032	1638831
2033	1647567
2034	1656350
2035	1665180
Total	31678156

S2. Economic analysis of landfilling

This section explains the methodology used for performing the detailed economic analysis of the landfilling operation.

The variable cost estimation, such as the cost of fuel for transportation and the cost of electricity are based on the consumption rates and the prevailing prices in Mumbai. The capital cost estimation, in contrast, is challenging. The capital cost values are generally available in literature only at fixed throughput/capacity values. These values need to be scaled based on the actual capacity of the plant/process being set-up. This is done by using the well known engineering approach of cost scaling, which is given as per the following equation:

$$C_2 = C_2\left(\frac{V_2}{V_1}\right)^{\varphi}$$

where, C_1 is the cost of the equipment for a throughput/capacity of V_1 as reported in literature. V_2 is the new throughput/capacity for which the cost C_2 needs to be determined. φ is known as the scaling coefficient, which is typically between 0.6-0.8. This approach is used for scaling the cost of all the equipment (Peters et al., 2003).

Further, if the original value reported in literature is for a different year, the cost further needs to be adjusted for the year of analysis to account for the time value of money. The Chemical Engineering Plant Cost Index (CEPCI) is commonly used for this purpose and is also used in this work. Once the total equipment capital cost is known, Peters et al. (2003) propose coefficients to calculate the other cost components, such as the maintenance cost, as a function of the total equipment capital cost. This approach is adapted here for the economic calculations.

S2.1. Transportation of waste

Transportation cost does not include the cost incurred in door-to-door collection of waste. Instead, only the cost associated with transport of waste to the landfill/dumpsite from different localities is considered. Capacity of truck (10 m^3) used for transporting waste is the weighted average of capacities of different types of vehicles used currently in Mumbai for collecting and transporting waste, as reported in Table S2 (Municipal Corporation of Greater Mumbai, 2017). Fixed capital investment is required for purchasing trucks at the start of the year and after 10 years, when the old trucks are to be replaced with new trucks. No extra truck is purchased in order to replace vehicles under maintenance. Operating and maintenance expenses constitute expenses on diesel, salaries and maintenance of trucks and are calculated annually. Annual maintenance cost of a truck is assumed to be 6% of CAPEX (Ministry of Urban Development, 2017). Number of workers per truck (one driver and one helper) always remains the same. Salary of a driver (INR15,000/month) is more than that of a helper (INR10,000/month). Each truck conducts one trip per day. A trip is a one-time journey of a truck from vehicle parking site to waste collection points to landfill site and back to the parking site. The average distance travelled by a truck per trip is 40 km (Pahade and Nagarabett, 1997). The calculations are reported in Table S3.

Table S2. Vehicles employed for MSW transportation by MCGM

Type of vehicle	Avg. vehicle capacity (m^3)	No. of vehicles	Total capacity (m^3)
Open trucks	7.5	47	353
Compactors	15	296	4440
Skip Vehicles	3.75	123	461
Dumpers	7.5	279	2093
Bulk refuse carriers	22	18	396
Total		**763**	**7742**

Therefore, weighted average of vehicle capacities = 7742/763 ~ 10 m^3

Table S3. Cost of transportation of MSW to dumpsite/landfill

Item	Value	Unit
Quantity of waste landfilled	4124	tonnes/day
Number of trips	1	trip/truck/day
Capacity of truck	10	m^3
	8.5	Tonnes
Number of trucks required	485	
Purchasing cost of 1 truck	0.2	INR crores
Total purchasing cost of trucks	97	INR crores
Replacement period of trucks	10	Years
Total cost of purchasing trucks	194	INR crores
Waste dumped in 1st year	1.51	mn tonnes
Transportation cost (capital)	**64**	**INR/tonne**
Number of drivers	485	

Number of helpers	485	
Salary of 1 driver	15,000	INR/month
Salary of 1 helper	10,000	INR/month
Annual expense on salaries	14.6	INR crores
Avg. distance travelled by 1 truck	40	km/day
Truck mileage	3	km/litre of fuel
Diesel price	58.1	INR/litre
Annual expense on fuel	13.7	INR crores
Annual maintenance cost	5.8	INR crores
Total annual O&M expenses	34.1	INR crores
Transportation cost (opex)	**227**	**INR/tonne**
Total cost (capex + opex)	**291**	**INR/tonne**

S2.2. Land acquisition

The landfill is assumed to be 20 metres high and the bulk density of waste to be landfilled is 0.85 tonne/m^3 (Ministry of Urban Development). Daily dirt cover requires 10% of the volume occupied by waste while liner and final cover occupy 12.5% of additional space. Moreover, 10% of the volume would be reduced and likely be available due to settlement or biodegradation over the period of time. 15% additional land would be required for infrastructural facilities such as roads, buildings, utilities, and weighing system. Land acquisition cost (INR7.8 million/hectare) is as decided by City and Industrial Development Corporation of Maharashtra Ltd. (2014). Land requirement for landfilling would be more than open dumping due to the space occupied by liner and cover system. The cost of land acquisition is reported in Table S4.

Table S4. Cost of land acquisition for dumpsite/landfill

Item	Value	Unit
Total amount of waste dumped	31.7	mn tonnes
Volume of waste dumped (= Capacity of open dumpsite)	37.3	mn m^3
Extra volume for daily dirt cover	10	%
Extra volume for liner and cover	12.5	%
Volume likely to be available due to settlement or biodegradation	10	%
Extra volume required	12.5	%

Total landfill capacity	41.9	mn m^3
Height of landfill	20	m
Waste disposal area required (OD)	186	ha
Waste disposal area required (SL)	210	ha
Addl. area for infrastructure	15	%
Total land requirement (OD)	**214**	**ha**
Total land requirement (SL)	**241**	**ha**
Total land acquisition cost (OD)	167	INR crores
	53	**INR/tonne**
Total land acquisition cost (SL)	188	INR crores
	59	**INR/tonne**

S2.3. Landfilling: Construction and operations

Landfilling constitutes five components: site development, construction, facility operations and maintenance, facility closure and facility post-closure costs. In this work, these costs are estimated based on economic analysis of an 88 tonnes/day landfill in rural Oklahoma (USA), occupying 22.5 acres of land and constructed in three phases of 6-7 years each (Eilrich et al., 2003). Costs for site selection and characterisation, landfill design & detailed engineering, mobilisation-demobilisation and consultancy are not considered. The costs are recalculated for year 2016 by adjusting for inflation. Some of the cost components are scaled up linearly for Mumbai landfill according to the landfill area. The rule of six-tenths is also used, wherever applicable, to determine costs for the bigger landfill with 4124 tonnes/day capacity (Whitesides, 2012). The detailed calculations are reported in Tables S5-S9.

Table S5. Cost for site development at landfill

Item	Value	Unit
Fuel storage tank with pump	2448	US$ (1996)
Compactor	245084	
Dozer	363164	
Front end loader	153997	
Grader	203100	
Total	967793	
	1265742	US$ (2016)
	8.43	INR crores (2016)

Linear scaling by area for Deonar landfill	29.11	INR crores (2016)

Table S6. Landfill construction cost for all phases

Item	Value	Unit
Structures and equipment	19694	US$ (1996)
Access roads	38306	
Office, furniture	58488	
Maintenance/storage buildings	38400	
Truck scale and weight system	23206	
Scale house	4320	
Fencing (8 feet, chain link)	50903	
Monitoring systems	20762	
Landscaping (berms)	33918	
Total	287997	
	375659	US$ (2016)
	2.50	INR crores (2016)
Site preparation	917619	US$ (1996)
Site utilities	14788	
Total	932407	
	1216218	US$ (2016)
	8.1	INR crores (2016)
Linear scaling by area for Deonar landfill	186.49	INR crores (2016)
Overall cost	188.99	INR cr

Table S7. Annual landfill site O&M cost

Item	Value	Unit
Bulldozer (1590 hours)	80422	US$ (1996)
Compactor (1590 hours)	76574	
FEL (1590 hours)	73728	
Grader (1590 hours)	44981	
Bulldozer (1590 hours)	23206	
Site repairs and maintenance	80693	
Total	356399	
	464882	US$ (2016)
	3.1	INR crores (2016)
Linear scaling by area for Deonar landfill	10.7	INR crores (2016)
Gas sampling and analysis	700	US$ (1996)
	913	US$ (2016)
	0.0061	INR crores (2016)
Final cap construction	878108	US$ (1996)
	1145392	US$ (2016)
	7.63	INR crores (2016)
Linear scaling by area of one phase	8.78	INR crores (2016)
Overall cost	19.5	INR crores (2016)

Table S8. Landfill facility closure cost

Item	Value	Unit
Environmental monitoring	97294	US$ (1996)
Drainage/erosion control system	13656	
Top soil sampling and analysis	1441	
Gas sampling and analysis	175	
Total	112566	
	146830	US$ (2016)
	0.98	INR crores (2016)

Table S9. Landfill facility post-closure cost

Item	Value	Unit
Maintain drainage/erosion control system	132935	US$ (1996)
Maintain gas control	71393	
Top soil sampling and analysis	10806	
Gas sampling and analysis	10500	
Total	225634	
Scaling according to post-closure period	188028	
	245261	US$ (2016)
	1.63	INR crores (2016)
Maintain final cap	698022	US$ (1996)
Scaling according to post-closure period	581685	US$ (1996)
	758742	US$ (2016)
	5.05	INR crores (2016)
Linear scaling by area for Deonar landfill	116.3	INR crores (2016)
Overall	118	INR crores (2016)

S2.4. Leachate management (collection and treatment)

Leachate contains organic matter, ammonia-nitrogen, heavy metals and chlorinated organic and inorganic salts (Renou et al., 2008). This leachate, when untreated, can contaminate the ground and surface waters in which it gets released. Thus, leachate management becomes an important concern and landfilling technique, using waterproof covers, liner materials such as clay, geotextiles and/or plastics, becomes essential to control the amount of water entering the waste and thus, to minimise pollution (Lema et al., 1988). Leachate system construction costs, which majorly constitute liner costs, are calculated based on a similar landfill in rural Oklahoma, USA (Eilrich et al., 2003). These costs are scaled up linearly for Mumbai landfill according to the landfill area and also adjusted for inflation. The initial capital investment for the leachate treatment plant as well as operation and maintenance costs are determined based on a World Bank Guidance Note (Johannessen, 1999) for a 100 m^3/day plant. The treatment method is biological treatment with air stripping. It is assumed that leachate would be treated at landfill site and hence, not transported. Although leachate would be generated primarily in the months of June-September during monsoon season in Mumbai, it is assumed to be stored and equal volume be treated daily so that capacity and hence, initial capital investment required for the plant, is reduced. The cost of storing leachate is not considered. Calculations are reported in Tables S10-S11.

Table S10. Leachate system construction cost

Item	Value	Unit
Cell and leachate system liner	1875904	US$ (1996)
Leachate management system	284086	
Total	2159990	
	2817460	US$ (2016)
	18.8	INR crores (2016)
Linear scaling by area for Deonar landfill	432	INR crores (2016)
Surface water controls	22112	US$ (1996)
	32559	US$ (2016)
	0.22	INR crores (2016)
Overall	432.2	INR crores (2016)

Table S11. Cost for leachate collection and treatment

Item	Value	Unit
Leachate system construction cost	**136**	**INR/tonne**
US plant (100 m^3/d) initial cost	3.60	mn US$ (1996)
	5.51	mn US$ (2016)
	36.7	INR crores (2016)
New plant (845 m^3/d) initial cost	132	INR crores (2016)
Plant initial investment cost	**42**	**INR/tonne**
Treatment cost	10	US$/$m^3$ (1996)
	15.34	US$/$m^3$ (2016)
	1022	INR/m^3 (2016)
Treatment expenses	**448**	**INR/tonne**
Total cost (capex + opex)	**626**	**INR/tonne**

S2.5. Landfill gas flaring system

CH_4 and CO_2 are the major constituents of the landfill gas (LFG), with their concentrations varying between 40% and 60%. The concentration of non-methane organic compounds (NMOCs) is less than 1%. In order to reduce these GHG emissions from dumpsites/landfills, it is assumed that the gas is collected and flared in an enclosed system. The economic analysis of such a flaring system is based on a pre-feasibility report of LFG recovery and flaring system at Deonar dumpsite (Mumbai), where gas was collected from a total area of 40 hectares and the maximum LFG flow rate was 3900 m^3/hr (US EPA, 2007). It is assumed that the LFG recovery and flaring system becomes operational from the 2nd year of the landfill's active period and continues till the end of the post-closure care period i.e. for a total of 44 years from 2017 to 2060. Cost components are a function of either landfill area, maximum LFG flow rate or both and are scaled up accordingly after adjusting for inflation. Average annual operating and maintenance costs are 7% of the capital expenditure. Costs for mobilisation and project management, security fencing, registration, validation and legal fees are excluded. Calculations are reported in Table S12.

Table S12. LFG collection and flaring system costs

		Reference system			New system
		US$ '07	**US$ '16**	**INR cr. '16**	**INR crores**
Vertical extraction wells and wellheads	a	601,000	698,135	4.65	24.4
Main gas header collection pipe	a,g	748,000	868,893	5.79	70.0
Lateral piping	a,g	161,000	187,021	1.25	15.1
Condensate management	a,g	103,000	119,647	0.80	9.6
Blower and flaring equipment	g	375,000	435,608	2.90	6.7
Total					126
LFG system capex (INR/tonne)					**40**
O&M expenses					8.81
Total O&M expenses (44 years)					388
Flaring O&M cost (INR/tonne)					**122**
Total cost (INR/tonne)					**162**

S3. Economic analysis of composting

This section describes the economic calculations associated with composting and CO_S scenario.

S3.1. Transportation of waste

All assumptions stated earlier for transporting waste to dumpsite/landfill are applicable in this scenario as well, except the average distance covered by a truck per trip. It is assumed that each of the five zones be a circular area whose radius would be equal to the one-way distance travelled by a truck from its parking site to the waste collection point and then to the composting facility. The total area of Greater Mumbai is 437.71 sq. km. Table S13 reports these calculations for year 2016.

Table S13. Cost of transportation of MSW to composting site

Item	Value	Unit
Quantity of waste composted	2121	tonnes/day
Number of trucks required	250	
Total cost of purchasing trucks	100	INR crores
Waste composted in 1st year	0.77	mn tonnes
Transportation cost (capital)	**64**	**INR/tonne**
Annual expense on salaries	7.5	INR crores
Area of each zone	87.5	sq. km.
Avg. distance travelled by 1 truck	10.6	km/day
Annual expense on fuel	1.9	INR crores
Annual maintenance cost	3.0	INR crores
Total annual O&M expenses	12.3	INR crores
Transportation cost (opex)	**159**	**INR/tonne**
Total cost (capex + opex)	**223**	**INR/tonne**

S3.2. Land acquisition and site development

A layout of the composting facility area includes tipping floor, area for shredding and trommeling, composting pad, curing pad, storage area for rejects and equipment, roads, buildings and buffer land (Diaz et al., 1993). Typical flow diagram of a high quality composting facility (HQCF) is shown in Fig. 1. Waste is piled on the composting pad in the form of windrows, which have a trapezoidal cross-section. Here, the dimensions of a windrow are assumed to be: length - 100 m, height - 1.8 m, base width - 4.2 m, top width - 0.6 m, and alley width between two windrows is assumed to be 1.0 m. The dimensions of a curing pile, with triangular cross section, are: length - 100 m, height - 2.75 m, base-to-height ratio - 2 (US EPA, 2000). Retention time for producing high quality compost is eight weeks on the composting pad and four weeks on the curing pad (Komilis and Ham, 2004). Land area required for other facilities is assumed to be 15% of the area under the composting pad. Paving, grading and composting pad building costs are sourced from literature, whereas the office and storage building costs are assumed to be one-ninth of the compost pad building cost (Komilis and Ham, 2004). Tables S14-S16 report the calculations.

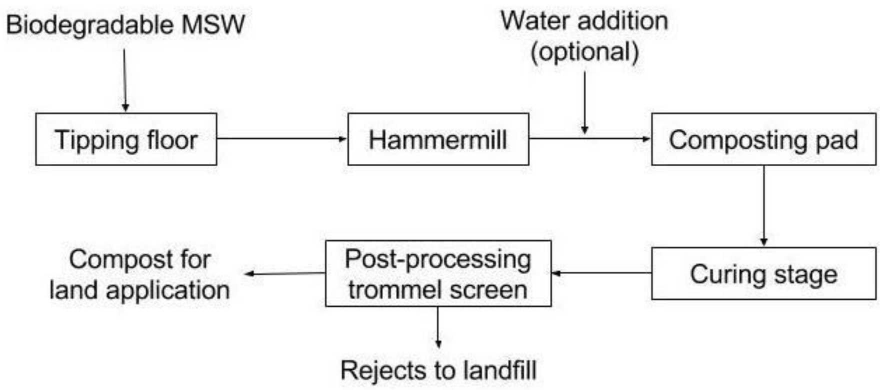

Figure S1: Flow diagram of a high quality composting facility. Water is added if moisture content in MSW is less than 50%. A pre-processing trammel screen precedes a hammermill if incoming waste is not segregated

Table S14. Land requirement for composting pad per zone

Item	Value	Unit
Waste to be composted	424	tonnes/day
Density of waste	850	kg/m^3
Volume to be composted	499	m^3/day
Height of windrow	1.8	m
Base width of windrow	4.2	m
Top width of windrow	0.6	m
Length of windrow	100	m
Volume of one windrow	432	m^3
Composting pad retention time	56	days
Volume of waste generated in 56 days	27951	m^3
Number of windrows	64.7 ~ 65	
Total area for windrows	6.7	acre
Distance between two windrows	1.0	m
Area for empty space (alley)	1.6	acre
Total land for composting pad	8.3	acre
Land for curing stage	0.84	acre
Extra land requirement	15	%
	9.5	acre
Total land requirement per zone	10.4	acre
	4.2	ha

Table S15. Land requirement for curing pad per zone

Item	Value	Unit
Waste reduction post-composting	66.6	%
Waste to be cured	142	tonnes/day
Density of waste	850	kg/m^3
Volume to be cured	166	m^3/day
Height of curing pile	2.75	m
Base to height ratio	2	
Base of curing pile	5.5	m
Length of pile	100	m
Volume of one pile	756	m^3
Curing pad retention time	28	days
Volume of waste cured in 28 days	4662	m^3
Number of windrows	6.2 ~ 6	
Total area for curing pad per zone	0.84	acre

Table S16. Cost of land acquisition and site development of HQCF

Item	Value			Unit
	US$ '98	**US$ '16**	**INR cr. '16**	
Cost of paving	72,500	106,752	0.71	per acre
Cost of grading	5,000	7,362	0.05	per acre
Cost of compost pad	283,280	416,827	2.78	per acre
Cost of land acquisition			0.32	per acre
Total cost for building pad			3.85	per acre
Land for building pad (all zones)	41			Acres
Cost of building pad (all zones)	**158**			INR crores
Land for curing pad (all zones)	4.2			Acres
Total cost of curing pad	**1.3**			INR crores
Extra land required (all zones)	6.2			Acres
Extra land acquisition cost	**1.9**			INR crores
Extra land development cost	0.3			INR cr./acre
Total extra land devpt. cost	**1.9**			INR crores
Overall cost	**163**			INR crores
	100			INR/tonne biodegrdable MSW

S3.3. Equipment acquisition

The major equipment required at a composting facility are windrow turner, trommel screens, tub grinder, hammermill, front end loader and an odour-control system. The number of units required for each of the five zones is calculated based on the waste input flow rate. The composting facility is assumed to be enclosed and fitted with fans which direct air to the odour-control system, operating continuously using the biofiltration technique. Height of the building is 4.57 m and the air inside it would be exchanged every two hours (US EPA, 2000). Table S17 shows the calculations.

Table S17. Cost of equipment acquisition for composting

Equipment	No. of units		Unit cost			Total cost (INR crores)
	Per tpd	**Per zone**	**US$ ’98**	**US$ ’16**	**INR cr. ’16**	
Windrow turner	0.173	1.75 ~ 2	180,000	265,038	1.76	3.53
Trommel screens	0.0025	1.06 ~ 1	100,000	147,244	0.98	0.98
Tub grinder	0.0038	1.61 ~ 2	180,000	265,038	1.77	3.53
Hammermill	0.0029	1.23 ~ 1	250,000	368,109	2.45	2.45
Front end loader	0.003	1.27 ~ 1	150,000	220,865	1.77	1.47
Total cost		7				12.0
Cost for all zones		35				**60**
Odour control system			52	77	5128	per ft^3/min
Odour control system flow rate					223017	ft^3/min
Total cost for odour control system					**114**	INR crores
Overall cost					**174**	INR crores
					107	INR/tonne biodegrad-able MSW

S3.4. Operations and maintenance

Energy requirements, labour wages and overheads are considered for determining the operating cost. Windrow turner, tub grinder and front end loader run on diesel while hammermill, trommel screen and the odour-control system use electricity. Requirement of 0.1 employees per tonne per day at the facility is assumed, with an average monthly salary of INR12,000 per employee. Overheads comprised 40% of the labour expenses (Komilis and Ham, 2004). Annual maintenance costs are also associated with each equipment. Tables S18-S19 report the calculations (BEST, 2016).

Table S18. Annual operating cost of composting

Item	Value	Unit
Labour requirement	0.1	person/tpd
Total people employed	212	
Total expense on salaries	3.05	INR crores
Expense on overheads	40	% of labour
	1.22	INR crores
Fuel requirement		
Turner	0.13	kWh/tonne
	100655	kWh/year
Tub grinder	10.2	kWh/tonne
	7897536	kWh/year
FEL	0.37	kWh/tpd
	6875502	kWh/year
Annual energy requirement from diesel	14873693	kWh/year
Energy obtained on combustion of diesel	11.1	kWh/litre
Annual diesel requirement	1339972	litre/year
Expense on diesel	7.79	INR crores
Electricity requirement		
Hammermill	15	kWh/tonne
	11614023	kWh/year
Post-processing trommel screen	0.8	kWh/tonne
	619415	kWh/year
Odour-control system	0.00005	kW/m^3 of air/day
	3983073	kWh/year
	5.14	kWh/tonne
Total electricity requirement	16216511	kWh/year
	20.94	kWh/tonne
Cost of unit electricity	7.5	INR/kWh
Expense on electricity	12.2	INR crores/year
Total annual O&M costs	24.2	INR crores/year
	313	INR/tonne biodegrdable MSW

Table S19. Annual equipment maintenance cost for composting

Item	Value			Unit
	US$ ’98	US$ ’16	INR ’16	
Windrow turner	22	32	2131	per hour per turner
(8*365 hours)			5.44	INR crores (all zones)
Trommel screen	500	736	49018	per year per screen
			0.026	INR crores (all zones)
Tub grinder	0.741	1.09	73	per tonne per year
			0.015	INR crores (all zones)
Hammermill	0.741	1.09	73	per tonne per year
			0.015	INR crores (all zones)
FEL	1000	1472	98035	per year per FEL
			0.062	INR crores (all zones)
Odour control system	500	736	49018	per year
			0.0049	INR crores (all zones)
Total			5.6	INR crores (all zones)
			72	INR/tonne biodegradable MSW

S3.5. Landfilling of remaining MSW and rejects from composting

MSW constituents, which are neither composted nor recycled, end up in a sanitary landfill along with rejects from the composting facility. As mentioned earlier, the cost components of landfilling are transportation, land acquisition, site construction, and leachate management. It is assumed that landfill gas flaring system is not installed in the absence of generation of LFG since incoming waste does not contain biodegradables, and most of the decomposition of rejects has already happened at the composting site.

S4. Methodology for Life Cycle Assessment (LCA)

This section provides detailed related to the calculation of the emissions inventory for the various scenarios and the specific steps of each scenario.

S4.1. Emissions from transportation

Trucks used for transporting waste are assumed to be diesel-run heavy duty vehicles (HDVs) with gross vehicle weight of more than 3.5 tonnes and which also complied with Bharat stage IV norms of emissions (equivalent to Euro IV norms). Average mileage of the truck is 3 km/litre of diesel burnt

(Malik et al., 2015). The method of testing emission standards is European Transient Cycle (ETC) test which estimates the emissions in terms of g/kWh. These emissions are then converted to g/km using equation (2) and later to g/km/tonne MSW, since the functional unit of the study is 1 tonne MSW.

$$E = \frac{E_0 \times \eta \times GCV \times \rho}{m} \quad (1)$$

where, E is emissions (g/km), E_0 is emission (g/kWh), η is fuel efficiency (kWh available/kWh generated), GCV is gross calorific value of the fuel (kWh generated/kg fuel burnt), ρ is fuel density (kg/litre), and m is vehicle mileage (km/litre). Table S20 in reports the emission inventory (Baidya and Borken-Kleefeld, 2009; Malik et al., 2015). Fuel efficiency is taken to be 0.47 (Holmberg et al., 2014). GCV of diesel is 10800 kcal/kg (12.55 kWh/kg) (Kumar, 2010) and the density of diesel is 0.8325 kg/litre.

Table S20. Emissions from transportation of waste in trucks

Gas component	**E_o (g/kWh)**	**E (g/km)**	**g/km/tonne MSW**
CO	4.0	6.54	0.77
HC	0.55	0.90	0.11
NO_x	3.5	5.72	0.67
PM	0.03	0.05	0.01
CO_2	-	706	83.06
SO_2	-	0.44	0.05

S4.2. Landfill Gas Generation

A number of models such as IPCC (1997, 2006), LandGEM (US EPA, 2005), and Shell Canyon model are available to predict the gas emissions from the decomposition of MSW in a landfill. After comparing these models for methane potential from landfill site, it has been concluded that the accuracy of LandGEM is better than other models (Sil et al., 2014a). Hence, LandGEM, abbreviated for Landfill Gas Emissions Model (Version 3.02), developed by the Environmental Protection Agency of the U.S. has been used in this study. LandGEM uses a first-order decomposition rate equation for quantifying methane emissions.

$$Q_{CH4} = \sum_{i=1}^{n} \sum_{j=0.1}^{1} \left[\frac{M_i}{10} \right] e^{-kt_{ij}} \quad (2)$$

Where, Q_{CH4} is annual methane generation in the year of calculation (m^3/year), i is 1 minus the year time increment, n is the difference between the year of the calculation and the initial year of waste acceptance, j is 0.1 minus the year time increment, k is the methane generation rate ($year^{-1}$), L_o is the potential methane generation capacity (m^3/tonne), M_i is the mass of waste accepted in the i^{th} year (tonnes), and t_{ij} is the age of the j^{th} section of waste mass M_i accepted in the i^{th} year (decimal years, e.g., 3.2 years).

LandGEM is based on anaerobic decomposition of landfilled waste which has CH_4 content between 40 and 60%. LandGEM allows users to input landfill characteristics and quantifies emissions of 46 air pollutants along with CH_4, CO_2 and NMOC. These pollutants are categorised either as hazardous air pollutant (HAP), volatile organic compound (VOC), both or none. Concentration of few pollutants such as benzene and toluene depends on type of disposal – either 'co-disposal' when hazardous wastes are also dumped along with MSW or 'no or unknown co-disposal' when hazardous wastes are separated from MSW (Alexander et al., 2005). 'Co-disposal' type of disposal is assumed for this study on account of poor segregation of wastes in India. The model quantifies emissions for 140 years from 2017 to 2156. However, emissions only till the end of post-closure care period are considered i.e. from 2017 to 2060, as these constitute 99.5% of the total emissions during 140 years. The CO_2 emitted from dumpsite/landfill is assumed to be of biogenic origin.

The two key model parameters, methane generation rate (k) and potential methane generation capacity (L_o), are adjusted to Indian conditions by taking into account the composition of MSW in Mumbai and comparing with that in the US, which forms the basis of the default model parameters. The input parameters are applicable for anaerobic degradation conditions. The potential methane generation capacity (L_o) is assumed to be 72.4 m^3/tonne in case of sanitary landfill (US EPA, 2007). Methane generation rate constant gives the fraction of waste which decomposes in a given year to produce methane and, hence, varies according to the type of waste. The values of rate constant for fast-decaying, medium-decaying and slow-decaying waste are 0.40, 0.08 and 0.02 $year^{-1}$, respectively. The overall rate constant for entire landfill has been calculated by adding the products of weight fractions of different wastes and their respective rate constants, as shown in Table S21 (Sil et al., 2014a). 50% of green waste is assumed to degrade at a fast rate while remaining 50% degraded at a moderate rate (US EPA, 2007). Overall methane generation rate constant is calculated to be 0.17 $year^{-1}$ and is the same for open dumpsite as well as sanitary landfill. Default values of NMOC concentration (4000 ppmv as hexane) and methane content (50% by volume) are assumed (US EPA, 2007).

LandGEM has been adjusted to quantify emissions in open dumping scenario as well. In presence of aerobic conditions at an open dumpsite, potential methane generation capacity (L_o) reduces and has been assumed to be 57.9 m^3/tonne by taking a correction factor of 0.8 (US EPA, 2007). It is assumed that the same amount of carbon present in MSW undergoes degradation to form CH_4 and CO_2 in aerobic conditions as that in anaerobic conditions. Thus, CH_4 emissions decrease and CO_2 emissions increase in an open dumpsite compared to a sanitary landfill. Tables S21-S24 report the emission inventory for dumpsite and landfill, as quantified by LandGEM. However, Sil et al. (2014b) recommends a correction factor of 0.13 for predicting CH_4 emissions from open dumping sites in India, owing to poor level of segregation.

Table S21: Overall methane generation rate constant for dumpsite/landfill for use in LandGEM

Component	Degradability category	Composition (%)	Rate constant (k, $year^{-1}$)	% * k
Food	Fast	35.7	0.40	0.143
Green waste	Fast	3.15	0.40	0.013
Green waste	Medium	3.15	0.08	0.003
Paper	Medium	11.8	0.08	0.009
Rubber, leather, textiles	Slow	10.0	0.02	0.002
Plastics, metal, glass	Inert	6.2	0	0
Other inorganic	Inert	30.0	0	0
Total		100.0		0.17

Table S22. Emission rates of CH_4 and CO_2 for sanitary landfill

Year	CH_4 generated		CH_4 recovered		LFG recovered	CO_2 generated	LFG gener-ated
	m^3/year	tn/year	m^3/year	m^3/hr	m^3/hr	tn/year	tn/year
2017	17181934	11463	10309160	1177	2354	31452	42914
2018	31771434	21196	19062861	2176	4352	58158	79354
2019	44174300	29471	26504580	3026	6051	80861	110332
2020	54732894	36515	32839736	3749	7498	100188	136703
2021	63736056	42521	38241634	4365	8731	116669	159190
2022	71427476	47653	42856486	4892	9785	130748	178401
2023	78012746	52046	46807648	5343	10687	142802	194848
2024	83665323	55817	50199194	5731	11461	153149	208966
2025	88531546	59064	53118927	6064	12128	162057	221121
2026	92734882	61868	55640929	6352	12703	169751	231619
2027	96379496	64299	57827698	6601	13203	176423	240722
2028	99553274	66417	59731964	6819	13637	182232	248649
2029	102330363	68270	61398218	7009	14018	187316	255585
2030	104773323	69899	62863994	7176	14353	191787	261687
2031	106934935	71341	64160961	7324	14649	195744	267086
2032	108859731	72626	65315839	7456	14912	199268	271893
2033	110585287	73777	66351172	7574	15149	202426	276203
2034	112143305	74816	67285983	7681	15362	205278	280094
2035	113560535	75762	68136321	7778	15556	207872	283634
2036	114859547	76628	68915728	7867	15734	210250	286879
2037	96902958	64649	58141775	6637	13274	177381	242029
2038	81753617	54542	49052170	5600	11199	149650	204192
2039	68972650	46015	41383590	4724	9448	126254	172269
2040	58189798	38821	34913879	3986	7971	106516	145338
2041	49092685	32752	29455611	3363	6725	89864	122616
2042	41417771	27632	24850663	2837	5674	75815	103447
2043	34942716	23312	20965630	2393	4787	63963	87275

2044	29479940	19667	17687964	2019	4038	53963	73630
2045	24871189	16593	14922713	1704	3407	45527	62119
2046	20982947	13999	12589768	1437	2874	38409	52408
2047	17702574	11810	10621544	1213	2425	32405	44215
2048	14935039	9964	8961023.3	1023	2046	27339	37302
2049	12600167	8406	7560100.1	863	1726	23065	31471
2050	10630317	7092	6378190.4	728	1456	19459	26551
2051	8968425	5983	5381054.9	614	1229	16417	22400
2052	7566344	5048	4539806.7	518	1036	13850	18898
2053	6383459	4259	3830075.2	437	874	11685	15944
2054	5385499	3593	3231299.6	369	738	9858	13451
2055	4543556	3031	2726133.8	311	622	8317	11348
2056	3833239	2557	2299943.2	263	525	7017	9574
2057	3233969	2158	1940381.2	222	443	5920	8077
2058	2728386	1820	1637031.3	187	374	4994	6815
2059	2301843	1536	1381105.7	158	315	4214	5749
2060	1941984	1296	1165190.3	133	266	3555	4850

Table S23. Emission rates of CH_4 for open dumpsite

Year	CH_4 emitted (tn/year)	Year	CH_4 emitted (tn/year)	Year	CH_4 emitted (tn/year)	Year	CH_4 emitted (tn/year)
2017	9167	2028	53115	2039	36799	2050	5672
2018	16951	2029	54597	2040	31046	2051	4785
2019	23569	2030	55900	2041	26193	2052	4037
2020	29202	2031	57053	2042	22098	2053	3406
2021	34005	2032	58080	2043	18643	2054	2873
2022	38109	2033	59001	2044	15729	2055	2424
2023	41622	2034	59832	2045	13270	2056	2045
2024	44638	2035	60588	2046	11195	2057	1725
2025	47235	2036	61282	2047	9445	2058	1456
2026	49477	2037	51701	2048	7968	2059	1228
2027	51422	2038	43618	2049	6723	2060	1036

Table S24. Emission inventory of CH_4 and CO_2 for dumpsite/landfill

Item	Value	Unit
Landfill		
CH_4 generated	1537983	tonnes
CH_4 flared	913562	tonnes
Remaining CH_4 emitted	624421	tonnes
	19.7	kg/tonne MSW
CO_2 generated	4219866	tonnes
CO_2 produced from CH_4 oxidation	2512296	tonnes
Total CO_2 emitted	6732162	tonnes
	212.5	kg/tonne MSW
Total C released	2304360	tonnes
Dumpsite		
CH_4 emitted	1229962	tonnes
	38.8	kg/tonne MSW
C emitted as CH_4	922471	tonnes
Total C released	2304360	tonnes
C emitted as CO_2	1381889	tonnes
CO_2 emitted	5066925	tonnes
	160.0	kg/tonne MSW

Table S25. Emission inventory of NMVOC and 46 pollutants for landfill

Gas/Air pollutant	kg/tonne MSW
NMVOC	2.09
1,1,1-Trichloroethane (methyl chloroform) – HAP	0.00039
1,1,2,2-Tetrachloroethane - HAP/VOC	0.0011
1,1-Dichloroethane (ethylidene dichloride) - HAP/VOC	0.0014
1,1-Dichloroethene (vinylidene chloride) - HAP/VOC	0.00012
1,2-Dichloroethane (ethylene dichloride) - HAP/VOC	0.00025
1,2-Dichloropropane (propylene dichloride) - HAP/VOC	0.00012
2-Propanol (isopropyl alcohol) – VOC	0.018
Acetone	0.0025
Acrylonitrile - HAP/VOC	0.002
Benzene - No or Unknown Co-disposal - HAP/VOC	0.0009
Benzene - Co-disposal - HAP/VOC	0.0052
Bromodichloromethane – VOC	0.0031
Butane – VOC	0.0018
Carbon disulfide - HAP/VOC	0.00027
Carbon monoxide	0.024
Carbon tetrachloride - HAP/VOC	0.000004
Carbonyl sulfide - HAP/VOC	0.00018
Chlorobenzene - HAP/VOC	0.00017
Chlorodifluoromethane	0.00068
Chloroethane (ethyl chloride) - HAP/VOC	0.00051
Chloroform - HAP/VOC	0.00002
Chloromethane – VOC	0.00037
Dichlorobenzene - (HAP for para isomer/VOC)	0.00019
Dichlorodifluoromethane	0.012
Dichlorofluoromethane – VOC	0.0016
Dichloromethane (methylene chloride) – HAP	0.0072
Dimethyl sulfide (methyl sulfide) – VOC	0.0029
Ethane	0.16

Ethanol – VOC	0.0075
Ethyl mercaptan (ethanethiol) – VOC	0.00087
Ethylbenzene - HAP/VOC	0.003
Ethylene dibromide - HAP/VOC	0.000001
Fluorotrichloromethane – VOC	0.00063
Hexane - HAP/VOC	0.0034
Hydrogen sulphide	0.0074
Mercury (total) – HAP	0.0000004
Methyl ethyl ketone - HAP/VOC	0.0031
Methyl isobutyl ketone - HAP/VOC	0.0011
Methyl mercaptan – VOC	0.00073
Pentane – VOC	0.0014
Perchloroethylene (tetrachloroethylene) – HAP	0.0037
Propane – VOC	0.0029
t-1,2-Dichloroethene – VOC	0.0016
Toluene - No or Unknown Co-disposal - HAP/VOC	0.022
Toluene - Co-disposal - HAP/VOC	0.095
Trichloroethylene (trichloroethene) - HAP/VOC	0.0022
Vinyl chloride - HAP/VOC	0.0028
Xylenes - HAP/VOC	0.0077

S4.3. Leachate generation

Volumetric flow rate and composition are the main characteristics of leachate. The amount of leachate produced can be estimated either empirically or using techniques that use site-specific data. Climatic conditions such as precipitation and water evaporation rate significantly impact the amount of leachate generated. A water balance method has been used for the purpose of this study (Worrell et al., 2017). The schematic for water balance at a landfill is depicted in Fig. S2. The mass balance equation for 1-dimensional analysis of water movement is:

$$C = P(1 - R) - S - E \tag{3}$$

where, C is the total percolation into the top soil layer (mm/year), P is the precipitation (mm/year), R is the runoff coefficient, S is the storage within the soil or waste (mm/year), and E is the evapotranspiration (mm/year).

Average precipitation in Mumbai is 2142 mm/year (Rana et al., 2012). The type of land for the landfill is assumed to be the same as that for parks and undeveloped land. Runoff coefficient for such land type is between 0.10 and 0.20, and a value of 0.15 is used in this study (Chawathe, 2013). Evapotranspiration rate at landfill site is considered to be the same as India's average rate of 39% of precipitation (Jain, 2012). The soil is assumed to be at field capacity when water balance is applied, giving S = 0 (Worrell et al., 2017). Volumetric flow rate of leachate is calculated using the rate of percolation into top soil layer and landfill area. Each landfill phase is active for one year and closed for remaining years till the end of post-closure care period. For example, phase 1 is active in the first year of landfill operation (2016) and closed subsequently for 44 years (2017-2060), phase 2 is active in the second year (2017) and closed thereafter for 43 years (2018-2060) and so on. Different leachate generation rates during active and post-closure care period have been reported for different landfills and it is assumed that the rate during post-closure period is one-sixth of the rate during active period (Hjelmar et al., 2000; Worrell et al., 2017). Leachate generation calculations are reported in Tables S26-S27.

De et al. (2016) discussed the composition of leachate from an unmanaged landfill in Dhapa, Kolkata, giving concentrations of some important compounds during active and closed landfill periods. It was reported that the concentrations of some components in leachate highly exceeded discharge standards during both active and closed periods. The composition of MSW and untreated leachate produced in the cities of Mumbai and Kolkata are assumed to be the same owing to the metropolitan status of both cities. These concentrations, reported in Table S27, are used for calculating emission inventory in case of open dumpsite where leachate entered the groundwater. For the sanitary landfill scenario, it is assumed that the treated leachate would meet the regulatory standards for discharge into surface waters, as mentioned in Soild Waste Management Rules (2016), and reported in Table S27. These standards are used as emission inventory for components whose concentrations exceeded permissible limits.

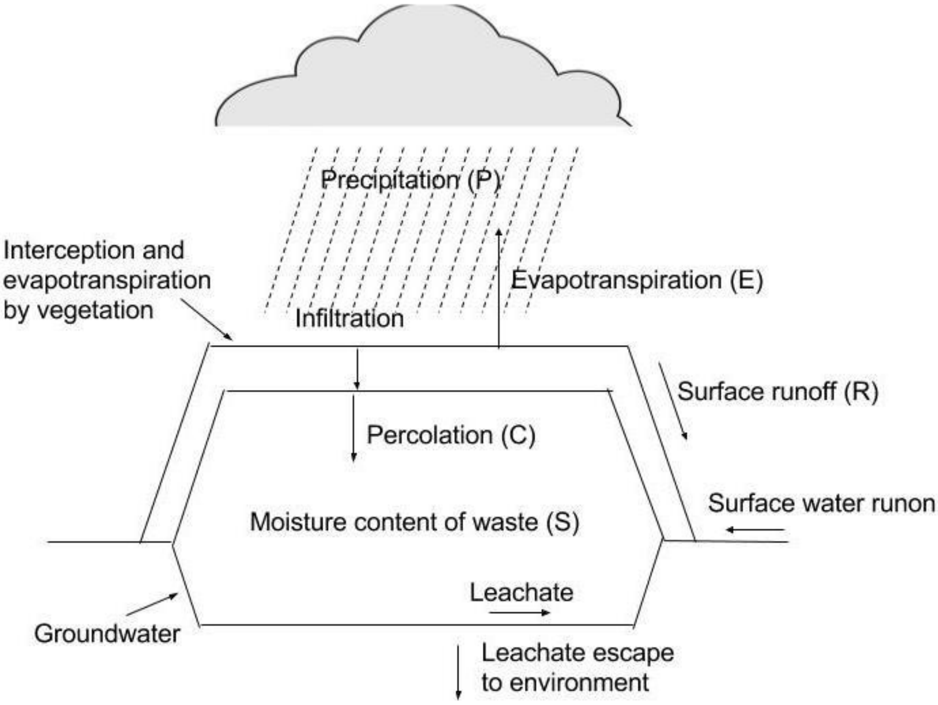

Figure S2: Schematic for water balance at a landfill

Table S26. Phase-wise leachate generation quantities

Phase	Area (m^2)	Leachate generated		
		Active (m^3/year)	**Closed (m^3)**	**Total/phase (m^3)**
1	99608	98146	719879	818025
2	100139	98669	707269	805938
3	100673	99195	694503	793698
4	101209	99724	681581	781305
5	101749	100255	668502	768758
6	102291	100790	655264	756054
7	102837	101327	641866	743193
8	103385	101867	628307	730174
9	103936	102410	614584	716994
10	104490	102956	600698	703654
11	105047	103505	586645	690150
12	105607	104057	572427	676483
13	106170	104611	558039	662651
14	106736	105169	543482	648651
15	107305	105730	528754	634484
16	107877	106293	513854	620147
17	108452	106860	498780	605640
18	109030	107430	483530	590960
19	109611	108002	468104	576106
20	110196	108578	452499	561077
Total	2096349	2065574	11818568	13884142
	m^3/tonne	**0.07**	**0.37**	**0.438**

Table S27. Average leachate generation rates

Item	Value	Unit
Avg. precipitation in Mumbai (P)	2142	mm/year
Runoff coefficient (R)	0.15	
Evapotranspiration (E)	39	% of precipitation
Storage within soil/waste (S)	0	mm/year
Percolation into top soil layer (C)	985	mm/year
Total leachate generated (active)	2.1	mn m^3
Avg. leachate generation rate (active)	**0.07**	m^3/tonne MSW
Total leachate generated (post-closure)	11.8	mn m^3
Avg. leachate generation rate (post-closure)	**0.37**	m^3/tonne MSW
Total leachate generated (over 45 years)	**13.9**	mn m^3
Avg. leachate generation rate (over 45 years)	**0.44**	m^3/tonne MSW
	845	m^3/day

Table S28. Leachate characteristics for dumpsite/landfill

(* denotes within permissible limit)

Component	Disc. std.	Active dumpsite		Closed dumpsite		Total OD	Total SL
	mg/L	mg/L	mg/tn	mg/L	mg/tn	mg/tn	mg/tn
Total dissolved solids-TDS	2100	10014.17	$6.5x10^5$	5987.5	$2.2x10^6$	$2.9x10^6$	$9.2x10^5$
Biochem. O2 demand-BOD5	30	2641.58	$1.7x10^5$	1343.2	$5.0x10^5$	$6.7x10^5$	$1.3x10^4$
Chem. O2 Demand-COD	250	5653	$3.7x10^5$	2775	$1.04x10^6$	$1.4x10^6$	$1.1x10^5$
Total Kjeldahl Nitrogen-TKN	100	5529.22	$3.6x10^5$	2846	$1.06x10^6$	$1.4x10^6$	$4.4x10^4$
Total Fe	-	4.26	$2.8x10^2$	3.16	$1.2x10^3$	$1.5x10^3$	-
Cu	3	0.32*	20.9	0.27*	$1x10^2$	$1.2x10^2$	$1.2x10^2$
Ni	3	0.51*	33.3	0.43*	$1.6x10^2$	$1.9x10^2$	$1.9x10^2$
Zn	5	7.61	$5.0x10^2$	3.26*	$1.2x10^3$	$1.7x10^3$	$1.5x10^3$
Pb	0.1	0.6	39.1	0.69	$2.6x10^2$	$3x10^2$	44
Total Cr	2	3.22	$2.1x10^2$	1.19*	$4.4x10^2$	$6.5x10^2$	$5.7x10^2$
Hg	0.01	0.87	56.7	1.2	$4.5x10^2$	$5.0x10^2$	4
As	0.2	0.03*	2.0	0.22	82.1	84	77
CN^-	0.2	0.03*	1.96*	0.02	9.03	9	9
Na^+	-	2196.42	$1.4x10^5$	2105.6	$7.9x10^5$	$9.3x10^5$	-
K^+	-	1794.3	$1.2x10^5$	1297.6	$4.8x10^5$	$6.0x10^5$	-
PO_4^{3-}-P	-	18.88	$1.2x10^3$	9.09	$3.4x10^3$	$4.6x10^3$	-

S4.4. Emissions from composting facility

Table S29. Leachate characteristics for CO_SL

(Leachate generation rate: 29.7 (active) and 169.9 (closed) L/tonne MSW collected)

Component	mg/tonne MSW collected
Total dissolved solids – TDS	$4.2x10^5$
Total Kjeldahl Nitrogen – TKN	$2.0x10^4$
Cu	55
Ni	88
Zn	$7.0x10^2$
Pb	20
Total Cr	$2.62x10^2$
Hg	2
As	35
CN^-	4

Emissions resulting from generation and consumption of electricity at the composting site are included and the inventory is reported in Table S30 (Brander et al., 2011). Emissions due to combustion of diesel in the equipment at the site are also included and reported in Table S31 (US EPA, 2000). CO_2, NH_3 and VOCs are the main gaseous compounds released during composting of wastes and these emissions of biogenic origin are quantified using Equations (5)-(7) (US EPA, 2000; Komilis and Ham, 2004). Very high standard errors have been reported for the coefficients in equation (7).

$$YCO_2 = 220F_P + 240F_y + 370F_f \quad (4)$$

$$YNH_3 = 1.3F_P + 5.2F_y + 38F_f - 69F_PF_f \quad (5)$$

$$Y_{VOC} = 4162F_P + 831F_y + 458F_f - 7558F_PF_y - 6006F_PF_f \quad (6)$$

Where, $YCO_2$is the yield of CO_2 (g C/kg of dry organic fraction in MSW), YNH_3 is the yield of NH_3 (g N/kg of dry organic fraction in SW), and Y_{VOC} is the mass of 12 VOCs volatilised from MSW mixture (µg VOCs/kg of dry organic fraction in MSW). F_P is the fraction of dry paper waste in dry organic fraction of MSW, F_y is the fraction of dry green/yard waste in dry organic fraction of MSW, and F_f is the fraction of dry food waste in dry organic fraction of MSW. Moisture content in paper, green and food waste is 10.2%, 60% and 70%, respectively (US EPA, 2000). The values of F_P, F_y and F_f are reported in Table 4. The reduction in weight of dry organic fraction leaving the composting pad is calculated using Equation (7) (Komilis and Ham, 2004).

$$DR = YCO_2/490 \quad (7)$$

Assuming the post-processing trommel screening efficiency to be 85% and moisture content in the compost to be 50%, the quantity of compost produced per tonne of MSW is calculated (US EPA, 2000). Results of mass balance at the composting site are reported in Table 5.

Table S30. Emission inventory for generation and consumption of electricity

Pollutant	kg/kWh electricity consumed
CO_2 (fossil)	1.8
CH_4	2.1×10^{-5}
N_2O	2.7×10^{-5}

Table S31. Emission inventory for diesel combustion in equipment (kg/kWh)

	HC	CO (fossil)	NO_x	PM (total)	SO_x	CO2 (fossil)
FEL	0.0009	0.0032	0.013	0.0009	0.0011	0.36
Grinder	0.0017	0.0067	0.011	0.0011	0.0013	0.36
Turner	0.0030	0.0092	0.014	-	-	0.3

Table S32: Fraction of dry waste constituents in dry organic MSW

Component	Waste composted (% of MSW collected)	Moisture content (%)	Dry weight (kg/ ton MSW collected)	Fraction of dry waste
Food (□□)	35.7	70	107.1	0.49
Green/yard (□□)	6.3	60	25.2	0.12
Paper (□□)	9.44	10.2	84.8	0.39
Total	51.44	57.8	217.1	1.00

Table S33: Waste flows through the composting facility - mass balance

Stage	Dry weight (kg/ton MSW collected)	Moisture (kg/ton MSW collected)	Total (kg/ton MSW collected)
Mass entering composting pad	217.1	297.3	514.4
Mass exiting composting pad/ entering curing pad	85.8	85.8	171.6
Mass exiting facility (compost)	73	73	146
Rejects to landfill	12.9	12.9	25.8

S5. Results and discussion

S5.1. Economic analysis

The component wise cost of landfilling is reported in Table S34. Site development cost comprised mainly of equipment costs, such as, fuel storage tanks, compactors, bulldozers, front end loaders and graders. Construction cost included the costs incurred in building structures, roads, buildings, scale house, weight system, fencing and monitoring systems. Annual facility operations and maintenance constituted operating cost of the equipment, site repairs, environmental monitoring (sampling and analysis) and final cap construction for each phase. Closure and post-closure costs included costs for environmental monitoring, drainage and erosion control system, maintenance of final cap and landscaping.

Table S34. Total expenses for setting up the sanitary landfill

Component	Total cost (INR billion)			Per tonne cost (INR)			Contribution (%)
	Capex	Opex	Total	Capex	Opex	Total	
Transportation	1.94	6.82	8.76	64	227	291	21%
Land acquisition	1.88	-	1.88	59	-	59	4%
Landfilling	2.18	5.09	7.27	69	160	229	17%
Leachate treatment	5.65	14.18	19.83	178	448	626	46%
LFG flaring	1.26	3.88	5.14	40	122	162	12%
Total	12.91	29.97	42.88	410	957	1367	100%
In US$ terms (m indicates million)	194 m	450 m	644 m	6.16	14.37	20.53	

Table S35. Component-wise landfilling cost

Component	Total cost (INR million)	Cost/tonne (INR/tonne)	Contribution towards final cost
Site development	291	9	4%
Construction	1892	60	26%
Facility operations & maintenance	3900	123	54%
Facility closure	10	0.3	0.1%
Facility post-closure	1181	37	16%
Total	7274	229	100%

Table S36: Actual cost of composting and landfilling (per tonne of MSW, as collected)

Composting				Landfilling			
Component	Cost (INR/tonne of biodegradable MSW)			Component	Cost (INR/tonne of MSW landfilled)		
	Capex	Opex	Total		Capex	Opex	Total
Transportation	64	159	223	Transportation	64	227	291
Land acquisition and site development	100	-	100	Land acquisition	59	-	59
Equipment acquisition	107	-	107	Landfilling	69	160	229
Equipment maintenance	-	72	72	Leachate treatment	178	448	626
Operations	-	313	313	Total	370	835	1205
Total	271	544	815	Actual cost (INR/ tonne of MSW collected)	169	380	549
Actual cost (INR/tonne of MSW collected)	140	280	420				
In US$ terms	2.1	4.2	6.3	In US$ terms	2.54	5.71	8.25

S5.2. Emissions inventory

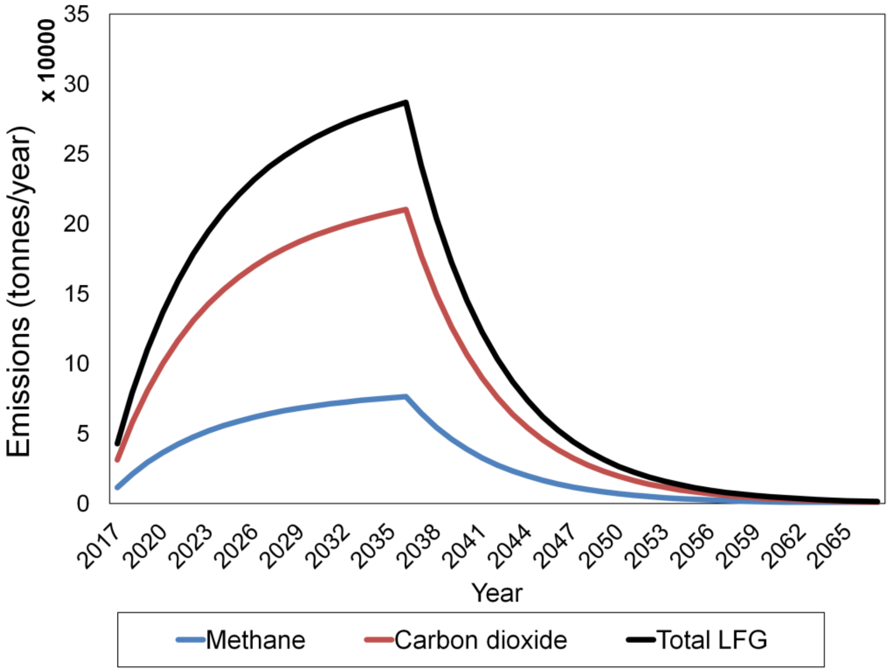

Figure S3: Annual emission estimates for sanitary landfill

Table S37. Emission inventory for open burning of waste

(PAH – polycyclic aromatic hydrocarbons, PCBs – polychlorinated biphenyls, PCDD/F – polychlorinated dibenzodioxins/dibenzofurans,

PCDD/F – polybrominated dibenzodioxins/dibenzofurans)

Pollutant	kg/tonne MSW burned	kg/tonne MSW collected
CO_2 biogenic	1453	145.3
CO biogenic	38	3.8
Methane	3.7	0.37
Acetylene	0.4	0.04
Ethylene	1.26	0.126
Propylene	1.26	0.126
Methanol	0.94	0.094
Formaldehyde	0.62	0.062
Acetic acid	2.42	0.242
Formic acid	0.18	0.018
HCl	3.61	0.361
HCN	0.47	0.047
Benzene	0.9	0.09
Total PAH	0.3	0.03
NMOC	30.1	3.01
NH_3	1.12	0.112
SO_2	0.5	0.05
NO_x (NO)	3.74	0.374
$PM_{2.5}$	9.8	0.98
PM_{10}	11.9	1.19
Hg	2.10×10^{-4}	2.10×10^{-5}
PCBs	1.30×10^{-4}	1.30×10^{-5}
PCDD/F	3.70×10^{-7}	3.70×10^{-8}
PBDD/F	2.12×10^{-7}	2.12×10^{-8}