METHANE EMISSIONS FROM OPEN DUMPSITES IN INDIA

Estimation and mitigation strategies

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1. Indian waste sector's contribution to GHG emissions

KEY HIGHLIGHTS

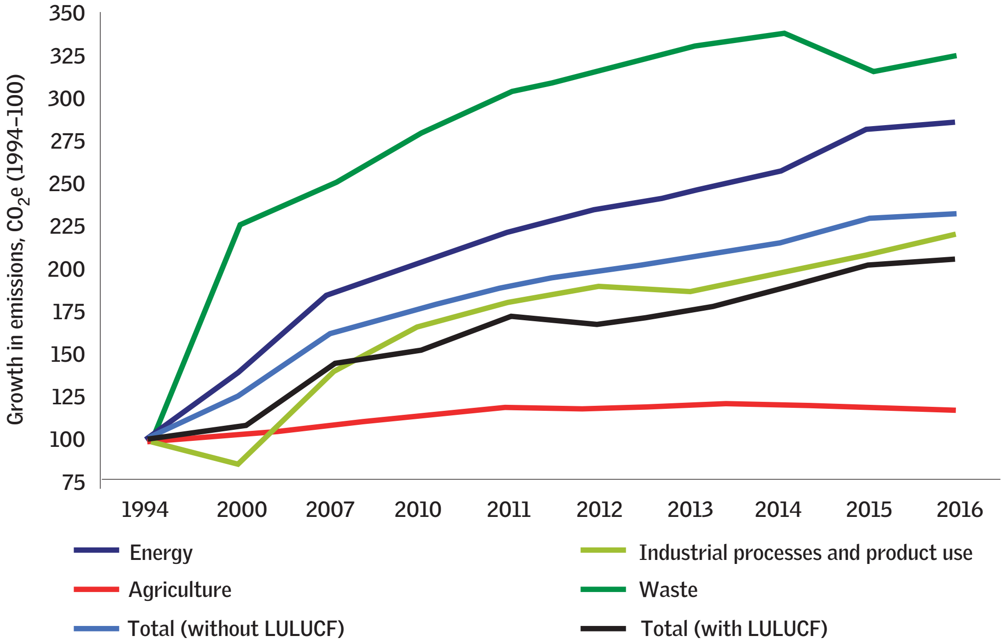
- **The waste sector contributed about 2.7 per cent to total GHG emissions in India in 2016.**
- **Wastewater treatment and discharge contributed to more than three-quarters (78.9 per cent) of the emissions from the waste sector. It was followed by solid waste disposal at 21.04 per cent.**
- **The waste sector witnessed the highest growth in GHG emissions (224 per cent) between 1994 and 2016.**

Large-scale demographic changes in India are leading to changing patterns of waste generation as well. An increasing amount of waste is being generated in urban areas because urban population is rising. According to the Ministry of Housing and Urban Affairs (MoHUA), India's urban population is expected to grow from about 500 million currently to 600 million by 2030 and to 814 million by 2050.[1]

In addition, India has experienced substantial economic growth since 1994, which has also meant substantial increase in its greenhouse gas (GHG) emissions. According to Third Biennial Update Report (BUR) prepared by the Ministry of Environment, Forest and Climate Change (MoEFCC) to be submitted to the United Nations Framework Convention on Climate Change (UNFCCC), India's GHG emissions—without accounting for land use and land-use change and forestry (LULUCF)—increased by 134 per cent between 1994 and 2016.[2]

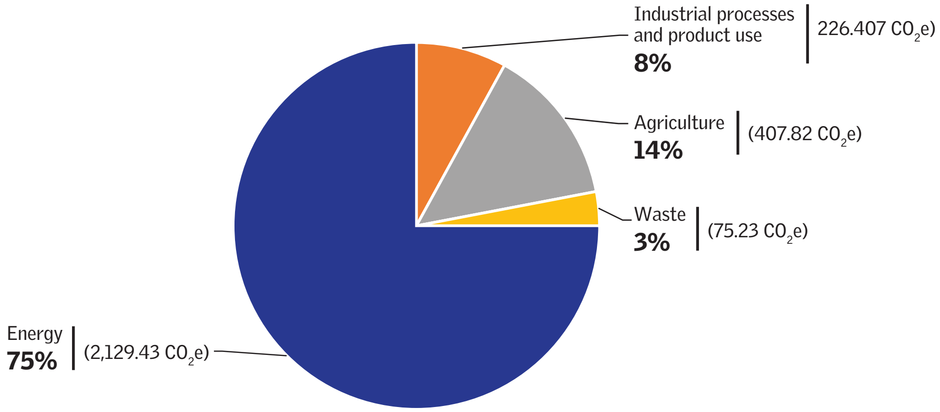
Although the waste sector contributed 2.7 per cent to total GHG emissions in 2016, it witnessed the highest growth in GHG emissions (224 per cent) between 1994 and 2016 due to the increase in population and industrial activities. The energy sector recorded second-highest growth in GHG emissions at 186 per cent for the same period due to a continuous increase in fossil fuel combustion. GHG emissions from the Industrial Processes and Product Use (IPPU) sector grew by 120 per cent while GHG emissions from the agriculture sector grew by 18 per cent and from the LULUCF sector by 38 per cent in the same period.[3]

Graph 1: Growth in emissions of greenhouse gases, relative to 1994



Source: India's third BUR, MoEFCC, 2016

Graph 2: Sector-wise distribution of India's GHG emission in 2016 (in million tonnes)



Source: India's third BUR, MoEFCC, 2016

Methane emissions from the waste sector

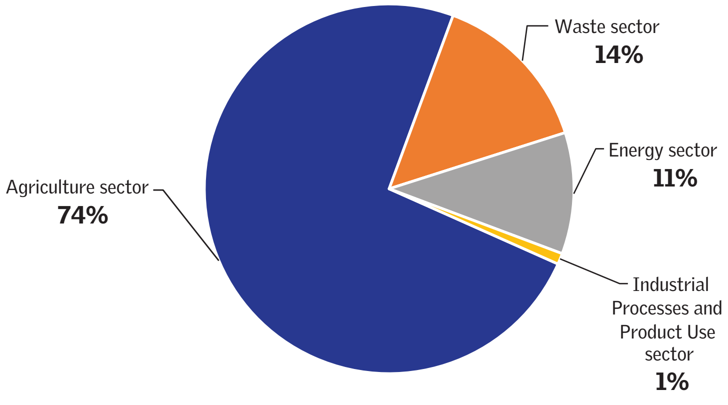
Methane is a potent greenhouse gas whose atmospheric concentration has more than doubled over the last two centuries primarily due to anthropogenic activities.[4] Its global warming potential (GWP)—the ability of the gas to trap heat in the atmosphere—is 25 times more than carbon dioxide (CO_2) and it has been second only to CO_2 in causing climate change during the industrial era.[5] Recently, the

Intergovernmental Panel on Climate Change (IPCC) has indicated a GWP for methane between 28 - 36 when considering its impact for a 100 year timeframe (GWP100). Methane is considered as a short-lived climate pollutant which means that it has a relatively short lifespan— of approximately 12 years—in the atmosphere.[6] In addition, methane potentially contributes to the formation of ground-level ozone or tropospheric ozone (O_3), which is a hazardous air pollutant and greenhouse gas, exposure to which causes 1 million premature deaths every year globally.[7]

Landfills are the third-largest source of methane emissions globally, after oil and gas systems and agriculture. An estimated 1.6 billion tonnes of CO_2e were emitted during landfill waste management worldwide in 2016. According to a report by the World Bank, this number is expected to reach 2.6 billion tonnes of CO_2e by 2050.[8]

As per India's third BUR, India's methane emissions in 2016 (excluding LULUCF) were 409 million tonnes CO_2e, of which, 73.96 per cent was from the agriculture sector, 14.46 per cent from the waste sector, 10.62 per cent from the energy sector and 0.96 per cent from the industrial processes and product use sector.[9]

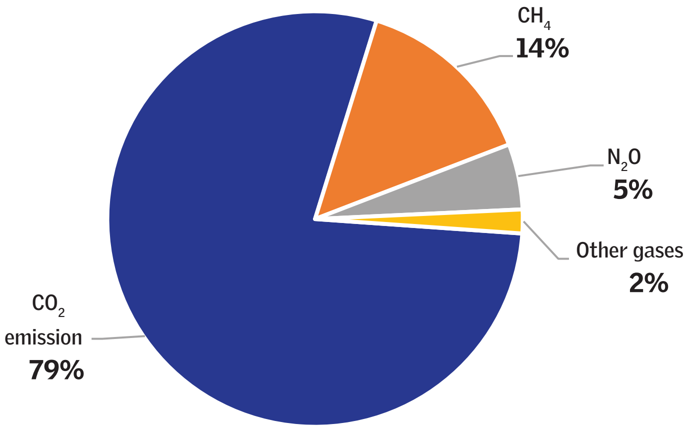
Graph 3: Methane contribution by different sectors in India



Source: India's third BUR, MoEFCC, 2016

GHGs produced from the waste sector include carbon dioxide, methane and nitrous oxide, among others. It is important to note that while methane accounts for only about 14 per cent of the GHG emissions from the waste sector, it has much higher short-term global warming potential (GWP) than CO_2. Over the typically used 100-year time horizon, methane has 25 times higher GWP, but over the shorter time frame of 20 years, methane has 72 times higher GWP than CO_2.[10]

Graph 4: Gas-wise emissions in 2016



Source: India's third BUR, MoEFCC, 2016

Wastewater treatment and discharge (both industrial and domestic) contribute highest to methane emissions from the waste sector. Methane is produced during the decomposition of organic matter in wastewater. This can occur in both wastewater treatment plants and after wastewater is discharged in the environment. The amount of methane produced depends on several factors, including the type of wastewater, the treatment process and the environmental conditions.

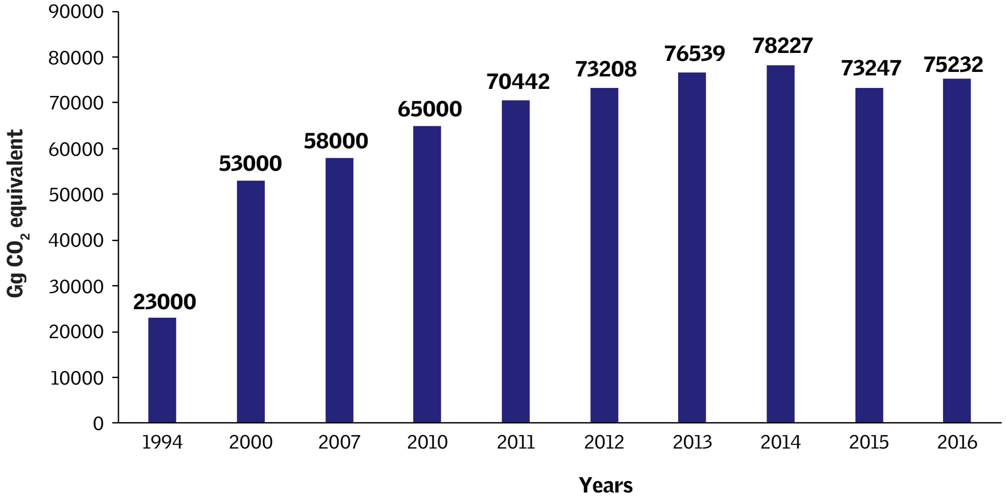
The other source is solid waste disposal on land. Methane is produced during the decomposition of organic matter in solid waste. This can occur in landfills, open dumps, and other waste disposal sites. The amount of methane produced depends on several factors, including the type of waste, the disposal method and the environmental conditions.

Table 1: Estimated methane emissions from the waste sector in India in 2016

Source	Emissions (Gg)
Industrial wastewater treatment and discharge	979
Domestic and commercial wastewater treatment and discharge	1,087
Solid waste disposal on land	754
Total	**2,820**

Source: India's third BUR, MoEFCC, 2016

Graph 5: Total methane emission from the waste sector (Gg CO_2 equivalent)



Source: Compiled by CSE based on NOTCOM and BUR reports by MoEFCC

Methane emissions from dumpsites in India

In 2004, MoEFCC initiated a project towards preparation of India's Initial National Communication (NATCOM) to the United Nations Framework Convention on Climate Change (UNFCCC) under its enabling activities programme through the United Nations Development Programme, New Delhi. The source-specific areas for the estimation of GHG inventories were land-use change and forestry, energy and transformation, agriculture and industrial process, and the waste sector.

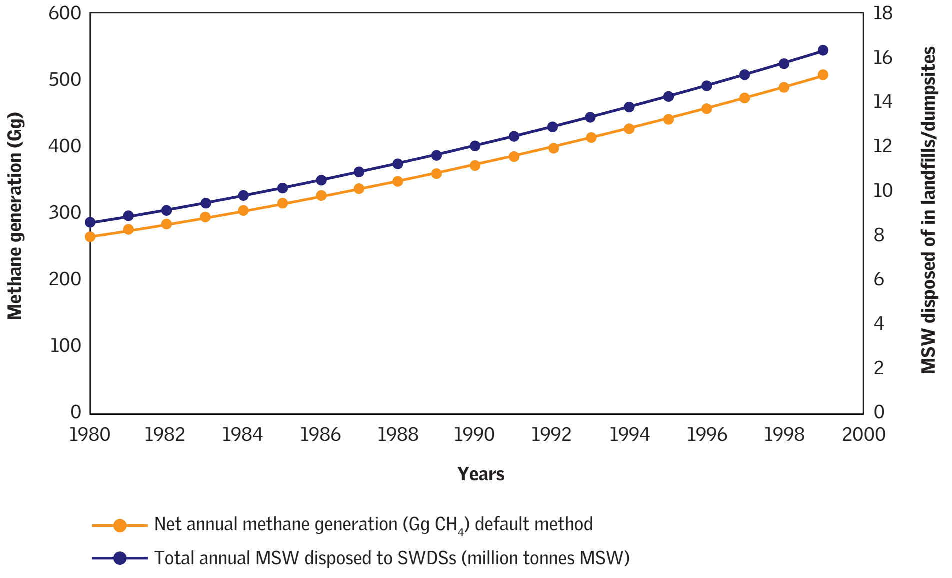
For the waste sector, NEERI, Nagpur was entrusted with the GHG inventory estimation. The detailed estimates under waste sector activity were published in 2004 by CSIR-NEERI in an international journal focussing on the year-wise methane emissions from dumpsites/landfills in India. National level methane emission from solid waste disposal sites using the default methodology varied from 263.02 Gg in 1980 to 502.46 Gg in 1999.

While methane emissions estimated using modified triangular method indicated that methane emissions vary between 119.01 Gg in 1980 and 400.66 Gg in 1999. It is important to note that the estimation of methane emissions from landfills done using a triangular model is more realistic. This model can very well be used in estimation globally.

However, according to the authors of the study, there were certain limitations in the inventory estimation of methane emissions for the years 1980–1999 in India. The inventory estimation was made mostly on the basis of published documents and a little on the generated data. Mostly, the default values suggested by IPCC have been used in estimation. These values are based on studies made in other situations. For realistic values for Indian conditions, a detailed study is required to arrive at appropriate factors. Similarly, several constraints have also been observed in data collection.

Most of the municipalities do not maintain solid waste data due to lack of awareness, small financial budgets and low priority. It is important to note that the assumption made in the default methodology is that all the methane from waste deposited that year is emitted in the same year itself, which is unrealistic as deposited waste gradually keeps emitting methane over a long period of time. The triangular method gives more realistic values as it assumes that waste keeps emitting gas for 15 years and the emissions follow a triangular form. Keeping this in mind, the emission graph here represents the estimated year-wise methane emissions by Indian dumpsites from 1980 to 1999. It is important to note that these methane emission estimates have been calculated by CSIR-NEERI and these values were used by MoEFCC in the first NOTCOM report. However, year-wise data is not made available in future reports.

Graph 6: Methane emissions from Indian dumpsites calculated by CSIR-NEERI (1980–1999)



Source: CSIR-NEERI, 2004

In the latest national estimations done by MoEFCC for the Third BUR submitted by India to the UNFCCC, methane emissions from landfills have been estimated using the following methodology:

1. The total amount of MSW generated in India is estimated.
2. Methane generation potential of MSW is estimated using a first-order decay (FOD) model.
3. Methane emissions from landfills are estimated by multiplying the methane generation potential by the fraction of MSW that is landfilled.

The FOD model used in the BUR is based on the following equation:

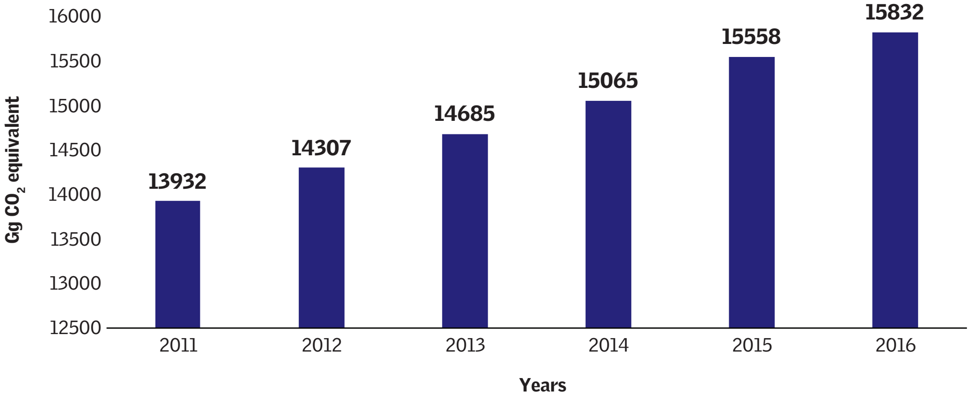
$$M_t = M_o * e^{-kt}$$

where:

- M_t is the amount of methane generated at time t
- M_o is the initial amount of methane generated
- k is the decay rate constant

The decay rate constant is a function of the temperature and moisture content of the landfill or dumpsite. As methane recovery is not practiced at most disposal sites, the BUR uses a default value of 'k' as zero in estimation.

Graph 7: Methane emissions from landfilling of waste, calculated by MoEFCC (2011–2016)



Source: India's third BUR, MoEFCC, 2016

In 2015, 58 million tonnes of MSW were generated in the country, accounting for 736 Gg of methane emissions. In 2016, 59 million tonnes of MSW were generated, accounting for 754 Gg of methane emissions. This proportionate increase of methane emissions with MSW landfilled implies that methane emissions are estimated based on the quantities of waste generated in the country. However, the emissions should be measured on the basis of quantities of waste reaching the landfills/dumpsites.

Table 2: MSW quantities generated and corresponding methane emissions for 2015 and 2016

Year	MSW quantities considered for methane estimation (in million tonnes)	Estimated methane generation (in Gigagrams)	Estimated emissions (in CO_2e Gigagrams)
2015	58	736	15,558
2016	59	754	15,832

This methodology has a number of limitations:

- The decay rate is assumed to be constant over time. However, it can vary depending on the temperature and moisture content of the landfill. This means that the methane emissions estimates may be inaccurate if the temperature and moisture content of the landfill change over time.
- The temperature and moisture content of landfills are assumed to be constant over time. However, the temperature and moisture content of landfills can vary depending on the location of the landfill, the depth of the landfill, and the type of waste that is landfilled.
- The fraction of MSW that is landfilled is assumed to be constant over time. However, the fraction of MSW that is landfilled can vary depending on several factors, including the waste management practices in the country, the economic development of the country, and the availability of other waste disposal options. This means that estimates of methane emissions may be inaccurate if the fraction of MSW that is landfilled changes over time.
- The FOD model is based on data from landfills in the United States, and it may not be accurate for landfills in India. The composition of waste in India can vary significantly from the composition of waste in the United States, and the climate in India can also be different from the climate in the United States.
- The FOD model is not as accurate as some other models that are available. For example, the LandGEM model is a more complex model that can account for a wider range of factors that can affect methane emissions from landfills.

In addition to these limitations, the accuracy of the methane emissions estimates is also dependent on the accuracy of the data used. The data used in the BUR is based on certain assumptions, especially the quantity of waste disposed of in landfills or dumpsites. Firstly, assumptions made in the methodology are not clearly mentioned in the report. Secondly, the accuracy of the data used can vary depending on the source of the data and the methods used to collect the data (see Chapter 4 for detailed discussion on accuracy of data on waste disposed of in dumpsites).

2. How is methane generated in landfills?

KEY HIGHLIGHTS

- **The overall decomposition of organic matter in a landfill follows four sequential biochemical reactions: hydrolysis, acidogenesis, acetogenesis and methanogenesis.**
- **The end-product of biochemical reaction—landfill gas—typically contains 45 to 60 per cent methane, 40 to 60 per cent carbon dioxide, and traces of nitrogen, oxygen, ammonia, sulphides, hydrogen, carbon monoxide and non-methane organic compounds (NMOCs).**
- **Methane generation starts one to two years after waste disposal into the landfill and continues for 15–25 years. The highest methane emissions are observed in 5–6-year-old landfills.**
- **Major factors affecting the amount of gas generation are waste composition, moisture content, temperature and landfill age.**

Over the last few decades, methane concentration has progressively increased in the atmosphere. From 1750 to 2010, the concentration of methane in the environment went from 700 ppb to 1,808 ppb.[11] Over the last three decades, the rate of increase was observed to be 1–2 per cent per annum.[12]

Open dumpsites and landfills are significant contributors of anthropogenic methane gas. A considerable portion of waste in India is biodegradable in nature, and mixed MSW emits methane for years, even if the landfill is scientifically closed.[13] Besides, methane emissions from MSW landfills represent a lost opportunity to capture, recover and use a significant energy resource. For example, the organic waste can be converted into compost or biogas.

Non-biodegradable waste can also be recycled and kept in the value chain. Their conversion into "secondary raw material" can help in reducing dependence on virgin raw material. Plastic use and waste are expected to triple by 2060, contributing to climate change and associated environmental hazards. Based on current consumer trends, the full lifecycle of plastic could contribute up to 15 per cent of global GHG emissions by 2050.[14]

Difference between engineered landfills and open dumpsites

It is imperative to understand the fundamental difference between a scientific landfill site and a “dumpsite”, especially in an Indian and developing economy context, as this will have a direct impact on methane emissions.

Engineered landfills are considered waste containment systems and are designed to ensure the least practicable impact on the surrounding environment. To ensure this and minimize health hazards in the longer term, they also have to be managed and operated in a sound manner. Scientific/sanitary landfills for MSW are provided with all the necessary mechanisms for collection and treatment of leachate and other pollutants.

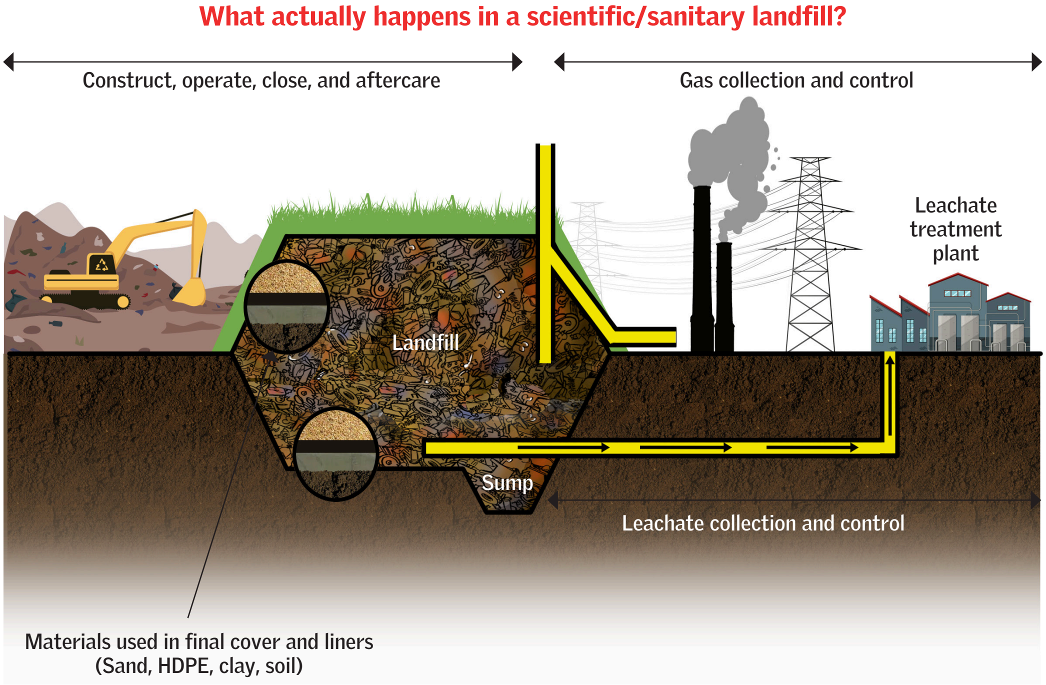
Most importantly, scientific landfills have a collection and treatment system for collecting the generated gases. As per the United States Environmental Protection Authority (USEPA), a sanitary landfill designed to receive mixed municipal solid waste (containing biodegradable organics) should be provided with a gas collection system in the design phase itself and the collected gases should be flared or treated appropriately with all the precautionary measures.

The overall objective of installing a landfill gas collection mechanism is to prevent people from being exposed to landfill gas emissions and to minimize the GHG emissions. This objective is typically achieved by adopting technologies used to control landfill gases separately or in combination.

Many countries have developed laws and regulations that govern the operation and maintenance of landfills, specially focussing on the collection and treatment of landfill gases. For example, under Subtitle D of the Resource Conservation and Recovery Act (RCRA) (which regulates the siting, design, construction, operation, monitoring and closure of MSW landfills) enacted in the US in 1976, landfills are required to control gas by establishing a program to periodically check for methane emissions and prevent off-site migration. However, Indian regulations do not mandate the monitoring of landfill or dumpsite gas emissions.

In 1991, USEPA issued standards for landfill design and performance that apply to MSW landfills active on or after 9 October 1993. The standards require methane monitoring and establish performance standards for methane migration control.[15] Monitoring requirements must be met at landfills not only during their operation, but also for a period of 30 years after closure. Landfill owners and operators must ensure that the concentration of methane gas does not exceed:

Figure 1: Processes involved in a scientific landfill with pollution control measures



Source: Adapted from: Y. Wang, J.W. Levis and M.A. Barlaz 2021. "Life-Cycle Assessment of a regulatory compliant US municipal solid waste landfill," Environmental Science & Technology 55 (20).

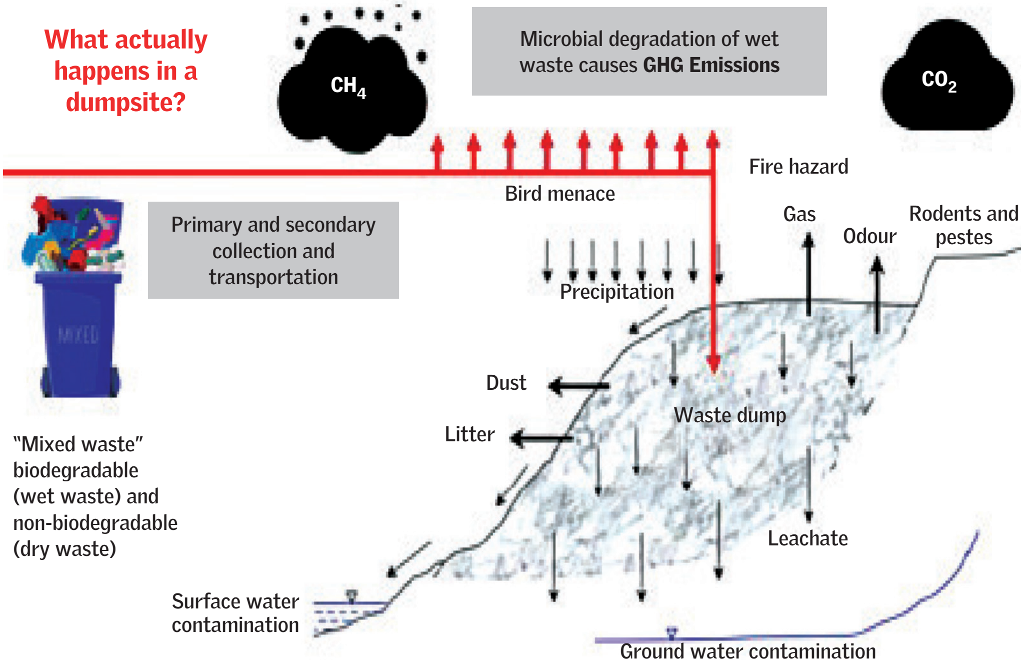
- 25 per cent of the explosive limit for methane in the facilities' structures (1.25 per cent by volume)
- The lower explosive or flammable limit for methane at the facility boundary (5 per cent by volume)

It is important to note that methane is explosive within the range of 5 to 15 per cent concentration in air. If methane emissions exceed the permitted limits, corrective action (i.e., installation of a landfill gas collection system) must be taken.[16] However, in the Indian scenario, installation of gas vents is not seen as an effective solution considering low gas recovery from unscientific landfills or dumpsites.

A dumpsite is a mere piece of land typically owned by the government but not selected as per the site selection criteria, site investigation criteria and Environmental Impact Assessment (EIA) protocols.

Such sites are neither constructed nor operated in a scientific manner, thus leading to several environmental and health hazards such as surface and ground water pollution, fire outbreaks, pests, vectors, bioaerosols and generation of GHGs such as methane, carbon dioxide, hydrogen sulphide and ammonia.

Figure 2: Unscientific landfill or open dumpsite with no pollution control mechanism



Source: Richa Singh 2022. *Toolkit: Legacy Waste Management and Dumpsite Remediation to Support Swachh Bharat Mission 2.0*, Centre for Science and Environment, New Delhi

In the Indian scenario, dumpsites have become a potential source of GHG emissions, especially methane, and several other health hazards. This is because of two primary reasons:

1. The dumpsites are unscientific. They are not provided with any barrier layer or impervious layer. There is no collection and treatment mechanism for leachate and landfill gases.
2. Open dumpsites are typically mere pieces of land which have been used for disposing of the waste (mostly in mixed form in India) which leads to generation of landfill gases and other associated hazards. The gases generated in the process of anaerobic decomposition in a dumpsite or landfill are called 'landfill gases'.

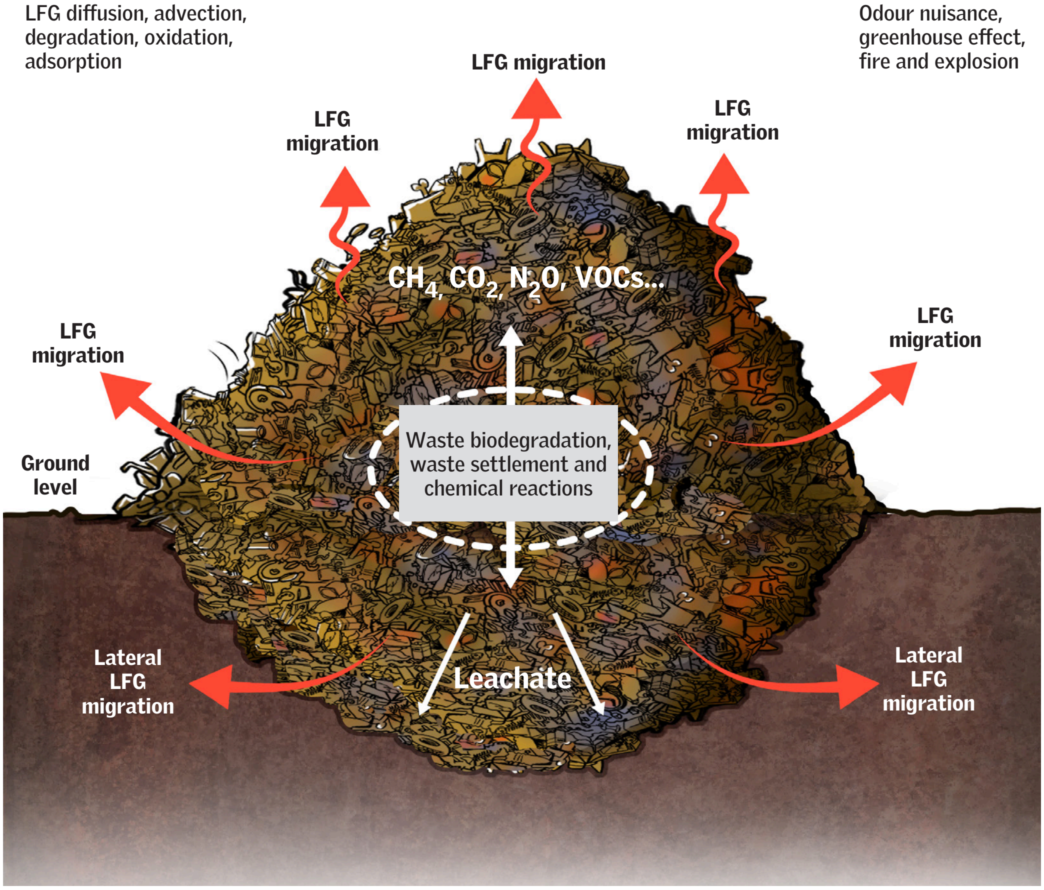
On the contrary, in many EU countries, only rejects (residual solid waste from the waste processing industries and inerts) finally end up in the landfills. EU's Directive (EU) 2018/850 introduces restrictions on landfilling of waste that is suitable for recycling or other kinds of material/energy recovery. As a result, landfill gas generation is a redundant issue for such landfills where only inerts are disposed of.

Production and migration of landfill gases in a dumpsite

Urban India generates nearly 1.6 lakh tonnes of municipal solid waste every day, 50 to 60 per cent of which is biodegradable in nature.[17] A significant portion of mixed MSW is disposed of in dumpsites. Landfill gases are generated due to various biochemical reactions mediated by microbial population. It is important to note that MSW contains nearly 150–250 kg of organic carbon per tonne of waste, microorganisms in which transform it into landfill gas during anaerobic processes.

Concentrations of landfill gas components vary depending on waste composition and the decomposition phase of the waste. During the biodegradation process, pressure, concentration and temperature gradients are developed within the dumpsite/landfill, and landfill gases migrate vertically and laterally towards areas of lower pressure, concentration and temperature. Direction and migration rates depend on site characteristics, soil permeability, depth of filling, compaction density of waste, etc.[18]

Figure 3: Emissions from a landfill/dumpsite

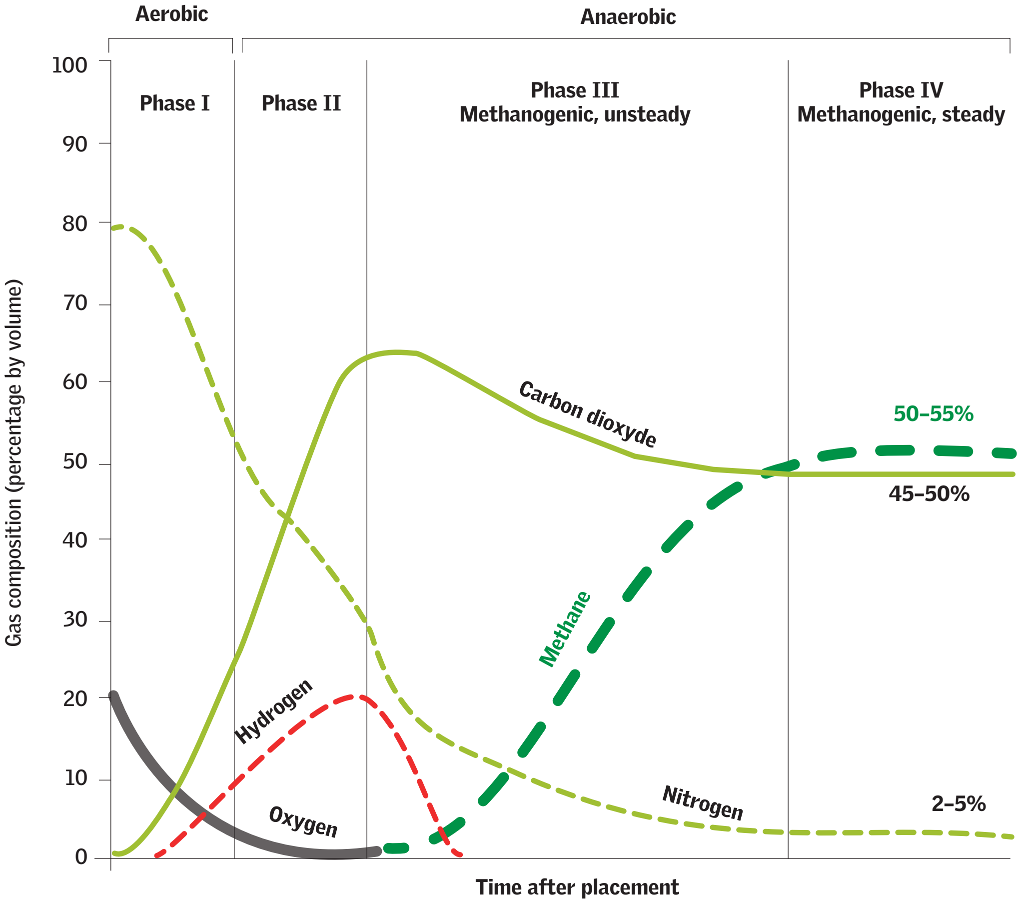


Source: Wang, Q., Gu, X., Tang, S., Mohammad, A., Singh, D.N., Xie, H., Chen, Y., Zuo, X. and Sun, Z., 2022. Gas transport in landfill cover system: A critical appraisal. *Journal of Environmental Management, 321*, p.116020.

Methane production from biodegradation of waste

GHGs including methane are produced by a series of biochemical reactions. Since methanogens are the most important organisms for methane production, preserving their activity is important for methane enhancement. To produce methane, methanogenic bacteria consume acetic acid, carbon dioxide and hydrogen. Optimum pH and temperature are critical sustenance conditions for the bacteria involved in the decomposition process.

Graph 8: Landfill gas generation and changes overtime



Source: D. Andriani and T.D. Atmaja 2019. "The potentials of landfill gas production: a review on municipal solid waste management in Indonesia," *Journal of Material Cycles and Waste Management* 21.

Table 3: Composition of landfill gas in different phases of the degradation process

Phases	Processes	Duration
Phase I	Oxygen and nitrate-reducing phase	Hours to 1 week
Phase II	Acidic phase	1 to 6 months
Phase III	Unstable methane generating phase	3 months to 3 years
Phase IV	Long-term stable methane generating phase	5 to 50 years
Phase V	Humus-generating and/or sulphide oxidation phase	1 min–40 years
	TOTAL	**1 min–90 years**

Source: IPCC[19]

The overall decomposition of organic matter has been assumed to follow four sequential biochemical reactions: hydrolysis, acidogenesis, acetogenesis and methanogenesis.[20] These biochemical reactions or microbial decompositions inside a landfill/dumpsite occur in the following five phases:

Phase I: During the first phase of microbial decomposition, there is a prevalence of aerobic bacteria. They consume oxygen while breaking down the long molecular chains of complex carbohydrates, proteins and lipids that comprise organic waste. The primary by-product of this process is carbon dioxide. Nitrogen content increases at the beginning of this phase, but declines as the landfill moves through the four phases. Phase I continues until available oxygen is depleted. Phase I decomposition can last for days or months, depending on how much oxygen is present when the waste is disposed of in the landfill. Oxygen levels will vary according to factors such as how loose or compressed the waste was when it was buried.[21]

Phase II: Phase II decomposition starts after all the oxygen in the landfill has been consumed. In the subsequent anaerobic process, bacteria convert compounds created by aerobic bacteria into acetic, lactic and formic acids, and alcohols such as methanol and ethanol. The landfill becomes highly acidic. As the acids mix with the moisture present in the landfill, they cause certain nutrients to dissolve, making nitrogen and phosphorus available to the increasingly diverse species of bacteria in the landfill. The gaseous by-products of these processes are carbon dioxide and hydrogen. If the landfill is disturbed or if oxygen is somehow introduced into the landfill, microbial processes will return to Phase I.[22]

Phase III: Phase III decomposition starts when certain kinds of anaerobic bacteria consume the organic acids produced in Phase II and form acetate, an organic acid. This process causes the landfill to transform into a more neutral environment in which methane-producing bacteria begin to establish themselves. Methane- and acid-producing bacteria have a symbiotic relationship. Acid-producing bacteria create compounds for the methanogenic bacteria to consume. Methanogenic bacteria consume the carbon dioxide and acetate, too much of which would be toxic to the acid-producing bacteria.[23]

Phase IV: Phase IV decomposition begins when both the composition and production rates of landfill gas remain relatively constant. Phase IV landfill gas usually contains approximately 45 to 60 per cent methane by volume, 40 to 60 per cent carbon dioxide, and 2 to 9 per cent other gases such as sulphides. Gas is produced at a stable rate in Phase IV, typically for about 20 years; however, gas will continue to be emitted for 50 or more years after the waste is placed in the landfill.[24] Gas production might last longer, for example, if greater amounts of organics are present in the waste, such as at a landfill receiving higher than average amounts of domestic animal waste.[25]

Phase V: In the maturation phase, most organic waste has already been decomposed and converted into landfill gas, and the rate of gas generation drastically declines as the landfill stabilizes. It is reported that the half-life of landfill gas production is about three to four years; however, slow but steady gas production continues to occur for 20 to 30 years or more.[26]

What is landfill gas composed of?

Landfill gas is produced from a series of chemical and biological reactions that typically occur in the disposed of waste in landfills. By volume, landfill gas typically contains 45 to 60 per cent methane and 40 to 60 per cent carbon dioxide. Landfill gas also includes small amounts of nitrogen, oxygen, ammonia, sulphides, hydrogen, carbon monoxide, and non-methane organic compounds (NMOCs) such as trichloroethylene, benzene, and vinyl chloride.

Table 4: 'Typical' landfill gases, their per cent by volume, and their characteristics

Gas	Per cent by volume	Characteristics
Methane	45–60	Methane is a naturally occurring gas. It is colourless and odourless. Landfills are the single largest source of man-made methane emissions.
Carbon dioxide	40–60	Carbon dioxide is naturally found in small concentrations in the atmosphere (0.03 per cent). It is colourless, odourless and slightly acidic.
Nitrogen	2–5	Nitrogen comprises approximately 79 per cent of the atmosphere. It is odourless, tasteless and colourless.
Oxygen	0.1–1	Oxygen comprises approximately 21 per cent of the atmosphere. It is odourless, tasteless and colourless.
Ammonia	0.1–1	Ammonia is a colourless gas with a pungent odour.
NMOCs (Non-methane organic compounds)	0.01–0.6	NMOCs are organic compounds (i.e., compounds that contain carbon). Methane is an organic compound but is not considered an NMOC. NMOCs may occur naturally or be formed by synthetic chemical processes. Most commonly found NMOCs' in landfills include acrylonitrile; benzene; 1,1-dichloroethane; 1,2-cis dichloroethylene; dichloromethane; carbonyl sulphide; ethyl-benzene; hexane; methyl ethyl ketone; tetrachloroethylene; toluene; trichloroethylene; vinyl chloride; and xylenes.
Sulphides	0–1	Sulphides (ex. hydrogen sulphide, dimethyl sulphide, mercaptans) are naturally occurring gases that give the landfill gas mixture its rotten-egg smell. Sulphides can cause unpleasant odours even at very low concentrations.
Hydrogen	0–0.2	Hydrogen is an odourless, colourless gas.
Carbon monoxide	0–0.2	Carbon monoxide is an odourless, colourless gas.

Source: USEPA

Factors affecting landfill gas generation

Major factors affecting the amount of gas generation are as follows: waste composition, moisture content, temperature and landfill age. Gas generation starts one to two years after waste disposal into the landfill and continues for 15–25 years.[27],[28]

The age of waste: Typically, fresh municipal waste, which is more recently buried waste (i.e., waste buried within 10 years), generates more landfill gas through microbial degradation, volatilization and chemical reactions than legacy waste or aged waste (buried for more than 10 years). Peak gas production usually occurs between 5–7 years after the waste is buried. The highest methane emission is observed in 5–6-year-old landfills.[29]

pH of waste: pH is also one of the critical factors affecting the decomposition of waste and gas generation.[30] Between pH 6.8–7.4 and at higher moisture contents, the methane emission in landfill areas is reported to be high.[31] A neutral pH is considered good for methanogenesis in landfills and dumpsites.[32]

Moisture content: The availability of moisture in unsaturated conditions in a landfill enhances gas production, including methane, because it promotes microbial degradation.[33,34] Moisture may also promote chemical reactions that produce gases. The optimum moisture content was reported as 38.8 per cent since the maximum decay rate occurred at this level of moisture content.[35]

Temperature: Typically, microbial activities are influenced by changes in temperature.[36] As the temperature rises inside a landfill, the bacterial activity increases, resulting in increased gas production.[37] Increased temperature may also increase rates of volatilization and chemical reactions. A progressive increase in methane flux happens at day time when the temperature is between 30–40 ˚C, as that is the optimum temperature and a critical factor for the generation of methane. An approximation states that each 10 ˚C increase in temperature doubles microbial activity.[38] However, this trend is valid only in the optimal range between 30 and 40 ˚C. Further increase in temperature marks a deterioration in microbial activity.[39]

Seasonal variation: Methane and carbon dioxide emissions are typically the highest during the summer season, followed by the monsoon and winter seasons.[40]

Presence of complex biomolecules: Major organic components of waste disposed of in landfills, which are converted to methane through chemical, physical and biological processes, include lignin, cellulose, hemicellulose and proteins. Lignins and cellulose vary considerably in their rates of decomposition. For instance, lignins are regarded as recalcitrant compounds under anaerobic conditions. Besides, pH and temperature play a critical role in microbial activity.

A study by National Environmental Engineering Research Institute (CSIR-NEERI) reported that fresh waste, which has a higher ratio of C + H : L (cellulose + hemicellulose : lignin), is responsible for maximum CH_4 and CO_2 generation. The ratio of C + H : L observed in fresh waste, 3-month, 6-month, 3-year and 5-year-old waste was 2.62, 1.70, 1.32, 1.21 and 1, respectively. There is a progressive decrease because of degradation of organics. As a result, gas generation would also decrease concomitantly. The study also showed that gas generation is directly proportional to lignocellulose biomass contents (garden waste) present in MSW.[41]

The same study also reported that the volume of gas generated reduces with the age of the waste deposited. For instance, the volume of initial CH_4 and CO_2 produced in 30 days from fresh waste, 3-month, 6-month, 3-year and 5-year-old waste was 66, 54, 57, 30 and 8 ml/g of dry volatile solids (VS), and 50, 456, 260, 75, 71 and 52 ml/g of dry VS, respectively. Similarly, the volume of CH_4 and CO_2 produced in the final 30 days from synthetic waste, fresh waste, 3-month, 6-month, 3-year and 5-year-old waste was 810, 821, 507, 501, 183 and 97 ml/g of VS, and 1,158, 1,031, 774, 706, 664 and 617 ml/g of VS, respectively.

3. Methods of estimating methane emissions from landfills/dumpsites

KEY HIGHLIGHTS

- **There are two ways of estimating methane emissions from landfills or dumpsites: theoretically and experimentally.**
- **Various theoretical models such as Intergovernmental Panel on Climate Change (IPCC) models, the Landfill Gas Emissions Model (LandGEM) and the Modified Triangular Method (MTM) are commonly used to predict annual methane emissions. They continue to receive criticism due to their poor accuracy and insufficient validation.**
- **The experimental ways of estimating methane emissions include flux chamber testing, plume measurement, micrometeorology measurement and dispersion modelling. These methods are substantially more expensive and give a wide variation in results.**

There are two ways of estimating methane emissions from landfills or dumpsites: theoretically and experimentally. Various theoretical models such as Intergovernmental Panel on Climate Change (IPCC) models, the Landfill Gas Emissions Model (LandGEM) and the Modified Triangular Method (MTM) are commonly used to predict annual methane emissions. However, landfill gas models continue to receive criticism due to their poor accuracy and insufficient validation.

Several studies have used these models with site specific parameters to estimate methane emissions from landfills. Among the available methods for the estimation of methane emissions from landfills, the simplest one was provided by Bingemer and Crutzen in 1987, which was further revised by the IPCC in 1996. It is a mass balance approach that provides actual emissions from the landfill, and it is widely used when detailed data is not available.[42]

Theoretical measurement

The four theoretical methods for measuring methane emissions from landfills are:

1) The Landfill Gas Emissions Model
2) USEPA's SWEET model
3) The IPCC default method
4) First Order Decay method

The Landfill Gas Emissions Model (LandGEM): This is an automated estimation tool with a Microsoft Excel interface developed by the USEPA to estimate emission rates for total landfill gas, including methane, carbon dioxide, nonmethane organic compounds, and other air pollutants from municipal solid waste.

LandGEM is based on a first-order decomposition rate equation and provides a relatively simple approach to estimating landfill gas emissions. Model defaults are based on empirical data from U.S. landfills. Field test data can also be used in place of model defaults when available.[43]

It is important to note that LandGEM depends on the availability of input data. The better the input data, the better the estimates. However, there are often limitations like unavailability of accurate data regarding waste quantity and composition, variation in design and operating practices over time, and changes occurring over time that impact the emissions potential. This is especially true in the case of Indian dumpsites and landfills.

USEPA's SWEET model: The Solid Waste Emissions Estimation Tool (SWEET) was developed by ABT Associates and SCS Engineers on behalf of the USEPA under the Global Methane Initiative and in support of the Climate and Clean Air Coalition. It is an Excel-based tool that quantifies emissions of methane, black carbon and other pollutants from sources in the municipal solid waste sector. The tool provides emissions and emissions reduction estimates at the project-, source-, and municipality-levels.[44]

A study done in 2019, *Estimation of methane emissions released from a municipal solid waste landfill site through a modelling approach: A case study of Akouédo landfill*, showed that LandGEM simulations using both default and site-specific parameters are higher than IPCC's waste model simulations, while SWEET predicts the lowest methane emissions. SWEET seems to make better simulations than LandGEM and IPCC's waste model, because it uses more parameters.[45]

High proportion of decomposable organic material and high moisture content in MSW favour gas generation. It is important to note that in most of the cases, theoretically calculated GHG emissions are less than the experimental estimates of GHG emissions. Many researchers have recommended that field trials at selected landfills should be conducted to assess the yield and composition of gases. The baseline data thus collected should be used to calibrate a theoretical model of gas yield.[46]

The IPCC default method: The IPCC default method is a simple mass balance calculation which estimates the amount of methane emitted from solid waste disposal sites assuming that all methane is released the same year the waste is disposed of.[47]

The default method will give a reasonable annual estimate of actual emissions if the amount and composition of deposited waste have been constant or varying little over a period of several decades. However, if the amount or composition of waste disposed of at the solid waste disposal site is changing more rapidly over time, the IPCC default method will not provide an accurate trend. For example, if there is a reduction in the amount of carbon deposited at the disposal site, the default method will underestimate emissions and overestimate reductions.[48] The IPCC model, similarly to the USEPA's LandGEM, uses a first-order decomposition rate equation.

First Order Decay (FOD) method: The FOD method factors in the time taken in the degradation process—which can take years, even decades—and produces annual emission estimates that reflect this process.

While the FOD method produces better estimates on annual emissions, the IPCC default method also has merits—for instance, in studies comparing the potential to reduce methane emissions by alternative waste treatment methods. The use of the IPCC default method and the FOD method require annual solid waste disposal data as input, including information on the composition of waste and on the conditions at the disposal site. The IPCC default method requires this data only for the inventory years, whereas the FOD method requires data for more than 20 years. In addition, the rate of degradation for disposed waste needs to be determined in the FOD method. IPCC Guidelines contain default values for most of the data needed in the use of the default method, whereas there are no clear guidelines about the default values needed in the use of the FOD method.

$$Q_{CH4}Emission = \sum \left[MSWt \times MSWf \times MCF \times DOC \times DOCf \times F \times \left(\frac{16}{12} - R \right) \right] \times (1 - OXt) (2)$$

Where Q_{CH4} Emission is the amount of methane emissions (Gg/year), MSWt and MSWf are respectively the waste mass (Gg MSW) and the fraction of municipal solid waste landfilled for the considered year; DOC and DOCf are respectively the Degradable Organic Carbon (Gg/Gg MSW) and the fraction of DOC dissimilated; F is the fraction of CH_4 in the landfill gas (set equal to 0.5); MCF is the methane correction factor based on landfill management strategy; R is the CH_4 recovered (Gg/year); OX = 0 (default value); 16/12 is the stoichiometric factor, the quotient of molecular weight of methane and carbon.

FOD models are known to be inaccurate for the estimation of landfill methane generation for individual sites, but a review of data collected by SCS as part of USEPA's GHG reporting programme suggests that the data may be more accurate when aggregated nationally, such as for a national inventory.[49] Individual sites have demonstrated methane recovery of more than twice what the FOD modelled generation predicted, and SCS believes that the model can similarly over-predict methane generation by a factor of more than two for individual sites.

The latest GHG inventory in the US reports that US landfills generated approximately 109.3 million metric tonnes of carbon dioxide equivalent (MMTCO$_2$e) of methane into the environment in 2020. That constitutes nearly 16.8 per cent of the total US anthropogenic methane emissions across all sectors. MSW landfills contributed 94.2 MMTCO$_2$e (14.5 per cent of total U.S. methane emissions) while industrial landfills contributed the remaining 15.1 MMTCO$_2$e (2.3 per cent of total).[50]

Table 5: Comparison of different methodologies used for GHG emissions estimation from landfills

Features	IPCC (1996) Default method (DM)/ Zero order method	Modified triangular method	IPCC (2006) First order decay method (FOD)	LandGEM
Data availability and required parameters	Timely data is required for proportion and characteristics of MSW disposed of in landfills (%) and MSW generated (Gg/y)	Requires CH$_4$ generated (Gg/y) to be calculated by the Default Method	a) Waste disposal history (Gg/y) b) Characteristics of MSW reaching the landfills	Timely data required for best results a) Landfill open year b) Landfill closure c) Methane yield (m^3/Mg) d) Methane generation rate, K (yr^{-1})
	Can be used where detailed data is not available		Requires history and present data with waste classified according to categories recommended by IPCC (2006)	
Model output	CH$_4$ emissions (Gg/y)	CH$_4$ emissions (m^3/y)	CH$_4$ emissions (Gg/y)	Time series of emissions (Mg/y) with future projections
Assumption(s) involved	1. All of methane generation occurs in the year of waste generation itself. 2. Assumes constant quantity of waste is added to the landfill each year	Degradation occurs in two phases: i) the first phase deposition increases linearly to maximum point, and ii) second phase deposition decreases linearly to zero	Degradation in landfills follows first order kinetics	Degradation in landfills follows first order kinetics

Features	IPCC (1996) Default method (DM)/ Zero order method	Modified triangular method	IPCC (2006) First order decay method (FOD)	LandGEM
Remarks	Recommended by IPCC	Useful where adequate data of waste characterization is not available	Recommended by IPCC	Recommended by USEPA with latest version 3.02
Limitations	1. Unrealistic assumptions 2. Will give over-estimated results as it does not consider that waste composition also varies with time	1. Parameters are depended on DM method 2. Data availability	1. Since it considers parameters of temperature and precipitation, wide range of data availability makes it uncertain 2. Often there is the lack of historic data	1. Unable to account for multiple waste disposal streams 2. Rate of gas generation is not constant as assumed in the model 3. Not much availability of quality waste flow data for model calibration

Source: Compiled from different sources cited in the report. Srivastava (2020)[51], US EPA (2005) LandGEM[52], Kumar (2014) [53]

Landfill methane measurement or the experimental methods

Landfill methane measurement is the direct measurement of methane emissions from landfills. All these measurement methods are substantially more expensive than the estimation methods outlined above due to the large amount of fieldwork, equipment and analysis required.[54]

However, there are many uncertainties involved in methane emission measurement using the available methods. The uncertainty of methane emissions from solid waste landfill sector is estimated to range from -56 to 49 per cent while the uncertainty of total GHG emissions is estimated to range from -2 to 5 per cent.[55] The four methods of landfill methane measurement are:

1. Flux chamber testing (Method B-1)
2. Plume measurement
3. Micrometeorology measurement
4. Dispersion modelling

Flux Chamber Testing (Method B-1): Flux chamber testing is the sampling of methane flux (mass emissions per area) at the landfill surface using either static or dynamic flux chambers.[56,57,58] Flux chambers are small (typically around one square meter) half-open chambers (typically a dome) that are placed on the surface being sampled. Sample locations are very small compared to the area of even a small landfill, so flux chamber testing must include a method of scaling the sampling results for the complete site.

Both the static and dynamic techniques have their own advantages and disadvantages.[59] For instance, the dynamic or open flux chamber simulates field conditions better than the static or closed flux chamber; however, the open chamber may indicate artificially high fluxes because of pressure changes inside the chamber.[60] Although the static chamber method has proven to be feasible in methane emission monitoring, there are still some disadvantages. For monitoring the whole landfill site, many points are needed to quantify the representative flux of the whole site.[61]

Plume measurement: This method uses a ground-based optical sensor to measure the methane plume emanating from a landfill.[62] Those plume measurements are then used to calculate the methane emission rates from the entire landfill. There is currently no standardized optical sensor method. The USEPA has published Other Test Method 10 (OTM 10), but it has generally fallen out of use and is not regarded as practical or accurate enough for regular use. The USEPA is not currently recommending this method on sites they regulate, but they have recently required monitoring using eddy covariance for specially regulated sites.

Air dispersion emission methods: Air dispersion emission calculation methodologies use field measurement of methane concentration data and contemporaneous meteorology data to calculate methane emissions from the landfill using an air dispersion model such as American Meteorological Society (AMS)/EPA Regulatory Model (AERMOD) or CalPUFF. There is no standardized method for obtaining methane measurements from the field.

Like methane measurement methods such as plume measurement and micrometeorology measurement, this method also requires the collection of extensive meteorological data, which must be collected contemporaneously with methane concentration data. Methane monitoring and associated meteorology data is expensive to collect if the data is not already being collected for other purposes, and the use of methane monitoring data from a single monitoring event is only reflective of methane emissions during that event.

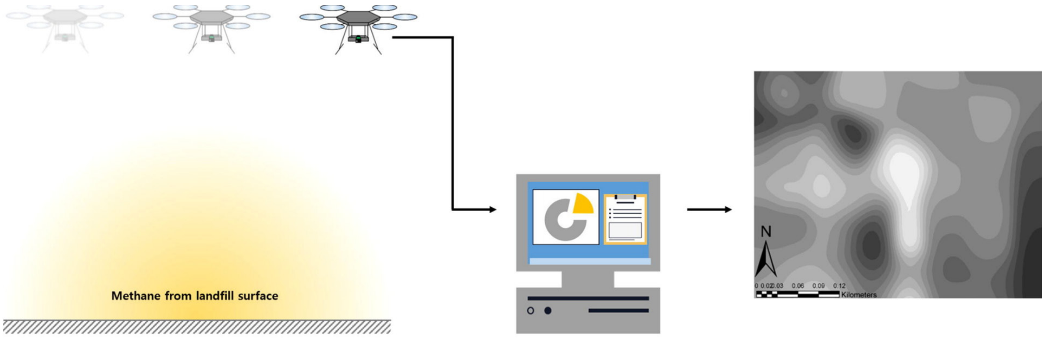
Aerial vehicles for estimation of methane emissions: Several methods have been used to monitor emissions of fugitive methane gas from landfills. Lately, there have been suggestions to use a framework utilizing an unmanned aerial vehicle (UAV) for landfill gas monitoring, and several field campaigns have proved that a rotary UAV-based measurement has advantages of ease of control and high-resolution concentration mapping.[63]

Radical progress was made in the field of remote sensing technology, which was associated with the rapid development and spread of unmanned aerial imagery technology and photogrammetric technology for the processing of aerial photographs that were obtained from UAVs.[64] A variety of platforms exist for the measurement of methane emissions. These can range from ground-based systems, to instrumentation fitted onboard aircraft, to satellites which monitor total atmospheric-column methane from a low-Earth orbit. Measurement platforms can be geospatially fixed, in the form of towers or long-term fixed-site monitoring stations; or geospatially flexible, as in a moving vehicle.

UAVs can complete the entire range of tasks that are associated with the monitoring of landfills—identification of illegal dumps, topographic mapping of waste disposal sites, etc. However, there remains a substantial sampling void between the ground, and altitudes of up to 100 m above ground, in which mobile platforms have been unable to operate until recently.

The advancements in UAV technology over the past decade have opened a new avenue for methane emission quantification. UAVs can be uniquely equipped to monitor natural and anthropogenic emissions at local scales, displaying clear advantages in versatility and maneuverability relative to other platforms. Their use is not without challenge, however: further miniaturization of high-performance methane instrumentation is needed to fully use the benefits UAVs afford.

Figure 4: UAV-based methane measurement



Rotary UAV-based methane measurment **Spatial methane data interpretation** **High resolution methane map**

Source: Kim, Y. M., Park, M. H., Jeong, S., Lee, K. H., & Kim, J. Y. (2021). Evaluation of error inducing factors in unmanned aerial vehicle mounted detector to measure fugitive methane from solid waste landfill. Waste Management, 124, 368-376.

Estimating methane emissions from landfills or dumpsites using satellite data is a valuable approach for monitoring and managing GHG emissions. Satellite data can provide a comprehensive and efficient way to assess and track these emissions. Here's an explanation of how this process generally works:

Figure 5: Various steps involved in methane estimation by satellites

Selection of satellite sensors: To estimate methane emissions from landfills, researchers typically use remote sensing satellite sensors that are capable of detecting methane concentrations in the Earth's atmosphere. Some commonly used sensors include those onboard the Copernicus Sentinel-5 Precursor (TROPOMI), the Japanese Greenhouse Gases Observing Satellite (GOSAT), and the upcoming MethaneSAT.

▼

Methane absorption spectra: Methane has characteristic absorption spectra in the infrared part of the electromagnetic spectrum. This means that it absorbs specific wavelengths of light. Satellite sensors are equipped with spectrometers that can detect these wavelengths, allowing them to measure the concentration of methane in the atmosphere.

▼

Data acquisition: Satellite sensors collect data by scanning the Earth's surface and measuring the intensity of sunlight reflected or emitted by the surface. Methane molecules in the atmosphere absorb some of this light, leaving a detectable signature in the data.

▼

Data processing: Raw satellite data must be processed to isolate the methane signal from other atmospheric and surface effects. This process involves atmospheric correction, which corrects for interference from other gases and atmospheric conditions. Researchers use algorithms and models to extract methane concentrations from the data.

▼

Spatial and temporal resolution: Satellite data can provide information about methane concentrations over a specific area (spatial resolution) and at specific time intervals (temporal resolution). The spatial resolution depends on the satellite sensor and can range from a few kilometres to several tens of kilometres.

▼

Validation and ground truth data: To ensure the accuracy of satellite-based methane estimates, ground-based measurements and monitoring are essential. Ground-based instruments, such as gas analysers, can provide direct measurements of methane concentrations at or near the landfill site. These measurements are used to validate and calibrate the satellite data.

▼

Modelling and estimation: Researchers often combine satellite data with atmospheric modelling and inversion techniques to estimate methane emissions from landfills. By analysing the concentration changes over time and accounting for atmospheric dispersion, they can estimate the emission rates from the landfill.

▼

Monitoring and reporting: The satellite-derived methane emission estimates can be used for continuous monitoring of landfill emissions. These estimates can inform regulatory agencies, landfill operators and policymakers about the effectiveness of mitigation measures and the overall environmental impact.

It is important to note that while satellite-based methane estimation is a powerful tool, it has some limitations, including the need for frequent satellite overpasses, challenges in differentiating between methane sources, and difficulties in capturing emissions from small or dispersed sources. Therefore, it is often used in combination with other monitoring methods, such as ground-based measurements and aerial surveys, to provide a comprehensive assessment of methane emissions from landfills and dumpsites.

4. Availability of data for the Indian waste sector

KEY HIGHLIGHTS

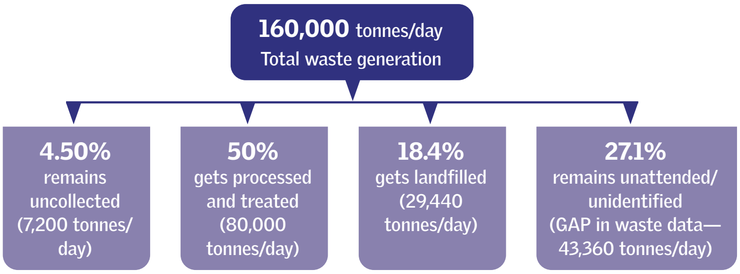
- **Around 50 per cent of the total waste generated in the country continues to remain uncollected, unattended or find its way to landfill sites**
- **CPCB's annual report 2020–21 shows that there are 3,159 operational dumpsites in India, while the SBM urban dashboard reports that there are 2,261 operational dumpsites in India (as on 2 August 2023). The discrepancy in data is a matter of concern.**
- **Around 170 million tonnes of legacy waste (which is 66 per cent of the total legacy waste) has to be remediated according to the SBM 2.0 Urban dashboard**

According to CPCB, the waste generated in India in 2020–21 was 160,000 TPD. This quantity represents an increment of 6 per cent compared to the previous year (2019–20).[65]

Around 50 per cent of the total waste generated was processed and treated during the year, which marks a significant increase of 6.38 per cent compared to the previous year. While there is improvement, the data also shows that 50 per cent of waste was still not collected, processed, or treated, leading to potential environmental and health risks.

While 4.5 per cent of total waste generated remained uncollected, 18.4 per cent was disposed of in landfills. Land disposal is often considered an unsustainable method of waste management due to its negative impact on the environment and public health. The gap in the data suggests that 27.1 per cent of the waste remained unattended and untreated.

Figure 5: Status of waste generation, collection, treatment and disposal in India



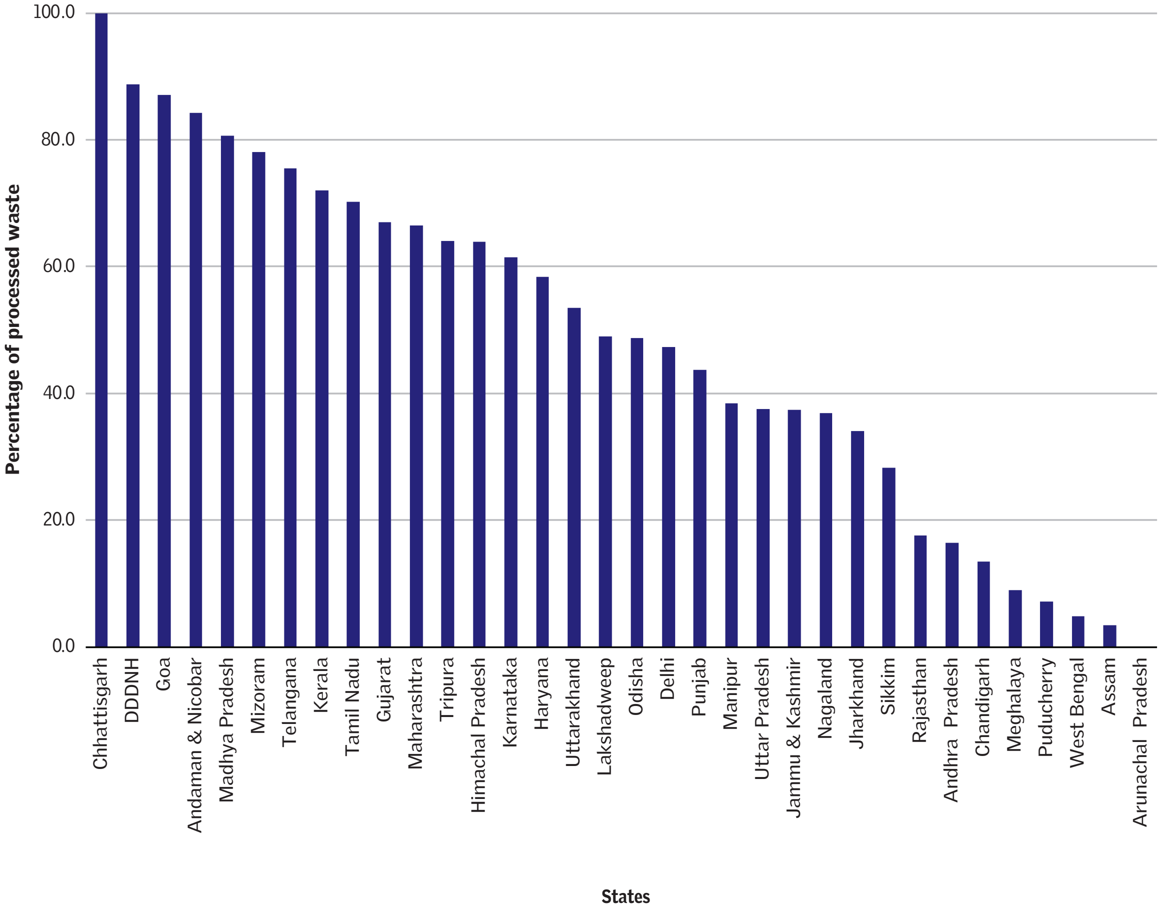
Source: Compiled from CPCB's annual report 2021–22

State-wise trends in waste processing

Chhattisgarh is the only state that shows 100 per cent treatment of its collected waste. The Union Territories of Daman and Diu and Dadra and Nagra Haveli (DD&NH) and Andaman and Nicobar Islands, along with the states of Goa and Madhya Pradesh, have also demonstrated impressive performance in waste treatment, with treatment percentages exceeding 80 per cent.

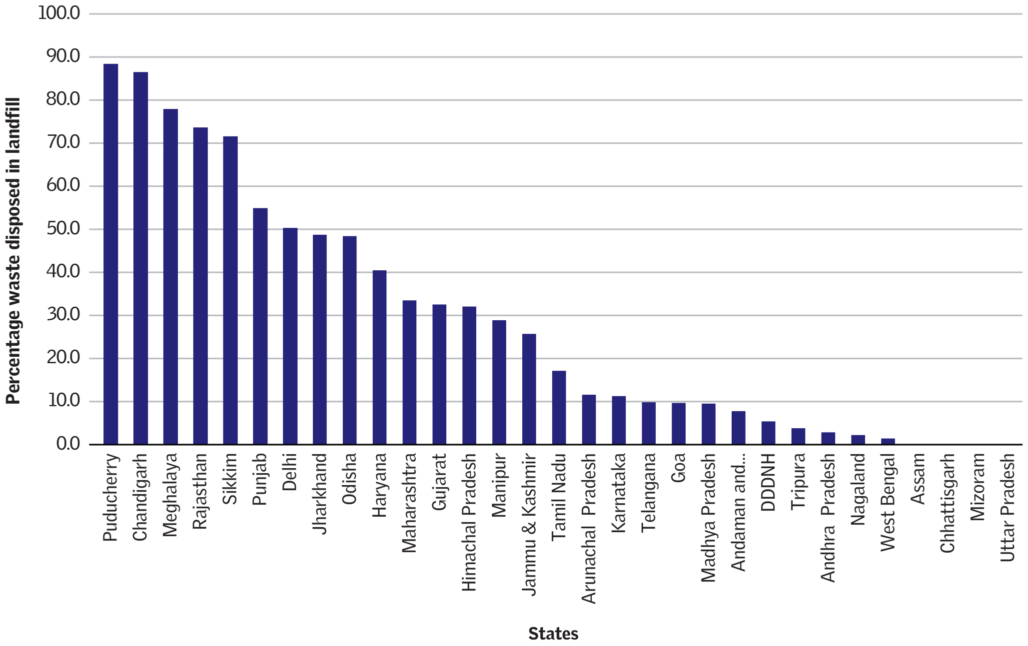
On the other hand, certain states have reported low percentages of treated waste. Arunachal Pradesh, Assam, West Bengal, Meghalaya and Puducherry have reported treatment percentages of less than 10 per cent, which implies that a major fraction of waste generated in these states is still ending up in dumpsites.

Graph 9: State-wise percentage of municipal solid waste processed as per CPCB



Source: CPCB's annual report 2020-21

Graph 10: Percentage of waste disposed of in dumpsites/landfills across Indian states



Source- CPCB's MSW annual report 2020-21

Other than Maharashtra, the data from all states is unclear about whether the waste is dumped or scientifically landfilled. Bihar, Kerala, Uttarakhand and Lakshadweep have not provided any data for landfilled waste.

Ideally, the states with poor percentage of waste treatment should show high fractions of waste dumped. The mismatching trends of processed waste and dumped waste makes the claims of these states (Assam, Goa, Chandigarh, West Bengal, Andhra Pradesh) suspect.

The total waste processed and landfilled should ideally match total waste collected. The gap is currently calculated as unattended waste.

Unattended/Untreated waste = Total waste generated - (Landfilled + Treated waste)

Status of dumpsites in India

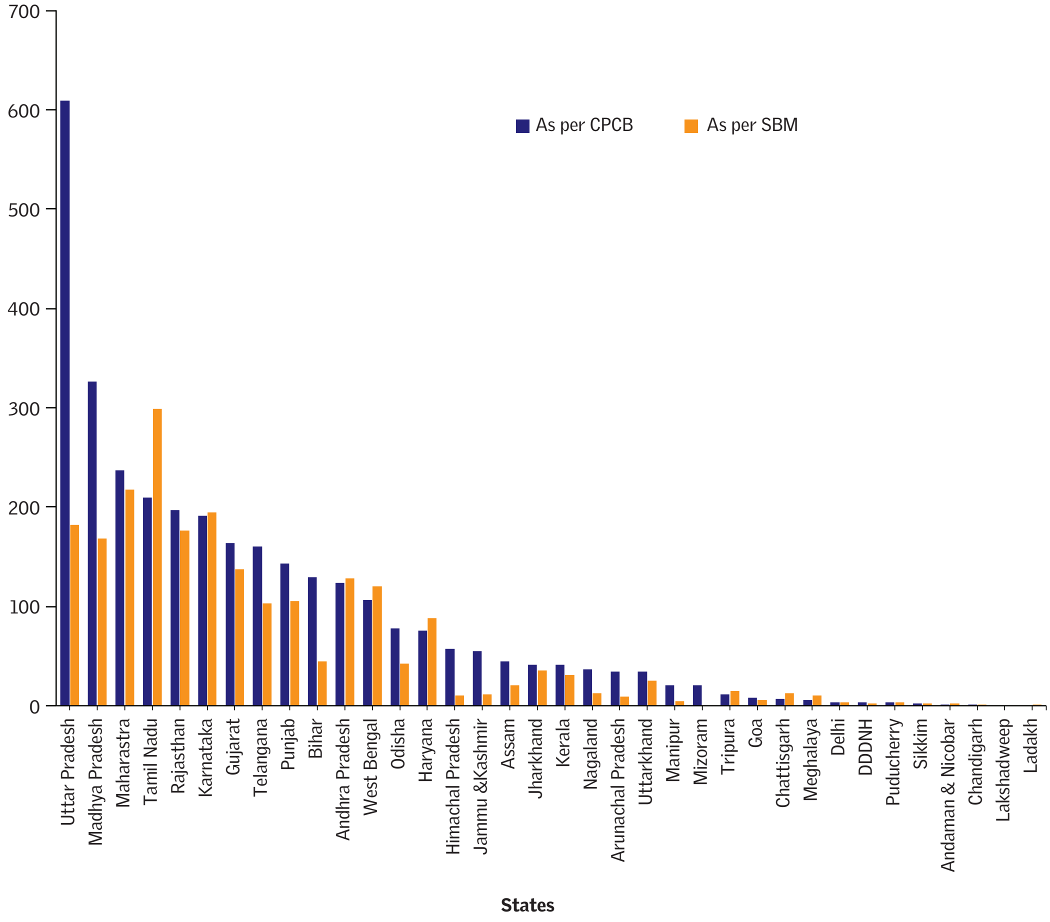
CPCB's annual report and the SBM urban dashboard are two of the most important sources of data on waste management in India. However, there is a discrepancy between the data reported by these two sources on the number of dumpsites in India.

CPCB's annual report 2020–2021 shows that there are 3,159 operational dumpsites in India, while the SBM urban dashboard reports that there are 2,261 operational dumpsites in India (as on 2 August 2023).[66,67]

One possibility for the discrepancy is that the two sources are using different methodologies for collecting data on dumpsites. The CPCB annual report collects data from state pollution control boards. The SBM urban dashboard, on the other hand, collects data directly from municipal corporations.

Whatever the reason for the discrepancy in data on the number of dumpsites between the CPCB annual report and the SBM urban dashboard, it is important to address this issue. Accurate data on dumpsites is essential for developing effective policies and for monitoring progress over time.

Graph 11: Number of dumpsites in India according to CPCB and SBM dashboard



Source: Compiled from CPCB Annual Report 2021-22 and SBM Urban dashboard

Status of Dumpsite remediation across Indian states

Table 6: Legacy waste in India

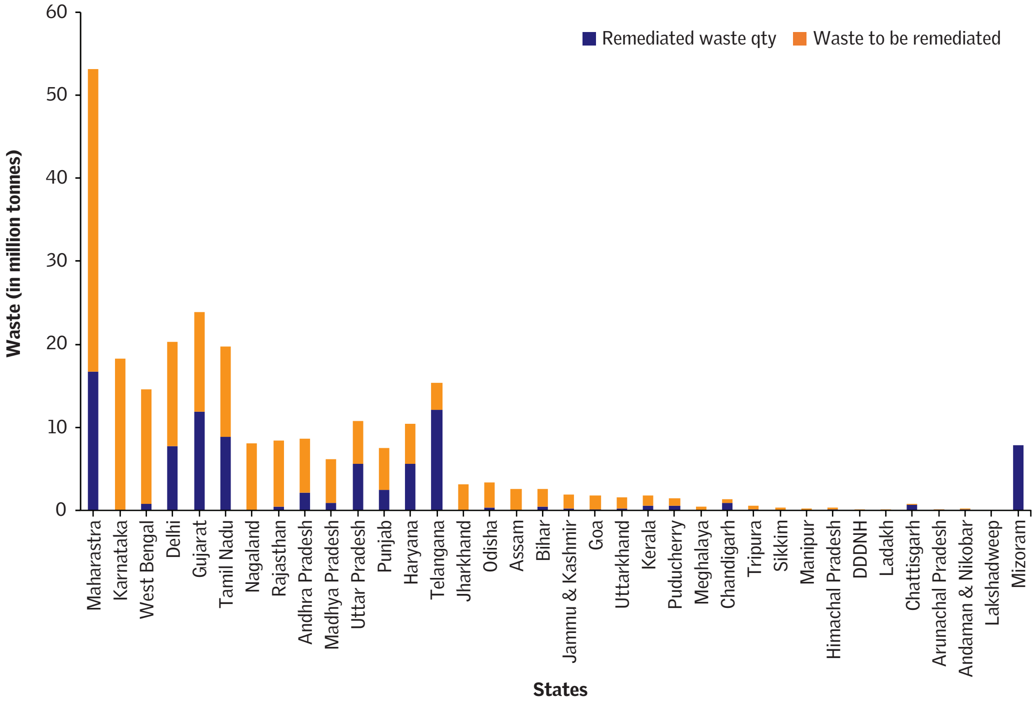
Sr. no.	States and UTs	Total legacy waste (in million tonnes)	Remediated waste quantity (in million tonnes)	Legacy waste to be remediated (in million tonnes)
1	Andaman & Nicobar	0.086	0.081	0.005
2	Andhra Pradesh	8.59	2.105	6.485
3	Arunachal Pradesh	0.036	0.017	0.019
4	Assam	2.549	0	2.549
5	Bihar	2.613	0.415	2.198
6	Chandigarh	1.277	0.86	0.417
7	Chhattisgarh	0.718	0.652	0.066
8	DDDNH	0.142	0	0.142
9	Delhi	20.3	7.698	12.602
10	Goa	1.801	0.133	1.668
11	Gujarat	23.864	11.872	11.992
12	Haryana	10.452	5.63	4.822
13	Himachal Pradesh	0.263	0.114	0.149
14	Jammu &Kashmir	1.907	0.184	1.723
15	Jharkhand	3.115	0.035	3.08
16	Karnataka	18.264	0.002	18.262
17	Kerala	1.767	0.533	1.234
18	Ladakh	0.132	0	0.132
19	Lakshadweep	0	0	0
20	Madhya Pradesh	6.201	0.905	5.296
21	Maharashtra	53.171	16.72	36.451
22	Manipur	0.16	0	0.16
23	Meghalaya	0.482	0	0.482
24	Mizoram	7.84	7.84	0
25	Nagaland	8.1	0	8.1
26	Odisha	3.293	0.271	3.022
27	Puducherry	1.486	0.59	0.896
28	Punjab	7.461	2.458	5.003
29	Rajasthan	8.42	0.463	7.957
30	Sikkim	0.286	0	0.286
31	Tamil Nadu	19.73	8.882	10.848
32	Telangana	15.329	12.14	3.189
33	Tripura	0.559	0.144	0.415
34	Uttar Pradesh	10.753	5.61	5.143
35	Uttarakhand	1.527	0.26	1.267
36	West Bengal	14.602	0.789	13.813

Source: SBM Urban dashboard (http://devwebsite.sbmurban.org/swachh-bharat-mission-progess)

In order to achieve the vision of "garbage-free" cities with SBM 2.0 guidelines, many ULBs across the country have accelerated the remediation process. More than 87 million tonnes of waste has been remediated all over the country, reclaiming 3,440 acres of land.

As per the SBM dashboard, out of 257 million tonnes of total legacy waste, around 34 per cent (87 million tonnes) has been remediated. That means nearly 66 per cent of total legacy waste still needs to be remediated. The union territory of Andaman and Nicobar Islands and states of Chhattisgarh and Telangana have successfully remediated a significant proportion, ranging from 80 per cent to 90 per cent of their legacy wastes. While Chandigarh, Haryana, UP and Gujarat have remediated approximately 50 per cent to 60 per cent of the total legacy waste present in their dumpsites.

Graph 12: State-wise status of legacy waste dumpsite remediation



Source: Compiled from SBM dashboard data as on 18th July 2023

However, this process has not picked up pace in some states. As per the SBM urban dashboard, a total of 13 states and 3 UTs are lagging behind the target, and have remediated less than 10 per cent of their legacy wastes. This showcases the uneven trends of remediation across different Indian states.

States of Assam, Nagaland, Manipur, Sikkim, Meghalaya and UTs of Ladakh and J&K are on mountainous terrains, making it difficult to transport and utilize the fractions after bio-mining. The cities are struggling to find economically viable options for the disposal of excavated segregated combustible fractions (SCFs) and fine soil-like material.

5. Estimating methane emissions from dumpsites in India

KEY HIGHLIGHTS

- **There is a huge disparity in methane emission estimates from Indian landfills/dumpsites. This can be attributed to factors such as inconsistent data collection, variable landfill practices, informal waste disposal, methodological differences, changes over time, and regulatory variations.**
- **The total methane emissions from Indian landfills, calculated by CSIR-National Environmental Engineering Research Institute (NEERI), worked out to be 0.334 Gt per year.**
- **No study has been conducted so far on the quantities of methane generated from individual dumpsites/landfills in cities all over the country.**

It is estimated that 30–70 Mt of methane gas is emitted per year from landfills throughout the world.[68] This is expected to increase to 365 Mt in 2030, assuming dumping of waste in landfills does not increase from current levels.[69]

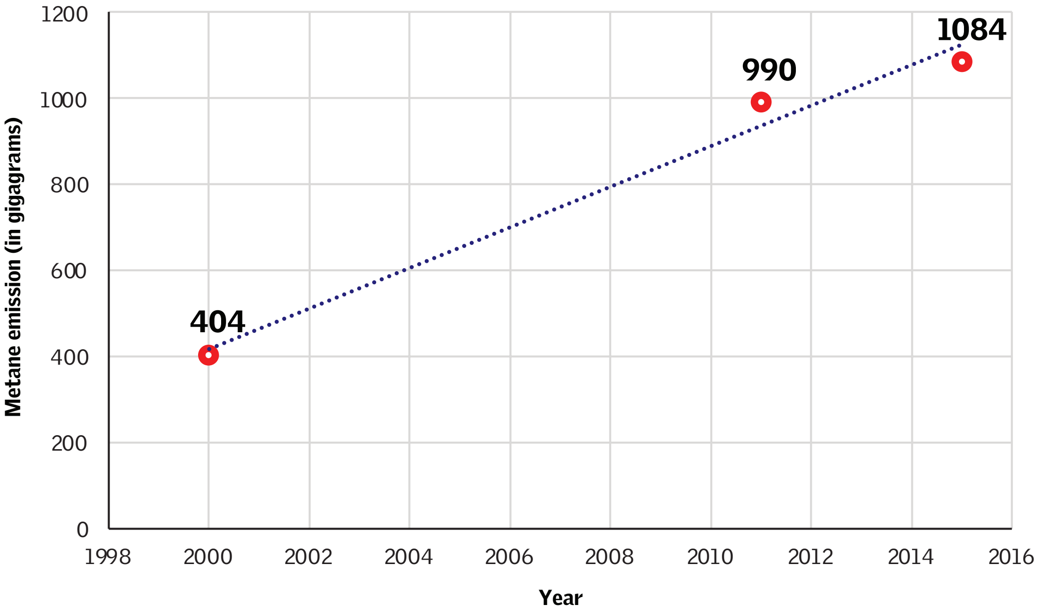
In India, most of the solid wastes are disposed of by haphazardly dumping in low-lying areas located in and around the urban centres. However, there is a serious lack of city-wise studies done on methane emissions from landfills in India. Most of the studies are confined to the domain of characterization, quantification and management practices of solid waste, not on emission of landfill gases and their utilization. Lately, there have been a few studies on methane emissions from Indian dumpsites situated in metropolitan cities like Delhi. Out of these, some employ field experiments while many others employ various theoretical estimation methods.

The total methane emissions from Indian landfills, calculated by CSIR-National Environmental Engineering Research Institute (NEERI), worked out to be 0.334 Gt per year.[70] The same has been reported in other studies as well.[71] As reported by a book, *Spatial Modelling and Assessment of Environmental Contaminants*, in 2021, India emitted 16 Mg CO_2e of methane, which is anticipated to increase to 20 Mg CO_2e by 2030.[72]

A study, "Quantitative analysis of methane gas emissions from municipal solid waste in India," published in the international journal *Scientific reports* in 2018 reported that methane emissions in India increased by approximately 2.5 times in a span of 10 years (1999–2009), reaching a total emission value of 1,084.03 Gg/year (1 Gg = 1,000,000 kg) by 2015. An increase of 245 per cent was observed between 1999 and 2011, while a total increase of 109 per cent was found between 2011 to 2015.[73]

Another study reported that the national-level methane emissions from solid waste disposal sites using the default methodology varied from 263.02 Gg in 1980 to 502.46 Gg in 1999; while calculated using the triangular pattern of gas generation, methane emissions varied between 119.01 Gg in 1980 to 400.66 Gg in 1999.[74]

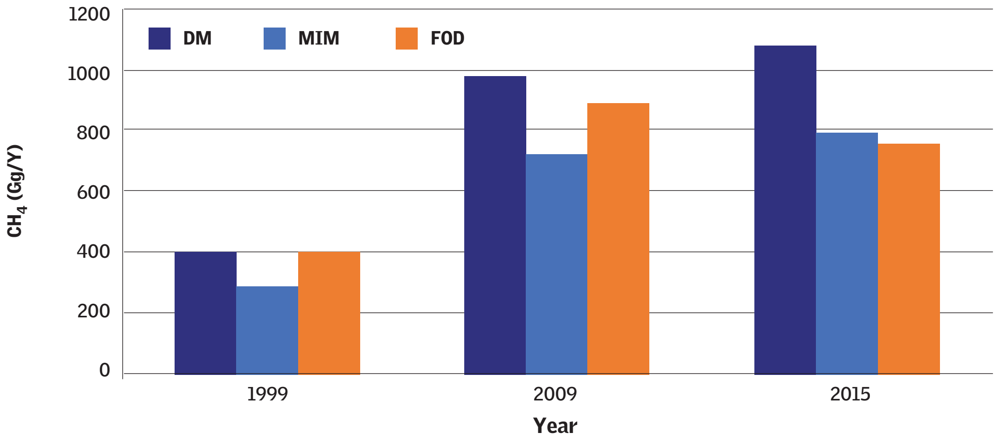
Graph 13: Quantity of methane emissions in India



Source: C.K. Singh, A. Kumar and S.S. Roy 2018. "Quantitative analysis of the methane gas emissions from municipal solid waste in India," Scientific reports 8(1).

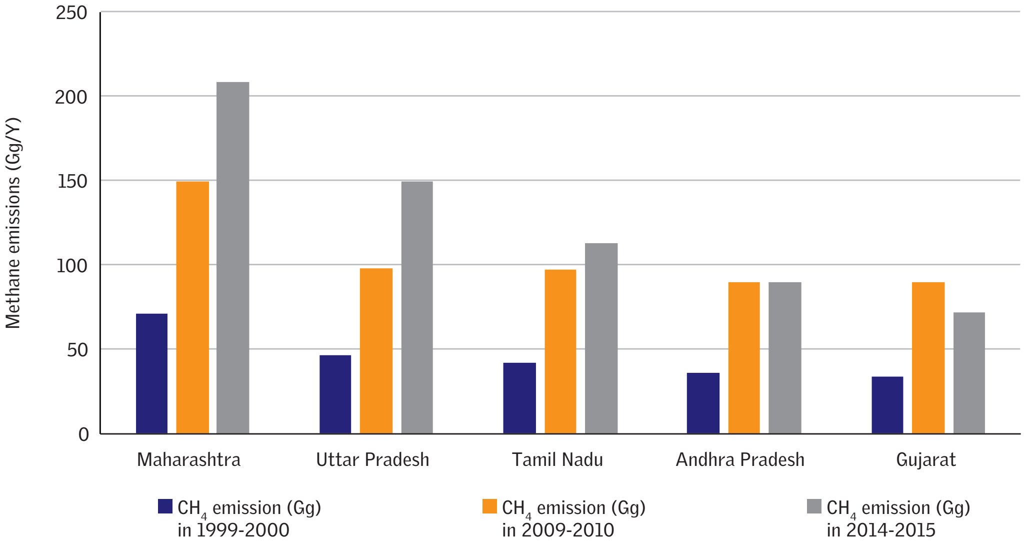
A study by the Indian Institute of Technology, Roorkee estimated the possible threat of global warming through GHG emissions by dumping of MSW in 23 Indian metro cities using LandGEM software version 3.02 for a period of 20 years (2001–2020). The total amount of methane and carbon dioxide emitted were computed as 8,001 Gg and 21,954 Gg respectively, while total global warming potential (GWP) of these GHGs was found to be 189,984 Gg of CO_2e, with 88.44 per cent contribution from CH_4 and the balance due to CO_2.[75]

Graph 14: Estimated methane emissions from MSW in India from 1999–2015 using DM, MTM and FOD methods



Source: C.K. Singh, A. Kumar and S.S. Roy 2018. "Quantitative analysis of the methane gas emissions from municipal solid waste in India," Scientific reports 8(1).

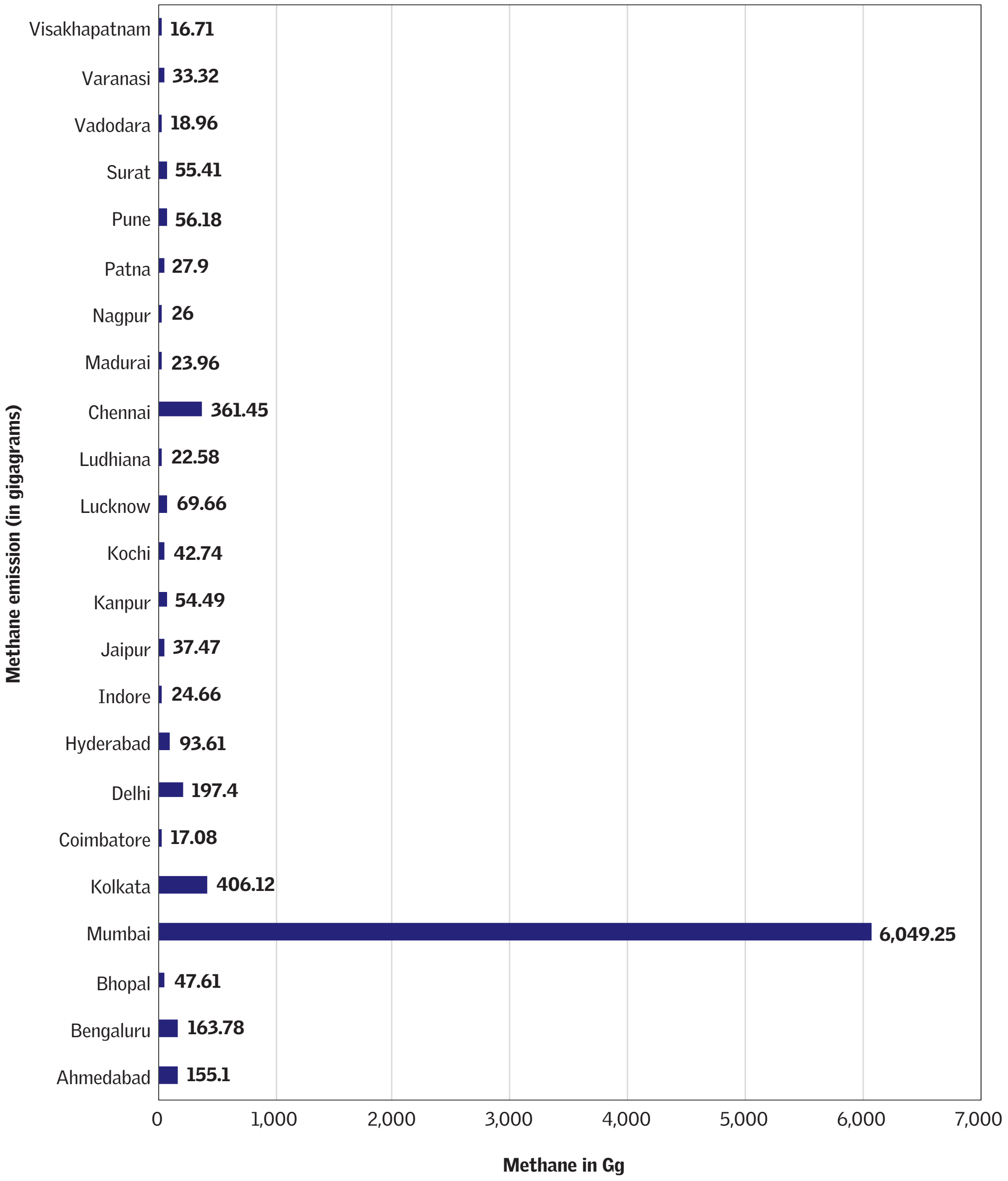
Graph 15: State-wise methane emissions



Source: C.K. Singh, A. Kumar and S.S. Roy 2018. "Quantitative analysis of the methane gas emissions from municipal solid waste in India," Scientific reports 8(1).

Results showed that, among metro cities, Mumbai has the highest emission of methane i.e., 6,049 Gg while Visakhapatnam has the least i.e., 16.71 Gg. The strikingly high emission of GHGs from Mumbai is attributed to the high methane generation rate i.e., 0.08 Gg/year, which also depends on average annual rainfall i.e., 2,334.60 mm/year. Further, the other supporting factor is the amount of waste being dumped, which ultimately depends on per capita collection rate of waste i.e., 3.38 kg/capita/day, which is significantly higher than other metro cities.[76]

Graph 16: Methane emissions from 23 Indian metro cities through dumping of MSW



Source: A. Kumar and M.P. Sharma 2014. "GHG emission and carbon sequestration potential from MSW of Indian metro cities," Urban climate 8

Methane emissions from Delhi's dumpsites have been extensively studied by various researchers across the country.

A study conducted by the Indian Institute of Technology, Delhi estimated the total annual methane generation potential of Delhi dumpsites. As reported by the study, Delhi, with 14 million inhabitants in 2006, generated 7,000 tonnes of waste daily, and based on the estimates of 32.3 kg methane generation/tonne of waste, an estimate of 1.68 Tg/year was obtained. Allowing for up to 20 per cent of scavenging, this value could be as low as 1.34 Tg/year.[77] According to their estimation, methane emission in Delhi currently would be nearly 162 tonnes/year. Total methane generation in India could be as much as 9.69 lakh tonnes of methane (estimates based on the assumption that 32.3 kg methane is generated from 1 tonne of waste).

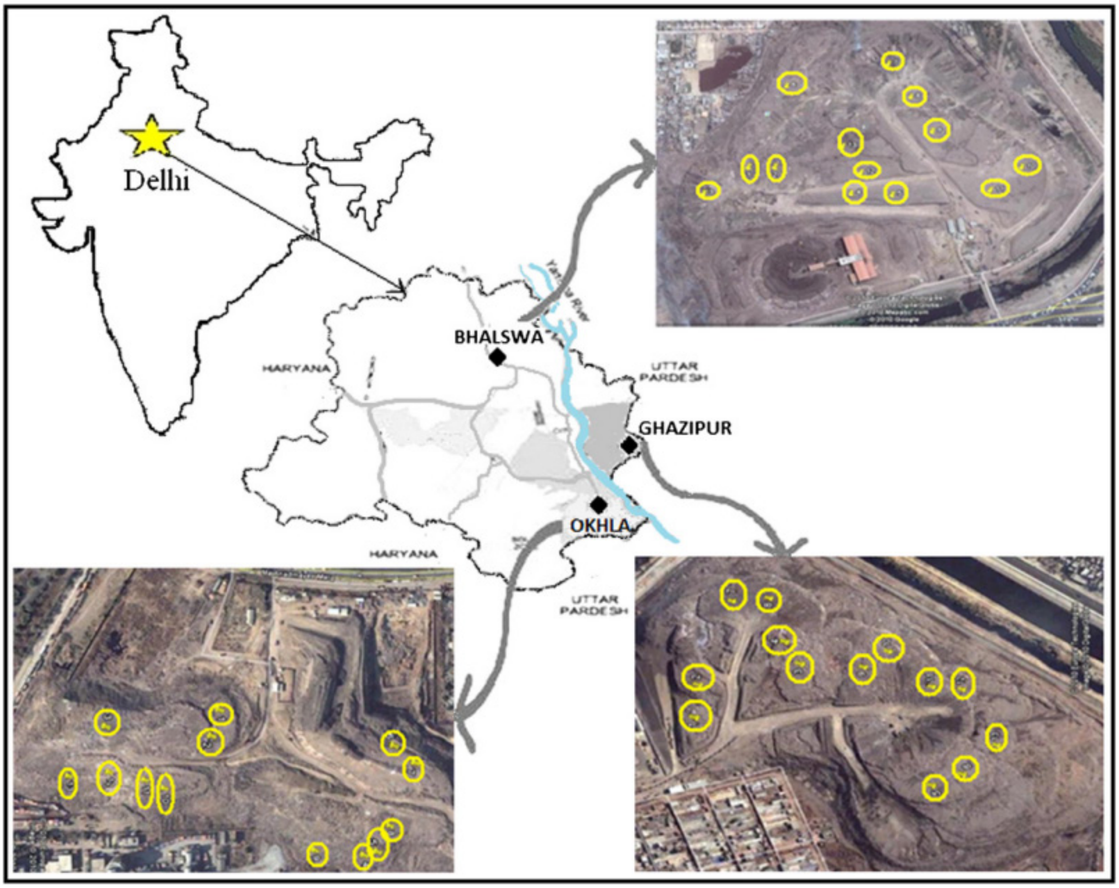
In a study conducted in 2019, IPCC's Default Method (DM), First Order Decay (FOD) method and LandGEM were used to estimate methane emissions from un-engineered landfill sites of Delhi—Okhla, Bhalswa and Ghazipur—between 1984 and 2015. During that period, total methane emissions were found to be 1,288.99, 311.18 and 779.32 Gg from the three landfill sites of Delhi as predicted by DM, FOD and LandGEM respectively.[78]

In another study conducted in 2020, the total estimated methane emissions till 2030 from all the three landfills in Delhi were reported to be 2,443.66, 1,114.61 and 1,642.51 Gg using DM, FOD and LandGEM respectively.[79] The average rates of emissions from Ghazipur, Bhalswa, and Okhla sites respectively were found to be 20.35, 24.10 and 17.51 Gg/year by DM; 18.69, 13.67, and 7.59 Gg/year by the FOD method; and 9.91, 9.81 and 8.40 Gg/year by LandGEM. The results showed that DM overestimated methane emissions due to variable input parameters such as fraction of landfilled waste and methane proportion in landfill gases. The FOD method provided the most accurate possible emission rates with comparatively lesser uncertainty and could relate to actual waste deposition practices. LandGEM also provided moderately accurate results with significant uncertainties caused by variation in MSW deposition data, gas generation rate and methane generating potential of waste.[80]

Another study presents methane emission estimations carried out for the three landfills currently operational in Delhi using the Modified Triangular Method (MTM), the FOD method and in-situ measurements with the IPCC Default Methodology (DM).[81] The in-situ methodology has yielded landfill-specific methane emission factors (EFs). The annual average methane emission rates from three landfills—namely Ghazipur, Bhalswa and Okhla respectively—are 14.6, 23.6

and 7.5 Gg/year by DM; 13.3, 10.6 and 7.2 Gg/year by the FOD method; 17.0, 13.7 and 10.7 Gg/year by MTM; and 4.6, 4.2 and 1.4 Gg/year by the in-situ measurement method. The methane emission factors have been found to be 9.7 ± 2.6, 5.5 ± 1.6 and 5.5 ± 1.7 g/kg of waste respectively for the Ghazipur, Bhalswa and Okhla landfills. The study reveals that in-situ methodology seems to provide more accurate emission estimation compared to other methods. The FOD method also yields comparable results with that of in-situ methodology in cases where good waste composition data is available.

Map 1. Sampling locations in Ghazipur, Bhalswa and Okhla landfills of Delhi



Source: M. Chakraborty, C. Sharma, J. Pandey, N. Singh, and P.K. Gupta 2011. "Methane emission estimation from landfills in Delhi: A comparative assessment of different methodologies," *Atmospheric Environment* 45(39)

Uncertainties with present models

1. The developed global landfill gas models lack some critical parameters like organic content of waste, moisture content, precipitation rate and temperature.[82]
2. The LandGEM model doesn't account for the factors associated with fire, leachate, average waste depth and waste composition.[83]

Table 7: Summary of methane emission studies done on Delhi dumpsites (in Gigagrams)

Landfills	Ghazipur		Bhalswa		Okhla	
References	Mor et al. (2006)[86]	Srivastava AN, & Chakma (2020)[87]	Sahu and Kumar, 2000	Srivastava AN, & Chakma (2020)	Kumar et al (2004b)[88]	Srivastava AN, & Chakma (2020)
In situ	4.6 ± 1.2		4.2 ± 1.3		1.4 ± 0.4	
IPCC 1996 Default Methodology	14.6	20.35	23.6	24.1	7.5	17.51
MTM	17		3.7		10.7	
FOD	13.3	19	10.6	13.67	7.2	7.59
Land GEM		9.91		9.81		8.4

Source: Compiled from different sources

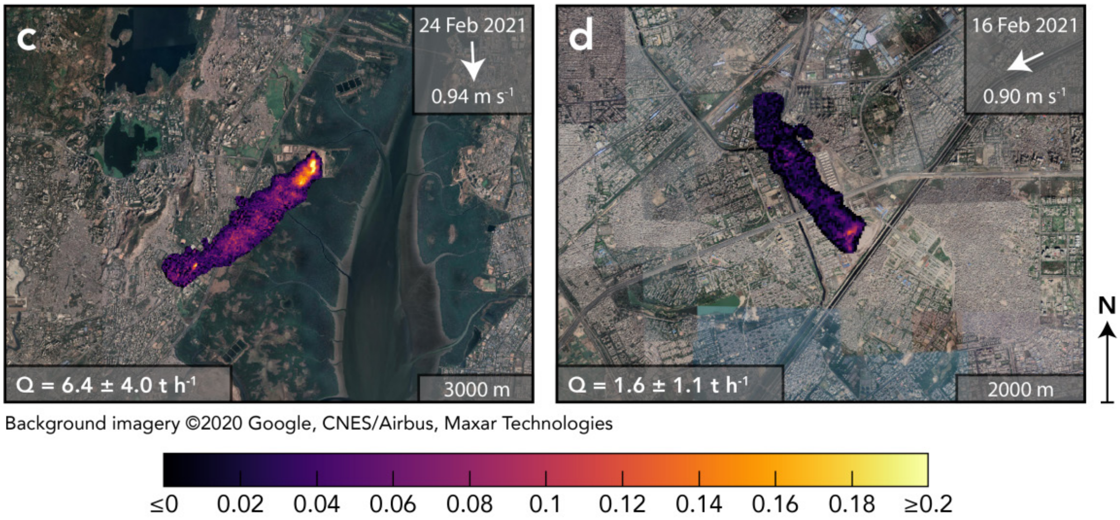
Uncertainties and variation in Indian scenario

1. Lack of historical data on waste: The historic data of solid waste generated and fraction disposed of, along with compositional studies and landfill data record keeping are lacking in Indian archives. This shortcoming leads to assumptions about data or extrapolation/interpolation from present data. As a result, there is a significant variation in the methane gas estimates derived from different models even for the same dumpsite.
2. Default values are not updated: Since the default values for developed models are mostly based upon the estimations of developed countries, they cannot be used for developing countries. IPCC default values must be updated.
3. Variations in waste composition due to the activity of the informal sector and accidental fires in dumpsites are not accounted for in estimations: India has mostly open dumpsites that are exposed to aerobic conditions with improper leachate management, weak regulations for scavenging activities, along with frequent fire accidents. These factors lead to lower emissions than developed countries.[84] However, there is no parameter to account for these activities in the proposed models.

Estimation of methane emissions using satellites

A combined study by SRON Netherlands Institute for Space Research, Harvard University, and GHGSat Inc. used the global surveying Tropospheric Monitoring Instrument (TROPOMI) to identify large emission hot spots, and then zoomed in with high-resolution target-mode observations from the GHGSat instrument to identify the responsible facilities and characterize their emissions. Using this ‘tip and cue’ approach, Delhi and Mumbai were detected. The study found that city-level emissions are 1.6–2.8 times larger than reported in commonly used emission inventories and that the landfills contribute 5–47 per cent of those emissions.[85]

Map 2: Methane plumes observed by GHGSat-C1/C2 from Kanjurmarg (Mumbai) and Ghazipur (Delhi) landfills, in 2020 and 2021



Background imagery ©2020 Google, CNES/Airbus, Maxar Technologies

Source: https://eartharxiv.org/repository/view/2985/

6. Carbon credits from dumpsite remediation

KEY HIGHLIGHTS

- **Carbon credits are measured in units of certified emission reductions (CERs), which are equivalent to one tonne of carbon dioxide or carbon dioxide equivalent reduction.**
- **There are several MSW projects in India that have been registered under the Clean Development Mechanism. For example, the Indore Municipal Corporation's waste-to-energy project (wet waste to bio-CNG).**
- **There is a lack of awareness about how biomining can potentially generate carbon credits in India.**
- **The III.AF./Version 01 methodology could be used as a reliable and credible methodology for estimating carbon credits from biomining projects.**

Carbon credits are certificates issued to countries which reduce their GHG emissions. Carbon credits are measured in units of certified emission reductions (CERs). Each CER is equivalent to one tonne of carbon dioxide or carbon dioxide equivalent reduction.

Carbon credits can be earned for reducing, avoiding or sinking six greenhouse gasses—carbon dioxide, methane, nitrous oxide, perfluoro carbons, hydrofluoro carbon and sulphur hexafluoride. International treaties like the Clean Development Mechanism (CDM) and Verified Carbon Standard (VCS) provide a robust platform to develop GHG emission reduction projects to earn carbon credits.

CDM is an arrangement under the Kyoto Protocol allowing industrialized countries with a greenhouse gas reduction commitment to invest in emission reducing projects in developing countries as an alternative to what are generally considered more costly emission reductions in their own countries. The developed country would be given carbon credits for meeting its emission reduction targets, while the developing country would receive the capital and clean technology to implement the project.

Between 2010 and June 2022, India issued 35.94 million carbon credits or nearly 17 per cent of all voluntary carbon market credits issued globally. The market for carbon credits increased by 164 per cent globally in 2021. It is anticipated to reach US $100 billion by 2030.[89] The Indian government plans to develop the Indian

Carbon Market (ICM) where a national framework will be established with an objective to decarbonize the Indian economy through trading of carbon credit certificates.[90]

In the waste sector, there are a number of MSW projects that have been registered under the CDM. For example, the Indore Municipal Corporation's waste-to-energy project (wet waste to bio-CNG) has been registered under the CDM and has earned carbon credits. In addition to the CDM, there are also a number of voluntary carbon credit programmes that can be used to earn carbon credits from MSW projects. These programmes are not regulated by the government, but they are still a valuable way to reduce greenhouse gas emissions and earn revenue.

From a general perspective, biomining projects are critical in reducing methane emissions in the waste sector and have a huge potential of carbon reduction. There are over 3,000 landfills in India that are currently in operation or closed. The cost of biomining varies depending on the size of the landfill and the specific techniques that are used. However, in general, biomining is a cost-effective way to reduce methane emissions and to generate carbon credits. But there is hardly any biomining project in India that is earning carbon credits.

The following are some of the benefits of biomining for carbon credit generation in India:

- Biomining can help reduce methane emissions from landfills.
- Biomining can help reclaim old landfills and clear land that can be used for other purposes.
- Biomining can generate carbon credits, which can be sold to companies or individuals who want to offset their own emissions.

  To earn carbon credits from biomining, a project must first be registered with a carbon credit programme. Once the project is registered, it must then demonstrate that it has reduced GHG emissions. This can be done by measuring the amount of methane that is prevented from being emitted from the landfill. If the project is successful in demonstrating that it has reduced GHG emissions, it will be awarded carbon credits. These carbon credits can then be sold to companies or organizations that are looking to offset their own GHG emissions.

The following are some of the challenges of biomining for carbon credit generation in India:

- There is a lack of awareness about biomining and its potential to generate carbon credits.

- There is a lack of financial support for biomining projects.
- There is a lack of technical expertise in biomining.

Despite these challenges, the potential for biomining to generate carbon credits in India is significant. With increased awareness, financial support, and technical expertise, biomining could become a major source of carbon credits in India. The Kullu Manali dumpsite remediation project the only remediation project claiming carbon credits. It is a promising example of how biomining of dumpsites can be used to earn carbon credits and benefit the environment and the community. The methodology adopted for estimating carbon credits from biomining of Kullu Manali dumpsites is the III.AF./Version 01 methodology, which is a standardized methodology developed by the International Carbon Reduction and Offset Alliance (ICROA).

For earning carbon credits from a biomining project, it is important to use a reliable and credible methodology for estimating carbon credits. The III.AF./Version 01 methodology is a good option for biomining projects in the waste management sector.

This methodology comprises of measures to avoid methane emissions from MSW that is already deposited in a closed solid waste disposal site (SWDS) without methane recovery. It consists of following sequential measure/steps:

(a) Aerobic pre-treatment by aerating the existing SWDS to achieve a safe operational environment for the subsequent excavation;
(b) Excavating MSW from the SWDS and separation into inert and non-inert materials; the excavation phase must commence immediately after the preparation phase, i.e., without significant time lag;
(c) Composting the non-inert material and proper soil application of the compost.

Project eligibility: The project activity involves avoidance of methane emissions in the atmosphere through uncontrolled decay of waste. Hence the project activity falls under Sectoral scope 13 i.e. Waste Handling & Disposal and is eligible under the scope of the VCS Program as VCS Standard Version-4.1.

The biomining of legacy waste in Kullu Manali project is promoted by Himadri Energy International Pvt. Ltd.

Table 8: Estimated quantities of waste in Kullu Manali dumpsites

ULB	Location	Area of dumpsite	Estimated quantity of waste (Metric tonnes)
Kullu (Himachal Pradesh, India)	Pirdi on NH-5	8,000m^2	18,000
Manali, (Himachal Pradesh, India)	Rangrion NH-5	4,200 m^2	40,000

Source: Verified Carbon Emissions, Methane avoidance through biomining of legacy waste in India; Document Prepared by-Himadri Energy International Pvt. Ltd.

The above MSW is already deposited in a closed SWDS without methane recovery. In the project activity, methane emissions will be avoided by applying the following sequential measure/steps:

(a) Aerobic pre-treatment by aerating the existing SWDS to achieve a safe operational environment for the subsequent excavation;

(b) Excavating MSW from the SWDS and separation into inert and non-inert materials; the excavation phase has to commence immediately after the preparation phase, i.e., without significant time lag.

The estimated annual average and the total CO_2e emission reduction over the fixed crediting period of 10 years are estimated to be 7,569 tCO_2e and 75,690 tCO_2e respectively. The estimations are done by Himadri Energy International Pvt. Ltd.

The process for earning carbon credits from dumpsite remediation projects would involve the following steps:

- **Register the project with a carbon credit programme:** There are several carbon credit programmes that can be used, such as the Clean Development Mechanism (CDM) and the Voluntary Carbon Standard (VCS).
- **Assess the baseline emissions:** This involves measuring the amount of methane that is being emitted from the dumpsite before the beginning of the project.
- **Implement the remediation project:** This could involve treatment and bioremediation of dumpsite with bio-culture, or using other methods to reduce methane emissions.
- **Measure the emission reductions:** This involves measuring the amount of methane that is no longer being emitted from the dumpsite after the remediation project is implemented.
- **Calculate the number of carbon credits:** The number of carbon credits that can be earned is calculated based on the amount of emission reductions achieved.
- **Sell the carbon credits:** The carbon credits can be sold to businesses or organizations that are looking to offset their carbon emissions.

7. Mitigation measures for methane reduction from the waste sector

KEY HIGHLIGHTS

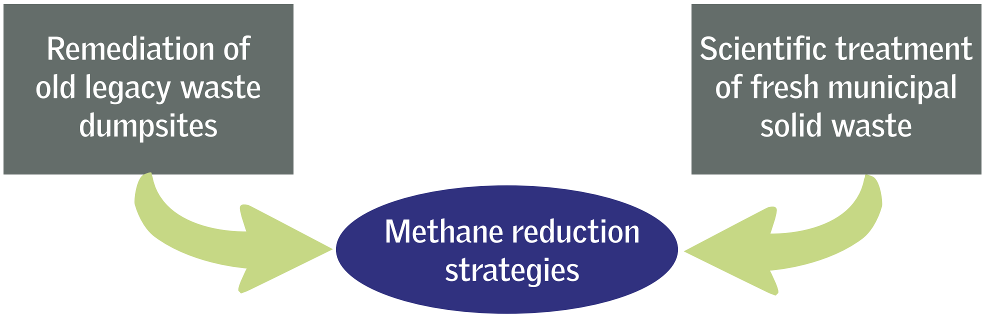
- **GHG reduction can be achieved by ensuring source segregation and scientific treatment of fresh waste.**
- **Biodegradable waste should not be dumped in landfills because the biodegradation process contributes significantly to methane and other GHG emissions**
- **Remediation of dumpsites plays a critical role in reducing emissions and combating climate change by removing a potential source of methane—legacy waste lying in the dumpsites.**

The Paris Agreement, signed in 2015 by 195 countries as a measure to stop and reverse the consequences of global warming and promote sustainable development, sets out strategies for reducing greenhouse gases. This also includes Agenda 2030, which contains 17 Sustainable Development Goals (typically referred to as UN-SDGs). The participating countries, including India, are expected to develop policies incorporating the targets and commitments of the agreement.

It is important to note that solid waste management is one of the critical agendas that needs to be addressed by the countries. They need to decrease the generation of waste by adopting the circular economy principles of prevention, reduction, recycling and reuse. Additionally, landfill mining or dumpsite remediation is recommended as a strategic tool across the globe that, if established properly within waste management public policies, can contribute to sustainable development and mitigation of climate change.[91] This is considered crucial as a mitigation action for the waste sector.

According to the report on circular economy in municipal solid and liquid waste published by the Ministry of Housing and Urban Affairs (MoHUA) in 2021, a total of 216 waste-to-energy (WTE) plants with aggregate capacity of 370.45 MWeq were set up in the country by September 2020 to generate power or biogas or bio-CNG from agricultural, urban, industrial and municipal solid wastes. The Ministry of New and Renewable Energy (MNRE) has also undertaken various other programmes on energy from urban, industrial and agricultural wastes/residues.[92]

At the same time, Swachh Bharat Mission 2.0 has been instrumental in promoting scientific treatment of all the fractions of municipal solid waste and remediation of existing dumpsites. Currently, GHG reduction can be achieved by ensuring scientific treatment of fresh waste and remediation of existing legacy waste dumpsites.



Circular economy principles for management of fresh waste

An analysis by MoHUA in 2021 identifies significant potential for resource recovery from various waste fractions—including wet biodegradable, dry recyclables and C&D waste—through the principles of circular economy. For example, dry waste recycling has a potential to generate approximately Rs 11,836 crores per annum; compost and bio-CNG from wet waste can generate revenues of nearly Rs 365 crores and Rs 1,679 crores per annum respectively. Similarly, C&D waste has the potential to generate revenues of approximately Rs 416 crores per annum.[93] However, this can only be realized by investing in promotion of source segregation—backed up by information, education and communication (IEC) activities and behaviour change communication (BCC)—and developing the required infrastructure for waste treatment.

Source segregation

Unscientific dumpsites are currently perhaps the largest GHG emitters in the waste sector. Reducing their emissions and subsequent climate impact is relatively easy to achieve. Bioremediation is an excellent interim solution to quickly save on emissions from such sites, while the systems prior in the hierarchy of waste management are improved, i.e., source segregation and resource recovery.

It has been recognized that treating 'mixed waste' is extremely challenging in terms of efficiency and cost-effectiveness. As a result, a significant fraction of waste generated in the country becomes untreatable and ends up in the dumpsite. Source segregation is critical and non-negotiable to ensure that waste can be diverted to different recycling facilities.

Many cities in India—including Indore, Surat, Bhopal, Panaji and Alappuzha—are practicing 4-way to 6-way segregation. For this, a robust communications strategy to bring about behavioural change at the mass-level is essential. It has been observed that source segregation has not been given adequate attention by many Indian cities. As a result, a major fraction of wet biodegradable waste remains unattended and untreated and find its way to the dumpsites.

No biodegradable organic waste in dumpsites

Biodegradable waste should not be dumped in landfills because the biodegradation process contributes significantly to methane and other GHG emissions. The average concentration of methane in a dumpsite ranges between 3 to 15 per cent by volume, which is much higher than the ambient concentration of methane (0.00017 per cent by volume).

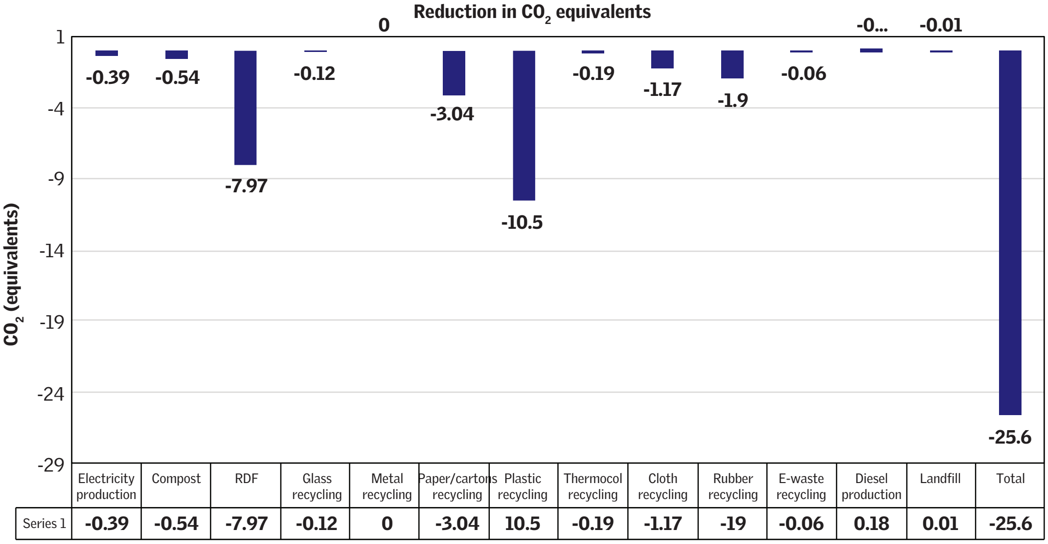
At this temperature, any ignitable source can lead to fire outbreaks in the dumpsites. Surface and sub-surface fire accidents are common in many of the bigger dumpsites across the country, like in Delhi, Chennai and Mumbai. Besides several environmental and health hazards, dumpsite fires cause sudden exponential increases in GHG emissions.[94] The GHGs emitted (CO, NOx, SO_2, CO_2, and CH_4) due to dumpsite fires need to be estimated.

Many countries like England, Canada, Australia and some European nations have discouraged MSW disposal in landfills by enforcing 'landfill tax' and have diverted waste to viable treatment processes.[95]

Scientific treatment of municipal solid waste fractions

It is imperative to understand that treatment of municipal solid waste fractions is critical for minimizing GHG emissions. A long-term viability analysis of a 100 tonne per day mechanical biological treatment (MBT) plant, for municipal solid waste valorization and material and energy recovery (biomethanation), was conducted by the Indian Institute of Technology, Roorkee in 2021. It involved material recovery and organic extraction (pulping), biomethanation, composting and effluent treatment, producing: 11.90 per cent recyclables, 33 per cent refused derived fuel (RDF), 5 per cent compost, 70 m^3/day recyclable water and 0.435 MWh/day electricity.

Graph 17: GHG emissions from treatment of 100 tonnes of MSW waste in the MBT plant in Goa



	Electricity production	Compost	RDF	Glass recycling	Metal recycling	Paper/cartons recycling	Plastic recycling	Thermocol recycling	Cloth recycling	Rubber recycling	E-waste recycling	Diesel production	Landfill	Total
Series 1	-0.39	-0.54	-7.97	-0.12	0	-3.04	10.5	-0.19	-1.17	-19	-0.06	0.18	0.01	-25.6

Source: V.K. Tyagi, A. Kapoor, P. Arora, J.R. Banu, S. Das, S. Pipesh, and A.A. Kazmi 2021. "Mechanical-biological treatment of municipal solid waste: Case study of 100 TPD Goa plant, India," *Journal of Environmental Management* 292.

Total GHG emission reduction by adopting scientific treatment of municipal solid waste in Goa was estimated to be 25.68 tonnes of CO_2e per 100 tonnes of MSW. The negative emissions result from the export of electricity, compost and RDF, which are expected to replace grid electricity, fertilizers and fuels, thereby reducing the dependence on non-renewable fossil-based resources. A significant proportion of the negative emissions are attributed to the recycling of paper and plastic products. The products recycled by the MBT plant are expected to replace new products in the market and avert the emissions associated with the production of these new products.[96]

It is important to note that less than 3 per cent of total waste received was disposed of in landfills. The only direct emissions from the plant are emissions from the combustion of biogas, landfills, and diesel utilization in equipment such as loaders, lifts and tractors.

Similarly, converting organic waste into biogas and bio-CNG also can be a game-changer. On one hand, bio-CNG can be utilized to fulfil the city's demand—including vehicle fuel requirements or requirements of bulk gas consumers like industries or institutions—and the liquid soil conditioner as well as solid compost can be supplied to farmers for use as organic manure. On the other hand, it can potentially reduce the GHG emissions that could otherwise be produced due to dumping of organic waste in landfills. A study by the University of Edinburgh reported that the total GHG impact of biogas plants is around 691 gCO_2e/m^3.[97]

Indore in Madhya Pradesh has installed a bio-CNG plant and produces 17,000 kg of CNG every day by treating 550 tonnes of biodegradable wet waste. Reportedly, they are earning more than Rs 50 crore from bio-CNG and carbon credits. Indore Municipal Corporation, as part of the initiatives for sustainable development of Indore city, had implemented municipal solid waste treatment projects to treat the domestic waste generated in a scientific manner. Indore Smart City Development Limited (ISCDL) is the first smart city in South Asia to successfully sell carbon credits and generate a significant amount of revenue. ISCDL had registered three projects under the Verified Carbon Standard (VCS) programme.[98] Total GHG emission reductions from 1 July 2019 to 31 December 2020 were found to be 1,69,506 tCO_2e.[99]

Table 9: MSW projects and revenue earned from selling the carbon credits earned

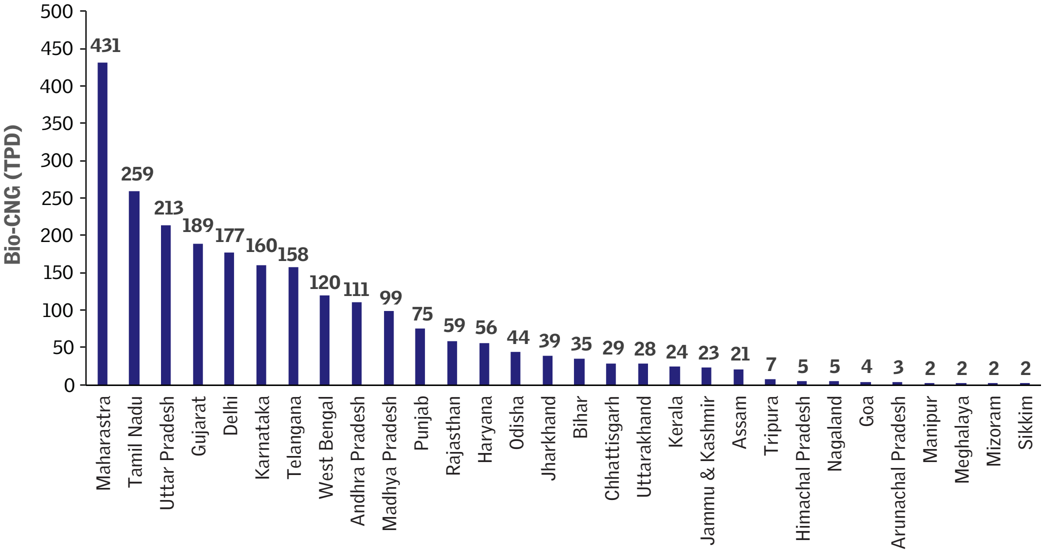
Year	MSW project name	Capacity	Revenue from selling carbon credits
2020	Solid waste to compost, Devguradia	600 TPD	Rs 69 lakh
	Biomethanation, Choithram Mandi	20 TPD	
	Biomethanation, Kabitkhedi	15 TPD	
2021	Solid waste to compost, Devguradia	600 TPD	Rs 8.34 crore
	Biomethanation, Choithram Mandi	20 TPD	
	Biomethanation, Kabitkhedi	15 TPD	
	Solar PV	1.5 MW	

Source: EnKing | Carbon Credits Trading Advisory Service (enkingint.org)

Delhi and other metropolitan cities can also adopt a similar model, as CNG is a cleaner fuel and has the potential to reduce pollution levels and GHG emissions to a great extent. This will also divert a significant fraction of waste (50 per cent) from reaching the dumpsites, thereby reducing methane emissions from landfills.

However, it is extremely important to understand that the success of any technological innovation or technology primarily depends upon the ‘quality of feedstock’. Whether it is waste-to-energy based on thermal decomposition or on bio-chemical conversions, the quality of feedstock (wet waste/dry waste) should be very good in terms of segregation level. For bio-CNG, the segregation level should be more than 90 per cent in order to get a considerable yield of gas.

Graph 18: State-wise bio-CNG potential from municipal solid waste



Source: Singh, P., & Kalamdhad, A. S. (2022). Biomethane plants based on municipal solid waste and wastewater and its impact on vehicle sector in India—An Environmental-economic-resource assessment. *Environmental Technology & Innovation, 26*, 102330

According to recent research by IIT Guwahati in 2022, biogas potential from municipal solid waste is around 6.09 million m^3/day, translating to 2,386.7 TPD compressed biogas (CBG). Maharashtra has a maximum CBG potential of 430.6 TPD (approximately 18.04 per cent), followed by Tamil Nadu which has a possibility of generating 258.8 TPD (approx. 10.8 per cent).[100]

The same study conducted an analysis of overall GHG emissions by vehicles driven with petrol, diesel and bio-CNG. It was reported that the overall emissions associated with CBG are lower than other fuels. It is interesting to note that the bio-CNG plant can generate significant emissions if not properly managed and operated. Segment-wise emissions analyses from the CBG supply chain found that the maximum emission is from the plant (56.90 gCO_2e per km). That is followed by emissions from the upgrading unit (43.24 gCO_2e per km), and indirect emission from electricity consumption (29.39 gCO_2e per km). Emission from the fuel station is observed to be negligible.[101]

Construction of scientific landfills for disposal of inerts and residual solid waste

It is important to note that waste treatment plants will generate some amount of rejects or waste in the process of converting waste into a usable resource. The waste generated from waste processing industries is typically referred to as 'residual solid waste'. Besides, inerts such as waste collected from street sweeping and drain silts are also the fractions which do not have any utility in the current scenario. For such waste fractions and the residual solid waste, it is important to construct scientific containment systems or sanitary landfills. It is required so that no new dumpsites are created in the future and only rejects are disposed of scientifically in the scientifically constructed landfills. The site selection criteria and design criteria are mentioned in the Solid Waste Management Rules, 2016.

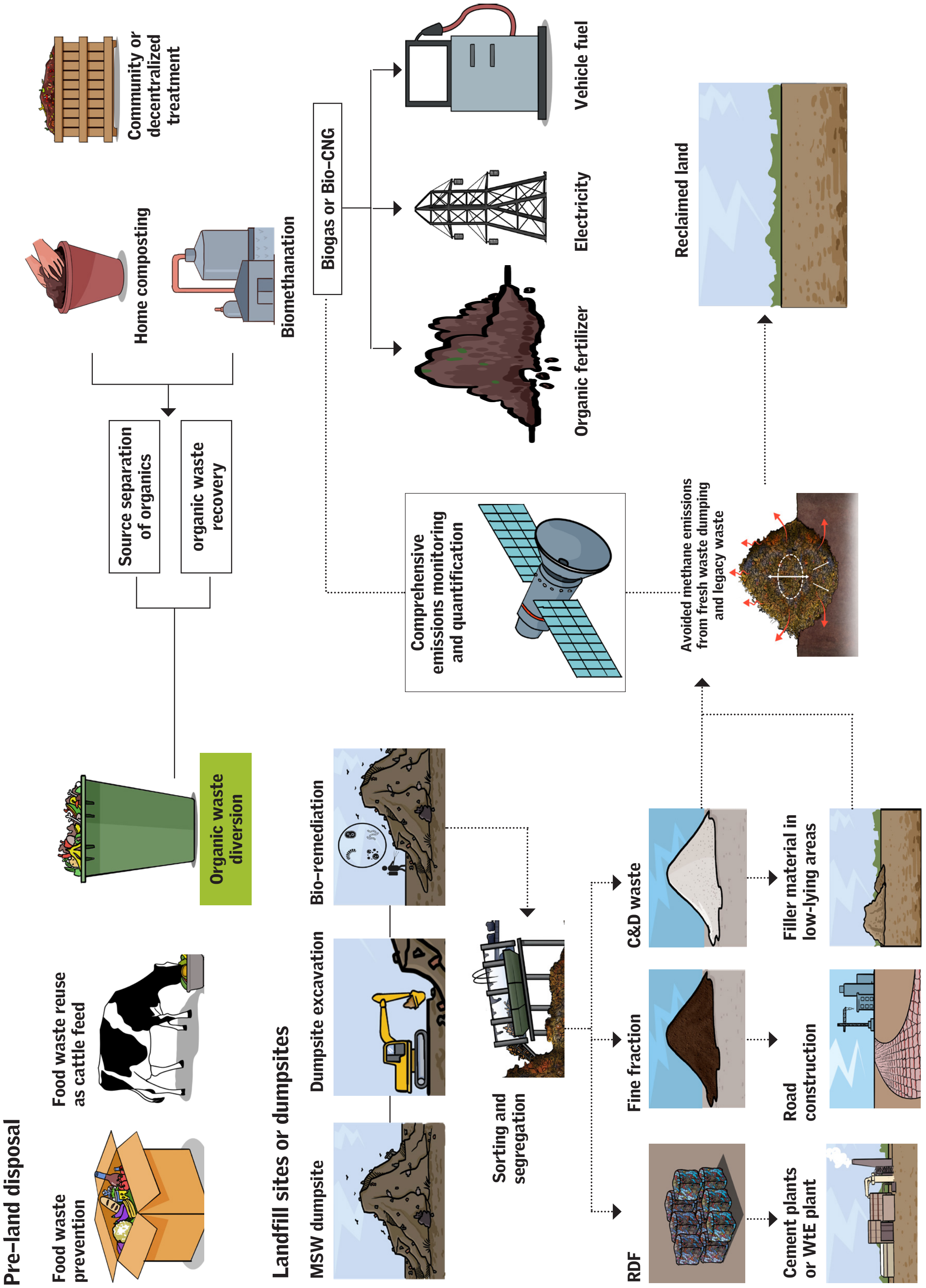
Modern, managed landfills are well-engineered facilities that are located, designed, operated and monitored to ensure compliance with regulatory norms. MSW landfills must be designed to protect the environment from contaminants which may be present in the solid waste stream. Additionally, sanitary landfills are required for the scientific and safe disposal of inert material and residual solid waste which cannot be utilized for any gainful applications. Requirements for MSW landfills primarily include:

- Siting requirements to protect sensitive areas (ex. airports, floodplains, wetlands, fault areas, seismic impact zones and unstable areas);
- Design requirements for new landfills to ensure that maximum contaminant levels (MCLs) will not be exceeded in the uppermost aquifer (ex. composite liners and leachate collection systems);
- Leachate collection and removal systems;
- Operating practices (ex. daily and intermediate cover, receipt of regulated solid wastes, use of landfill cover material, access options to prevent illegal dumping, use of a collection system to prevent stormwater run-on/run-off, record-keeping);
- Air monitoring requirements (explosive gases);
- Groundwater monitoring requirements;
- Closure and post-closure care requirements (ex. final cover construction); and
- Corrective action provisions.

Reduction of methane emissions through dumpsite remediation

Dumpsite remediation by bioremediation and biomining refers to the excavation and processing of formerly buried waste streams—aged waste (legacy waste)—by adopting environmentally sustainable methods and scientific disposal of the recovered legacy waste fractions. Worldwide, the mining of legacy waste dumpsites offers significant environmental and societal benefits including the mitigation of greenhouse gas emissions or the reduction of long-term waste management costs.[102,103,104]

Figure 6: Methane emission reduction strategies



Source: CSE, inspired by rmi.org

According to the USEPA, methane contained in landfills worldwide represents 12 per cent of total global methane emissions.[105] It is evident that landfills and dumpsites are a reservoir of methane which is a potent greenhouse gas. Therefore, remediation of dumpsites plays a critical role in reducing emissions and combating climate change by removing a potential source of methane—legacy waste lying in the dumpsites. It also contributes to the fulfilment of SDG 13 (action for climate) and the Paris Agreement. In addition, developing a green cover or forest area will act as a 'sink' for carbon dioxide.

However, no study has been done in India to estimate the GHG reduction potential by dumpsite remediation. In addition, there is an urgent need to estimate the amount sequestered by the green cover and forests developed at the land recovered from mining of legacy waste. This would help to provide the so-called 'net' contribution of dumpsite remediation in reducing global greenhouse gases.

Reduction of GHG emissions through RDF recovered from legacy waste dumpsites

The cement industry has sought to replace conventional fossil fuels with alternatives like plastics to minimize GHG emissions, thereby contributing to the decarbonization of cement industries in many developed countries.[106] However, India has underexploited this opportunity, especially considering the potential of refuse-derived fuel (RDF) to reduce the non-recycled waste disposed of in landfills, and its suitable performance as an alternative fuel for cleaner cement production.[107,108]

The combustible fraction (plastics, rubber, textiles, etc.) constitutes about 8 to 20 per cent of the legacy waste in an old dumpsite. That means India has to deal with nearly 13 to 32 million tonnes of combustible materials lying around in 3,159 dumpsites in the country. These combustible materials (typically referred to as Segregated Combustible Fraction or SCF) are excavated as end-products of the legacy waste dumpsite remediation process. As per the Basal Convention, variety of wastes including hazardous wastes and plastics, get disposed of in an environmentally safe and sound manner through the technology of co-processing in cement kilns.

Co-processing refers to the use of waste materials having high calorific value as alternative fuels or raw material (AFR) to recover energy and material from them. Due to the high temperature in cement kilns, different types of wastes can be effectively disposed of without harmful emissions. Disposal of different categories of plastic wastes through co-processing is practiced in many countries because it is environmentally sound. During the utilization of plastic wastes in cement kilns as

AFRs, the material and energy value present in them gets fully utilized in the cement kiln as replacement of fossil raw materials and fossil fuels that are conventionally utilized in the kiln.

However, the major challenge is that SCF is typically contaminated with inert material and high moisture content (more than 30 per cent) which makes it not so desirable for the cement factories. As a result, many urban local bodies are struggling to find economically viable options for disposal of recovered materials, including the combustibles.

8. Recommendations

- The data for quantity of municipal solid waste and methane emissions is highly unreliable and inconsistent, which makes it difficult to accurately estimate the landfill/dumpsite GHG emission potential. Methane could be better (more precisely and accurately) estimated by using the first-order decay (FOD) method based on field data and primary research on waste characteristics and composition.

- A pan-India study needs to be conducted on estimation of methane and other GHGs from each of the legacy waste dumpsites and organic waste processing facilities. There is lack of data on quantity of methane originating from the dumpsites and other waste management-related activities. Creating a system of comprehensive methane measurement and monitoring strategies will enable policymakers and regulators to develop data-driven, science-based targets to reduce methane emissions from the waste sector, especially from dumpsites.

- Phase out the disposal of biodegradable waste in landfills. Developing new or strengthening the already existing policies governing management of biodegradable waste can incentivize its diversion through source separation. In addition, developing infrastructure for treating biodegradable waste is critical. While preventing food loss and waste altogether is most preferable, organics diversion, such as in large-scale anaerobic digestion facilities, is the need of the hour to keep biodegradable waste out of landfills and reduce the burden on downstream mitigation technologies at the disposal site.

- In order to successfully expand organics processing pan-India, it is crucial to take into account both the demand from end-users and the capacity to utilize the products and commodities generated, such as biogas-based natural gas, compost and electricity. Without strong markets for these reduced-emission products or commodities, the financial feasibility of organics processing infrastructure can be jeopardized. The creation and maintenance of markets for products that reduce emissions are essential for effectively reducing methane through organics diversion.

- There are a limited number of cement industries accepting scrap combustible fraction (SCF) recovered from dumpsites and huge transportation cost is incurred. There must be a mechanism to create a win-win condition for urban local bodies and cement plants to promote the scientific disposal of the RDF fraction in cement co-processing industries. This will significantly contribute in reducing the emissions.

- Carbon credits for biomining projects should be promoted. Till today, only one dumpsite remediation project (in Kullu Manali) has claimed carbon credits.
- A mandate is needed to estimate the methane potential from already capped landfills/dumpsites. Currently, as per the SWM Rules 2016, urban local bodies need to maintain and operate the landfill gas collection system to meet the standards. However, it is extremely important to estimate the methane flux from existing landfill facilities which are already capped or still operational. No such monitoring exercise has been done so far. Similarly, it is extremely important to monitor fugitive gas emissions, particularly methane, from biodigesters and biogas storage balloons in biomethanation plants for organic waste processing. Incidences of methane leakages have been reported from several plants across the globe.
- Afforestation should be promoted in the reclaimed bioremediated land—recovered after biomining of legacy waste dumpsites. The green cover developed on the reclaimed land will act as a carbon sequester. According to BUR-3 submitted by the Government of India, forest and tree cover sequestered 331 million tonnes of CO_2 in 2016, which is around 15 per cent of the total CO_2 emissions in the country.

Annexures

ANNEXURE 1

Table 1: State-wise data from waste-management sector

Sr. no.	State	Solid waste generated (TPD)	Collected (TPD)	Treated (TPD)	Landfilled (TPD)	Unattended waste = Generated - (processed + landfilled)
1.	Andhra Pradesh	6,898	6,829	1133	205	5,560
2.	Arunachal Pradesh	236.51	202.11		27.5	209
3.	Assam	1,199	1,091	41.4	0	1,158
4.	Bihar	4,281 .27	4,013.55	Not provided	Not provided	Not provided
5.	Chhattisgarh	1,650	1,650	1,650	0	0
6.	Goa	226.87	218.87	197.47	22.05	7
7.	Gujarat	10,373.79	10,332	6,946	3,385.82	42
8.	Haryana	5,352.12	5,291.41	3,123.9	2,167.51	61
9.	Himachal Pradesh	346	332	221	111	14
10.	Jammu & Kashmir	1,463.23	1,437.28	547.5	376	540
11.	Jharkhand	2,226.39	1,851.65	758.26	1,086.33	382
12.	Karnataka	11,085	10,198	6,817	1,250	3,018
13.	Kerala	3,543	964.76	2,550	Not provided	-
14.	Madhya Pradesh	8,022.5	7,235.5	6,472	763.5	787
15.	Maharashtra	22,632.71	22,584.4	15,056.1	1,355.36 (Unscientifically disposed = 6,221.5)	6,222
16.	Manipur	282.3	190.3	108.6	81.7	92
17.	Meghalaya	107.01	93.02	9.64	83.4	14
18.	Mizoram	345.47	275.92	269.71	0	76
19.	Nagaland	330.49	285.49	122	7.5	201
20.	Odisha	2,132.95	2,097.14	1,038.31	1,034.33	60
21.	Punjab	4,338.37	4,278.86	1,894.04	2,384.82	60
22.	Rajasthan	6,897.16	6,720.476	1,210.46	5,082.16	605
23.	Sikkim	71.9	71 .9	20.35	51.55	0
24.	Tamil Nadu	13,422	12,844	9,430.35	2,301.04	1,691
25.	Telangana	9,965	9,965	7,530	991	1,444

Sr. no.	State	Solid waste generated (TPD)	Collected (TPD)	Treated (TPD)	Landfilled (TPD)	Unattended waste = Generated - (processed + landfilled)
26.	Tripura	333.9	317.69	214.06	12.9	107
27.	Uttarakhand	1,458.46	1,378.99	779.85	-	
28.	Uttar Pradesh	14,710	14,292	5,520	0	9,190
29.	West Bengal	13,709	13,356	667.6	202.23	12,839
30.	Andaman and Nicobar Islands	89	82	75	7	7
31.	Chandigarh	513	513	69	444	0
32.	DDDNH	267	267	237	14.5	16
33.	Delhi	10,990	10,990	5,193.57	5,533	263
34.	Lakshadweep	35	17.13	17.13	Nil	18
35.	Puducherry	504.5	482	36	446	23
	TOTAL	160,038.9	152,749.5	79,956.3	29,427.2	50,655

Source: CSE's analysis from CPCB Annual Report 2020-21[109]

Table 2: Year-wise percentage of waste collected, treated, landfilled and gap analysis

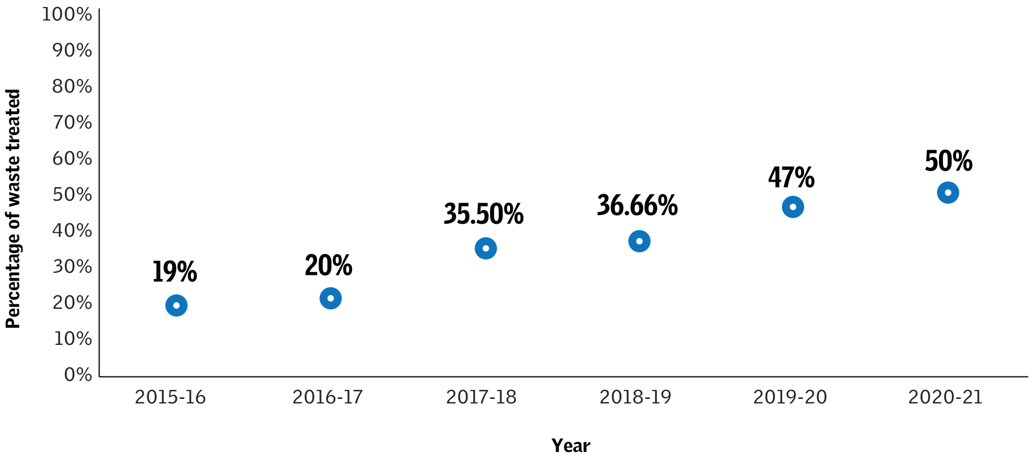
Year	Solid waste generated (TPD)	Collected (TPD)	Treated (TPD)	Landfilled (TPD)	% Treated	% Landfilled	Gap%
2015-16	101,066.27	86,531.55	20,288.95	37,953.62	20.1	37.6	42.37
2016-17	119,140.9	116,685.9	24,045.05	49,836.5	20.2	41.8	37.99
2017-18	43,298.39	45,082.15	15,386.81	22,904.7	35.5	52.9	11.56
2018-19	152,076.7	149,748.6	55,759.6	50,161.33	36.7	33.0	30.35
2019-20	150,847	146,053.8	70,973.2	40,728.69	47.0	27.0	25.95
2020-21	160,038.9	152,749.5	79,956.3	29,427.2	50.0	18.4	31.65

Source: Compiled from CPCB Annual Report 2020–21

Yearly variations of waste

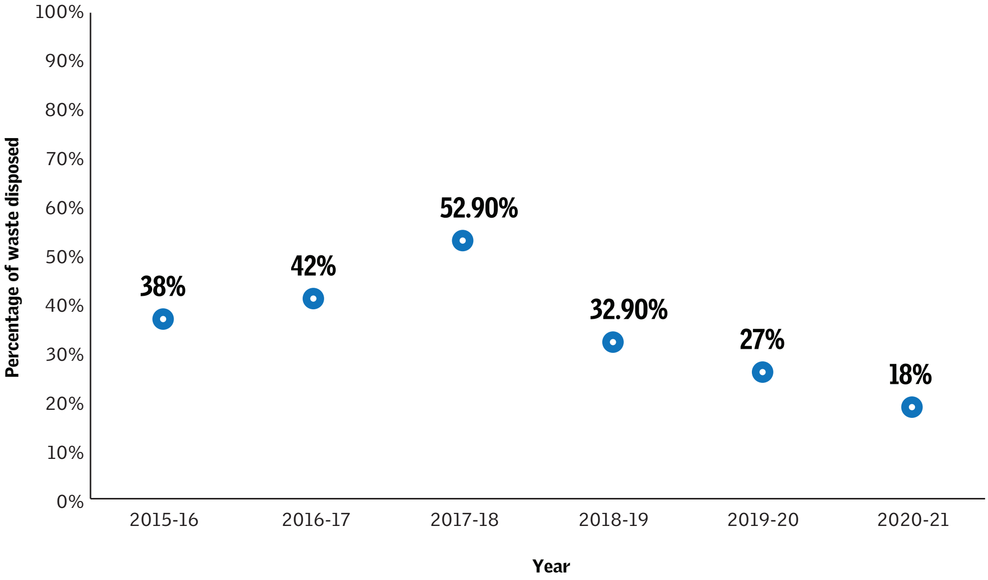
On comparing the annual reports on Municipal Solid Waste (MSW) across CPCB's data, irregular trends emerge in terms of waste treatment, waste disposal in landfills, and data gaps.

Graph 1: Year-wise trend in the percentage of waste processed in India



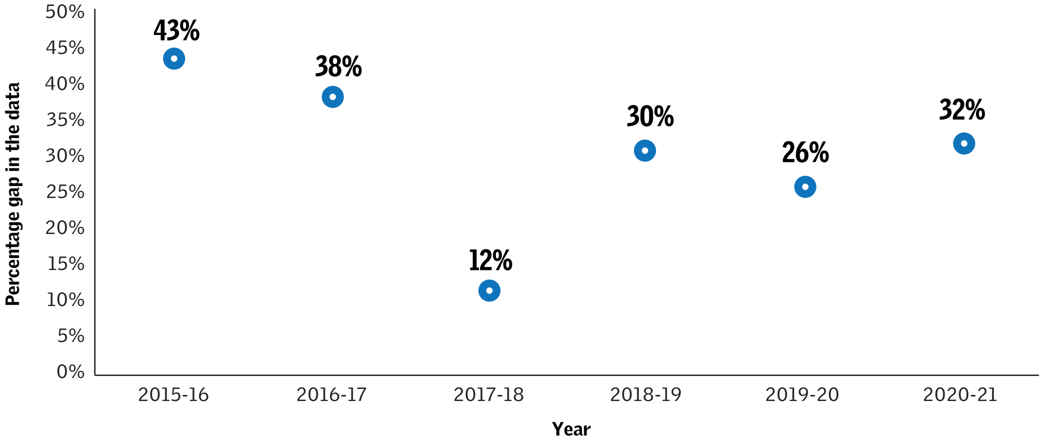
Source: Compiled from CPCB Annual Report 2020-21

Graph 2: Year-wise trend in the percentage of waste disposed in landfills



Source: Compiled from CPCB Annual Report 2020-21

Graph 3: Gap analysis



Source: Compiled from CPCB Annual Report 2020-21

ANNEXURE 2

Indicative simplified baseline and monitoring methodologies
for selected small-scale CDM project activity categories

TYPE III - OTHER PROJECT ACTIVITIES

Project participants shall take into account the general guidance to the methodologies, information on additionality, abbreviations and general guidance on leakage provided at: <http://cdm.unfccc.int/methodologies/SSCmethodologies/approved.html>.

III.AF. Avoidance of methane emissions through excavating and composting of partially decayed municipal solid waste (MSW)

Technology/measure

1. This methodology comprises measures to avoid emissions of methane to the atmosphere from MSW that is already deposited in a closed solid waste disposal site (SWDS) without methane recovery. In the project activity, methane emissions will be avoided by applying the following sequential measure/steps:

   (a) Aerobic pre-treatment by aerating the existing SWDS to achieve a safe operation environment for the subsequent excavation;

   (b) Excavating the MSW from the SWDS and separation into inert and non-inert materials; the excavation phase has to commence immediately after the pre-aeration phase, i.e., without significant time lag;

   (c) Composting the non-inert material and proper soil application of the compost.

2. For the purpose of this methodology, the following definitions apply:

   - Closed SWDS: Site that has stopped receiving waste for disposal, according to the record given by the competent authority, if applicable;
   - Aeration: Air injection (high pressure air enriched with oxygen at 20-40% (vol) or low pressure ambient air) into SWDS;
   - Gas extraction: Controlled extraction of the off-gases and treatment during the aeration phase, e.g., by means of bio-filters;
   - Excavation: Withdraw/extraction of the pre-treated MSW by diggers;
   - Separation: Segregation of the excavated material into inert and non-inert fractions by screens or sieves with mesh size of 25-60mm;
   - Non-inert: The undersize fraction which can pass through the screens/sieves used in the separation process, it is assumed this portion of MSW decomposes in the baseline (e.g., food, wood and paper);
   - Inert: The remaining oversize fraction which can not pass through the screens/sieves used in the separation process, it is assumed this portion of MSW does not decompose during crediting period (e.g., plastic, glass and metals).

3. The project activity does not recover or combust landfill gas from the disposal site (unlike AMS-III.G), does not undertake controlled combustion of the waste that is not treated biologically in a first step (unlike AMS-III.E), does not treat fresh MSW (unlike AMS-III.F), and is not aimed at emission reductions from recovery and reuse of recyclable inert material contained in the MSW.

4. Measures are limited to those that result in emission reductions of less than or equal to 60 kt CO_2 equivalent annually.

5. The location, characteristics of the SWDS and proportions of the different types of organic waste disposed in the SWDS and treated by the project activity, shall be known, in such a way as to allow the estimation of its methane emissions *ex ante*, according the latest version of "Tool to determine methane emissions avoided from disposal of waste at a solid waste disposal site".

6. Total amount of waste deposited in the SWDS per year, shall be obtained from recorded data of waste disposals, or estimated according to the level of activity that generated the waste (for example, considering the amount of MSW generated by the municipality and disposed in the SWDS in that year).

7. When compost is submitted to soil application, the place of compost application needs to be included into the project boundary and the proper conditions (i.e., handled aerobically) and procedures (not resulting in methane emissions) need to be ensured.

8. This methodology is applicable if the aerobic pre-treatment is realized either through high pressure air injection enriched with oxygen 20-40% (vol.) or low pressure aeration using ambient air. Both measures shall ensure aerobic conditions during the pre-treatment phase, allowing a safe MSW excavation during excavation phase. Sample based monitoring in the extraction gas pipes as well as in the monitoring wells shall be undertaken; oxygen content shall be at least 1% (v/v) and the permissible maximum methane concentration is 5 % (v/v).

9. If enriched oxygen is used for aeration in the project activity, emissions related to oxygen production shall be taken into account.

10. The use of the land after SWDS restoration shall be for non commercial purposes (e.g., municipal parks) and shall not be used for a landfill not equipped with methane recovery or flaring.

11. This methodology is not applicable in case the existing regulations require the capture and flaring of landfill gas of closed SWDS.

12. The measures are undertaken so as to comply with all local regulations, or, in the absence of such regulations, internationally accepted regulations for safety and environmental protection especially related to: fire risks, nuisance and odors control, quality of runoff water, final compost contamination and risks at workplaces shall be complied with.

13. This methodology is only applicable if the composting process is realized at enclosed chambers or roofed sites, outdoor composting is not applicable due to the possible generation of runoff water and consequently methane generation during waste treatment.

Boundary

14. The project boundary is the physical, geographical site:

   (a) Where the MSW is already deposited and the methane emission occurs in the absence of the proposed project activity;

(b) Where the treatment of MSW through composting takes place;

(c) Where the compost is handled and submitted to soil application;

(d) And the itineraries between them (a, b, and c), where the transportation of waste and compost occurs.

Baseline

15. The baseline scenario is the situation where, in the absence of the project activity, MSW is left to decay within the project boundary and methane is emitted to the atmosphere. The yearly baseline emissions are the amount of methane that would have been emitted from the decay of the quantity of the waste removed and composted from the disposal site by the project activity.

16. The baseline emission is calculated as the minimum of the two values below:

(a) *Ex ante* estimation as per the method described in paragraph 17 ($BE_{y,ex-ante}$);

(b) *Ex post* calculated as per the method described in paragraph 18 ($BE_{y,ex-post}$);

17. To determine *ex ante* baseline emissions from MSW that has partially decayed in a SWDS, the calculation of the yearly methane generation potential of the waste excavated and composted from the beginning of the excavation (x=1) up to the year *y* will consider the age of the waste at the start of the project. One of the following options may be used:

(a) Estimate the mean age of the waste contained in the disposal site in the beginning of the project activity ("ā"). It may be estimated as the weighted average age considering the yearly amount of waste deposited in the SWDS since its beginning of operation up to the year prior to the start of the project:

$$\bar{a} = \frac{1 \cdot A_1 + 2 \cdot A_2 + 3 \cdot A_3 + \ldots + a \cdot A_a}{A_1 + A_2 + A_3 + \ldots + A_a} = \frac{\sum_{a=1}^{a\max} A_a \cdot a}{\sum_{a=1}^{a\max} A_a} \qquad \textbf{(1)}$$

Where:

ā	Weighted mean age of the waste present in the SWDS prior to the project start
a	Years before project start, starting in the first year before project start (a=1) up to the maximal age of the waste contained in the SWDS after the waste disposal starts (a=amax.)
A_a	Total amount of waste deposited in the SWDS in each year "a". It shall be obtained from recorded data of waste disposals

If the yearly amount of waste deposited in the SWDS cannot be estimated, then an arithmetic mean age may be used (ā = 0.5 * amax). By using this option, the baseline emissions at any *year y* ($BE_{y,ex-ante}$) during the crediting period are calculated according to the latest version of "Tool to determine methane emissions avoided from disposal of waste at a solid waste disposal site", nevertheless, the exponential term for the first order decay model "exp [-k_j.(y-x)]" will be corrected for the mean age, and will be substituted by "exp[-k_j.(y-x+ā)]".

(b) Calculate the yearly methane generation potential of the SWDS as described in the latest version of "Tool to determine methane emissions avoided from disposal of waste at a solid waste disposal site", considering the total amount and composition of waste deposited since its start of operation. The methane generation potential of the waste removed to be composted up to the *year y* in the crediting period will be estimated as proportional to the mass fraction of these waste, relative to the initial amount:

$$BE_{y,ex-ante} = \frac{\sum_{x=1}^{y} A_x}{A} BE_{CH4,SWDS,y} \qquad \textbf{(2)}$$

Where:

A_x	Amount of waste removed to be composted in the year "x" (tonnes)
A	Total amount of waste present in the SWDS at the beginning of the project activity (tonnes)
$BE_{CH4,SWDS,y}$	Yearly methane generation potential of the SWDS at the *year y*, considering all the waste deposited in it since its beginning of operation, and without considering any removal of waste by the project activity.

(c) Estimate the quantity and the age distribution of the waste removed each year "x" during the crediting period, and calculate the methane generation potential of the waste in the *year y*. For example, in the year x=2 of the project activity, the amount "A2" was removed to be composted, and this amount can be divided into "A2,n" parts, each part belonging to the age "n". In the *year y* the methane generation potential of the portions removed from the SWDS may be estimated as:

$$BE_{y,ex-ante} = \sum_{n=nmin}^{nmax} BE_{CH4,SWDS,y,n} \qquad \textbf{(3)}$$

Where:

$BE_{CH4,SWDS,y,n}$	Yearly methane generation potential of the waste removed since the beginning of the project activity "x=1" up to the *year y* during the crediting period, segregated according to its age "n" at the time of removal (tCO2e). It is calculated using the tool referred to in AMS-III.G, substituting the exponential term for the first order decay model "exp [-k_j.(y-x)]" by "exp[-k_j.(y-x+n)]".

18. The *ex post* determination of the baseline emissions is based on laboratory analysis of a sample of non inert fraction of the excavated waste obtained after separation. The separated samples are tested for the methane generation potential (L_0, in tons CH_4/ tons waste), without any distinction for the waste types or categories, in accordance with methods described in literature[1, 2, 3]. The sampling shall ensure a confidence level/precision of 90/10 for the mean value of L_0, Standard such as EN TR 15310-3 /-4[4] or LAGA PN98[5] or an equivalent national/international standard shall be used for the purpose of sampling.

The annual average value of $L_{0,x}$ for any year "x" during the excavation phase is used to calculate the baseline emissions as follows:

$$BE_{y,ex-post} = \varphi * (1-f) * GWP_{CH4} * (1-OX) * MCF * \sum_{x=1}^{y} A_{lf,x} * L_{0,x} * e^{-k_{CH4}(y-x)} * (1-e^{-k_{CH4}}) \qquad \textbf{(4)}$$

Where all the terms are defined and determined according to the latest version of "Tool to determine methane emissions avoided from disposal of waste at a solid waste disposal site", except the following:

$BE_{y,ex-post}$	Baseline methane emissions that would be produced in the landfill in absence of the project activity in year y (t CO_2/y)
$A_{lf,x}$	Amount of non inert waste separated and aerobically composted in year "x", (tons)
$L_{0,x}$	Annual average methane generation potential of the non-inert fraction of the partially decayed waste separated during the year "x" (tons CH_4/tons waste)
k_{CH4}	Decay rate of the excavated waste, see table 1 below
x	Year during the crediting period: x runs from the first year of the first crediting period (x = 1) to the year y for which avoided emissions are calculated (x = y)
y	Year for which methane emissions are calculated

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[1] Ryan J. Kelly, Bradley D. Shearer, Jongmin Kim, C. Douglas Goldsmith, Gary R. Hater, John T. Novak (2006): Relationships between analytical methods utilized as tools in the evaluation of landfill waste stability, Waste Management, 26, p.1349–1356, download at <http://www.scsengineers.com/Papers/Kelly_WMAnalytical_Tools_LF_Waste_Stability.pdf>.

[2] J.M. Owens, J.M., D.P. Chynoweth, (1993): Biochemical methane potential of municipal solid waste (MSW) components. Water Science and Technology 27 (2), p. 1–14.

[3] Train L. Hansen, Jens Ejbye Schmidt, Irini Angelidaki, Emilia Marca, Jes la Cour Jansen, Hans Mosbaek, Tomas H. Christensen (2004): Method for determination of methane potential of solid organic waste, Waste Management, 24, p. 393-400.

[4] EN TR 15310 "Characterization of waste - Sampling of waste materials"; Part 3 "guidance on procedures for subsampling in the field, Part 4 "Guidance on procedures for sample packaging, storage, preservation, transport and delivery.

[5] LAGA – Länderarbeitsgemeinschaft Abfall, PN 98 "Richtline für das Vorgehen bei physikalischen, chemischen und biologischen Untersuchungen im Zusammenhang mit der Verwertung/Beseitigung von Abfällen" available in German at <http://www.laga-online.de/mitteilungen/docs/LAGA%20PN%2098.pdf>.

The value for the decay rate of the excavated waste (k_{CH4}) is taken from the following table referenced from AM0083. The local climate conditions and the average age of the waste within the landfill at the project starts (calculated according to paragraph 17(a)) are used for the selection of the appropriate decay rate.

Table 1 Decay rate of the excavated waste

Waste age	MAT ≤ 20°C; boreal		MAT > 20°C; tropical	
	Dry (MAP/PET <1)	Wet (MAP/PET >1)	Dry	Wet
≤ 2a	0.045	0.100	0.055	0.170
>2a ≤ 10a	0.035	0.060	0.045	0.100
> 10a	0.030	0.045	0.035	0.050

Leakage

19. If the project technology is the equipment transferred from another activity leakage effects are to be considered.

Project activity emissions

20. Project activity emissions consist of:

(a) CO_2 emissions from transportation;

(b) CO_2 emissions from electricity and/or fossil fuel consumption by the project activity facilities;

(c) Emissions from the oxygen consumption during aeration process, if applicable;

(d) Methane emissions during composting process.

$$PE_y = PE_{y,transp} + PE_{y,power} + PE_{y,O2} + PE_{y,compCH4} \tag{5}$$

Where:

PE_y	Project activity emissions in the year y (tCO_2e)
$PE_{y,transp}$	Emissions from transportation in the year y (tCO_2e)
$PE_{y,power}$	Emissions from electricity or fossil fuel consumption in the year y (tCO_2e)
$PE_{y,O2}$	Emissions from the oxygen consumption during high pressure aeration process (enriched oxygen), if applicable. In the absence of project specific data a default value of 0.64 tCO_2e/Nm^3 O_2 (normal volume) shall be used.
$PE_{y,compCH4}$	Methane emissions during composting process in the year y (tCO_2e)

21. Project emissions from transportation ($PE_{y,transp}$) are calculated based on distances:

(a) The SWDS and the treatment site where composting process takes place;

(b) The treatment site and the site for soil application.

$$PE_{y,transp} = (Q_y / CT_y) * DAF_w * EF_{CO2} + (Q_{y,treatment,i} / CT_{y,treatment,i}) * DAF_{treatment,i} * EF_{CO2} \qquad \textbf{(6)}$$

Where:

Q_y	Quantity of raw waste treated in the year *y* (tons)
CT_y	Average truck capacity for transportation (tons/truck)
DAF_w	Average incremental distance for raw solid waste transported (km/truck)
EF_{CO2}	CO_2 emission factor from fuel use due to transportation (kgCO_2/km, IPCC default values or local values may be used)
i	Type of compost
$Q_{y,treatment,i}$	Quantity of compost *i* produced in year *y* (tons)
$CT_{y,treatment,i}$	Average truck capacity for compost *i* transportation (tons/truck)
$DAF_{treatment,i}$	Average distance for compost *i* transportation (km/truck)

22. For the calculation of project emissions from electricity and/or fossil fuel consumption by the project activity facilities ($PE_{y,power}$) all the energy consumption of all equipment/devices installed by the project activity shall be included e.g., energy used for aerobic pre-treatment, SWDS excavation, MSW separation, turning of compost piles/heaps, screening, drying of the final compost product. Emission factors for grid electricity used shall be calculated as per procedures described in AMS-I.D. Project activity emissions from fossil fuel consumption shall be calculated as per the latest version of the "Tool to calculate project or leakage CO_2 emissions from fossil fuel combustion". Local values are to be used, if local values are difficult to obtain, IPCC default values may be used.

23. Methane emissions during composting ($PE_{y,compCH4}$) shall be calculated as follows:

$$PE_{y,compCH4} = Q_{y,treatment} * EF_{composting} * GWP_{CH4} \qquad \textbf{(7)}$$

Where:

$Q_{y,treatment}$	Quantity of waste treated by composting in year *y* (tonnes)
$EF_{composting}$	Emission factor for composting of organic waste (t CH_4/ton waste treated). Emission factors can be based on facility/site-specific measurements, country specific values or IPCC default values (table 4.1, chapter 4, Volume 5, 2006 IPCC Guidelines for National Greenhouse Gas Inventories). IPCC default values are 10

g CH_4/kg waste treated on a dry weight basis and 4 g CH_4/kg waste treated on a wet weight basis.

$EF_{composting}$ can be set to zero for the portions of $Q_{y,treatment}$ for which the monitored oxygen content of the composting process is above 8%. This can be done via sampling with a maximum margin of error of 10% at a 90% confidence level. For this purpose a portable oxygen meter can be used with lancets of at least 1 m length. In the case of forced aerated in-vessel and forced aerated pile composting systems continuous measurements may also be done using online sensors

Monitoring

24. The emission reduction achieved by the project activity will be measured as the difference between the baseline emission and the sum of the project emission and leakage.

$$ER_y = BE_y - (PE_y + Leakage_y) \quad \textbf{(8)}$$

Where:

ER_y Emission reduction in the year y (tCO_2e)

The following parameters shall be monitored and recorded annually during the crediting period:

- Quantity of raw waste removed (Q_y) and quantity of compost produced ($Q_{y,treatment,i}$);
- Quantity of oxygen consumed for high pressure aeration process, if applicable;
- Parameters related to ($PE_{y,transp}$) described above such as: (CT_y), (DAF_w), ($CT_{y,treatment,i}$), ($DAF_{treatment,i}$);
- Parameters related to *ex post* determination of baseline emissions: $L_{0,x}$;
- Amount of non inert waste excavated and aerobically composted in year x ($A_{lf,x}$).

25. The annual amount of fossil fuel or electricity used to operate the facilities or power auxiliary equipment shall be monitored, e.g., energy/fossil fuels used for aeration, excavation, separation, turning of compost piles and where relevant drying of the final compost product. Alternatively it shall be assumed that all relevant electrical equipment operate at full rated capacity, plus 10% to account for distribution losses, for 8760 hours per annum.

In case of composting facilities, its operation shall be documented in a quality control program, monitoring the conditions and procedures that ensure the aerobic condition of the waste during the composting process.

Soil application of the compost in agriculture or related activities will be monitored. This includes documenting the sales or delivery of the compost final product. It shall also include an in situ verification of the proper soil application of the compost to ensure aerobic conditions for further decay. Such verification shall be done at representative sample of user sites.

Project activity under a programme of activities

The following conditions apply for use of this methodology in a project activity under a programme of activities:

26. In case the project activity involves the replacement of equipment, and the leakage effect of the use of the replaced equipment in another activity is neglected, because the replaced equipment is scrapped, an independent monitoring of scrapping of replaced equipment needs to be implemented. The monitoring should include a check if the number of project activity equipment distributed by the project and the number of scrapped equipment correspond with each other. For this purpose scrapped equipment should be stored until such correspondence has been checked. The scrapping of replaced equipment should be documented and independently verified.

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History of the document

Version	Date	Nature of revision
01	EB 50, Annex 25 16 October 2009	Initial adoption.
Decision Class: Regulatory **Document Type**: Standard **Business Function**: Methodology		

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Open dumpsites and landfills are significant contributors of anthropogenic methane gas. Since a considerable portion of waste in India is biodegradable, municipal solid waste when disosed of in dumpsites or landfills, emits methane for years, even if the landfill is scientifically closed. The global warming potential of methane is 28 times higher than that of carbon dioxide.

While emissions from the oil and gas sector have received adequate attention, the waste sector also requires urgent intervention. The present report argues that quantities of methane emission from all the dumpsites across the country should be assessed based on the ground data. It also provides an insight on mitigation strategies for minimizing methane emissions from dumpsites by biomining and bioremediation, and by ensuring scientific treatment of municipal solid waste generated across the country.

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