ESTIMATION OF LANDFILL GAS EMISSION AND ENERGY RECOVERY POTENTIAL FROM AN OPEN DUMP SITE OF KOLKATA USING LANDGEM, IPCC AND MTM MODEL

A Thesis Paper Submitted for Partial Fulfillment of the Requirements for the Degree of Master of Engineering in Civil Engineering (Specialization: Environmental Engineering)

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Declaration

I declare that the work described in this thesis is entirely my own. No portion of the work referred to in this thesis has been submitted in support of an application for another degree or qualification of this or any other university or institute. Any help or source information, which has been availed in the thesis, has been duly acknowledged.

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This is to certify that the thesis entitled "**Estimation of Landfill Gas Emission and Energy Recovery Potential from an Open Dump Site of Kolkata using LandGEM, IPCC and MTM Model**" is hereby approved as an original work conducted and presented satisfactory to warrant its acceptance as a prerequisite to the degree for which it has been submitted. It is implied that by this approval the undersigned do not necessarily endorse or approve any statement made, opinion expressed or conclusion drawn therein, but approve the thesis paper only for the purpose for which it is submitted.

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- Babul Das

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List of Abbreviations

ADB	Asian Development Bank
BOD	Bio-chemical oxygen demand
C	Carbon
CO	Carbon monoxide
COD	Chemical oxygen demand
CCRs	Coal combustion residues
CPCB	Central pollution control board
CPHEEO	Central Public Health & Environmental Engineering Organisation
CSFs	carbon storage factors
CH_4	Methane
C/N	Carbon / Nitrogen ratio
CNG	Compressed natural gas
CO_2	Carbon dioxide
DM	Default Methodology
DOC	Degradable organic carbon
FOD	First order decay
F	Field factor
F	Fraction of methane in landfill gas
H	Hydrogen
H_2O	water
Ha	Hectare. 1 ha = 0.01 km^2
G	gram
Gg	Giga gram
GOI	Government of India
GWP	Global warming potential
Gt	Giga tone
GCL	Geo-synthetic Clay Liner
GHG	Greenhouse gas
GIS	Geographic information system
HDPE	high density polyethylene
HW	Hardwood
H_2S	Sulphur di oxide
IPCC	Intergovernmental panel on climate change
ISWM	Integrated Solid Waste Management
LandGEM	Landfill Gas Emission Model
K	Methane generation rate constant

Kg	Kilo gram
KJ	Kilo-joule
Km	Kilometer
km^2	Square kilometer
KMC	Kolkata municipal corporation
$k_{field,MSW}$	Methane generation rate constant at field
KEIP	Kolkata Environmental Improvement Project
L_0	Potential methane generation capacity
LFG	Landfill gas
LEL	lower explosive limit
LCS	leachate collection system
M	Meter
Mm	millimeter
m^3	Cubic meter
MCF	Methane correction factor
Mg	Mega gram
Mm^3	Million cubic meter
MSW	Municipal solid waste
MSWM	Municipal solid waste management
MTM	Modified triangular method
MT	Metric tone
mL	milliliter
MW	Mega Watt
N	Nitrogen
NH_3	amonia
N_2O	Nitrous oxide
NMOC	Non methane organic compound
NEERI	National Environmental Engineering Research Institute
O_3	Ozone
OX	Oxidation factor
O	Oxygen
PMGC	Potential Methane Generation Capacity
PM	Particulate matter
Q	Quantity of methane emission
RDF	Refuse derived fuel
R	Recovered methane
RBW	Rapidly biodegradable waste
S	Sulphur
SO_2	Sulphur dioxide
SBW	Slowly biodegradable waste

SW	Softwood
SWM	Solid waste management
T	Tone
td^{-1}	Ton per day
TM	Triangular method
TCLP	Toxicity characteristic leaching procedure
Tg	Tera gram
TOC	Total organic carbon
TPD	Tone per day
TJ	Tera joule
UNEP	United Nations Environmental Programme
UT	Union Territory
UEL	Upper explosive limit
USEPA	United States Environmental Protection Agency
VOCs	Volatile organic carbon
Yr	year
y^{-1}	Per year

ABSTRACT

With urbanization and changing life styles, per capita waste generation increases rapidly. Therefore, Solid Waste Management (SWM) and disposal is a major environmental concern in recent time and is getting rapidly complicated day by day. In India, urban area generates 62 million tons of municipal solid waste (MSW) per annum currently and it is expected to reach 165 million tons of waste annually by the year 2031(planning commission, 2014). About 95% of the solid wastes are disposed of by landfilling in low-lying areas located in and around the urban centres. Kolkata, a metropolitan city of India, generates about 3000 tonne waste per day containing 50% biodegradable organics and is dumping on open ground at Dhapa landfill without any segregation of waste components. In dumping sites, the waste subjected to various simultaneous and interrelated biological, chemical, and physical changes. The most important biological reaction occurring in the dumping sites is bacterial decomposition of organic materials under anaerobic condition. One of the bi-product of this conversion is landfill gas which consists of 45-60 % volume by methane and 40-55 % volume by carbon dioxide. These are the important greenhouse gases. On releasing of these gases in the atmosphere lead to global warming, environmental pollution and explosive hazard. Methane emission from landfill is estimated as 3–19% of the anthropogenic sources and it is the third major anthropogenic source of CH_4 (IPCC, 1996). On the other hand, conventional energy sources are limited and are going to be depleted day by day. In this situation finding of alternative energy source is necessary. One of the alternative sources can be Methane from landfill sites as methane has high energy generation potential having calorific value of 55.7 KJ/g and can be used as a fuel. Methane is the main component of compressed natural gas (CNG). Methane can be considered as wealth from waste since it can be used as renewable energy source. On successful implementation of energy recovery project from MSW landfill sites not only be potential source of revenue but also save the environment. Hence it is necessary to estimate the landfill gas emission from MSW landfill sites for feasibility analysis of the project. The present work aims to estimate landfill gas emission and energy recovery from an uncontrolled landfill site of Kolkata located in Dhapa, India using LandGEM, IPCC (2006) First Order Decay (FOD) and Modified Triangular Model (MTM) model. The present study revealed that there is a large potential for landfill gas generation from the landfill site in Kolkata. By LandGEM method, it is estimated that for the year 2010-2020 methane emission vary from 10.87×10^6 to 24.01×10^6 m^3/year and have annual energy generation potential of 432.6 TJ/year to 955.6 TJ/year (1TJ= 10^{12} Joule), where by MTM method, it is estimated that methane emission vary from 28.2×10^6 to 44.01×10^6 m^3/year and have annual energy rate of 1122.4 TJ/year to 1751.6 TJ/year. By IPCC method, it is estimated that methane emission varies from 8.2 Gg/year to 18.8 Gg/year and have annual energy rate of 456.7 TJ/year to 1047.16 TJ/year. This energy can be used for power generation. LandGEM method predicts the power generation 12.6 MW to 27.8 MW from the year 2010 to the year 2020 and for IPCC model is 14.5 MW to 33.2 MW. By using MTM, the value varies from 32.86MW to 51.3 MW.

On successful implementation of energy recovery project from landfill site reduce global warming potential (GWP). By using LandGEM, IPCC and MTM methods it is estimated that GWP can be reduced by 4950 Gg of CO_2 eq, 6755.2 Gg of CO_2 eq and 8071 Gg of CO_2 eq respectively during period 2010-2030.

Instead of using the default parameters for model applications, the present study calculates methane generation rate constant value as 0.04 y^{-1} using laboratory simulation method and 0.07 y^{-1} using precipitation methods. Methane yield (L_0) value of MSW in Kolkata is calculated as 46.51 m^3/Mg and degradable organic carbon (DOC) value as 0.12 kg C/ kg waste.

Key Words: Municipal solid waste, landfill, Greenhouse gas, methane emission estimation, Landfill gas emission model(LandGEM), IPCC(2006) FOD model, Modified triangular method (MTM), methane generation rate constant (k), methane generation potential (L_0), Global warming potential (GWP), Energy generation potential

Chapter -1
Introduction

1.1 Background

Solid wastes are the discarded solid materials generated through use of resources of the earth by humans and animals to support their life. Solid wastes may be generated from residential area, commercial area, institution, construction and demolition works, municipal services, treatment plant sites, industrial area and agricultural yard (Tchobanoglous, 1993). From the beginning of the civilization, solid waste has been produced. In earlier days, the disposal of waste did not create significant problems due to availability of large open space, less population and less generation of per capita solid waste. So there was no accumulation of huge solid waste. As a result the biodegradable organic materials decomposed aerobically and produce unobjectionable end products which have no significant harmful effect on environment. There was an affectionate relationship between human and nature which kept the environment pure and healthy. Hence there was no requirement of measurement of different environmental components and pollutants, source apportionment study and enforcement of rules and regulation on different activities etc.

With the advancement of time, population increases rapidly day to day. World population increases from 3.4716 billion in the year 1967 to 7.5304 billion in the year 2017 i.e. population increases nearly 115 % in 50 years (U.S. Census Bureau, 2018).Population in India increases from 0.519 billion in the year 1967 to 1.33 billion in the year 2017 i.e. population increase nearly 156 %in 50 years (U.S. Census Bureau, 2018). India is the second most populous country in the world. To meet the requirements of basic need and comfortable life of the population, different industries are developed. With this rapid industrialization and population growth, level of urbanization has increased in the last 50 years from 17.6 % to 28% and is expected to rise to 38% by the year 2026 (Talyan et al. 2008). With urbanization, economic development and changing life styles, per capita waste generation increases rapidly. Again the industries generate large amount of solid waste. About 2.01×10^9 tone of municipal solid waste was generated globally in 2016 and expected to generate 3.4×10^9 tone of MSW in 2050 (www.worldbank.org). About 48 million tonne of municipal solid waste (MSW) is generated in India per year (Sridevi et al., 2015). Kolkata, one of the metropolitan city of India and capital of West Bengal has a population of 4.49 million with a density of 24270 persons per km^2 (Census 2011). Kolkata generates 3005 tonne of solid waste per day (Jash et al., 2016).

Solid waste management have become a global problem and is getting rapidly complicated day by day due to large quantity, changing characteristics and less available land to assimilate the huge quantity of waste. The huge amount of solid waste after proper treatment must be disposed-off scientifically and environmentally in secured place, outside the city, so that there is no environmental hazard or production of any environmental pollutants (solid, liquid and gas). If environment and natural resources are polluted, human beings, animals and plants also being impacted (Sabour et al., 2007). So, waste management plays a key role in human’s life (Kamalan 2007). Solid waste management follow the following steps viz. waste generation, primary collection, followed by storage and handling of waste at source, secondary collection, transfer and transport, followed by treatment and transformation, at last disposal to landfill site (Tchobanoglous, 1993). To ensure proper management of solid waste, government of India published Solid Waste Management Rules 2016, which states that “Landfilling shall be restricted to non-biodegradable, inert waste and other waste that are not suitable either for recycling or for biological processing”. Unfortunately, the generated MSW (biodegradable, non-biodegradable and inert) from urban areas in India is managed by depositing in the low lying areas, called landfill, without prior treatment and with no or very negligible daily cover as it is low cost management option. In India, Almost 70–90% of landfills are open dump sites (Joseph et al., 2003). In landfill, the biodegradable wastes are subjected to complex bio-chemical reaction in presence of different micro-organism and formed different gases, called landfill gas (LFG), mainly consists of methane (CH_4) and carbon dioxide (CO_2) (Tchobanoglous, 1993). It also forms a complex characteristics liquid, called leachate. Leachates have the potential to contaminate groundwater aquifers (Srivastava et al., 2008). These leachates increase the acidity of the soil (Srivastava et al., 2008, Taylor et al., 1987) and also initiate the transportation of heavy metals present into the landfill wastes to groundwater (Singh et al., 2017). If landfilling is done in well managed and engineering way, then there is no environmental pollution or problem due to migration of leachate and emission of landfill gas. To ensure well management of these bi-products, Solid Wastes Management Rules 2016 states that there should be gas collection and leachate collection system and the collected bi-product must be treated before disposal to environment. Unfortunately, only a few properly managed landfills exist in India (Chakraborty et, al 2013) with proper leachate and gas collection and management system. Even in other countries in the world, most of the landfills are open dump except some developed country. As a result, a huge amount of landfill gases enter into the atmosphere and interfere with the natural atmospheric activity. Typically LFG consists of 45-60 % volume by methane and 40-55 % volume by carbon dioxide (USEPA, 2014). These two are major greenhouse gases. Methane has Global Warming Potential (GWP), 21 to 25 times more than CO_2 over a period of 100 years (Kumar et al. (2004)).

Methane emitted from landfills is considered as one of the most important sources to GHGs (Singh et al., 2017). CH_4 concentration in the atmosphere has increased rapidly over a last few decades. CH_4 concentration in the environment has increased from 700 ppb to 1808 ppb from 1750 to 2010 i.e. over a period of 260 years (Stocker et al, 2014). The rate of increase is 1–2% per year (IPCC 1996). 64 % of total global CH_4 emission comes from anthropogenic activities which include burning of fossil fuels, livestock farming, landfills and agriculture (Bousquet, et al., 2006). Methane emission from landfill is estimated as 3–19% of the anthropogenic sources and it is the third major anthropogenic source of CH_4 (IPCC, 1996). It has been estimated that the concentration of CH_4 is expected to increase from 6.88 Gt CO_2-eq in the year 2010 to 8.59 Gt CO_2-eq by the year 2020 (USEPA 2012). In the year 2014, India emitted 16 Mg CO_2 equivalent of methane per year which is expected to reach 20 Mg CO_2 equivalent by the year 2020 (Kumar and Sharma 2014). It is also estimated that methane contributes 29% of the total GHG emissions from the country, which is higher than the global average of 15% (Siddiqui, et al, 2011, Kumar and Sharma 2014).The emissions from wastes are also higher (6%) than the global average of (3%) (Siddiquiet al, 2011).

The increase in greenhouse gas emissions has changed the global temperature pattern and created a threat against human life and the environmental activities (Hughes et al, 2000). Methane escaping from landfill sites will react with other pollutants in presence of strong sunlight to produce tropospheric ozone and thereby contribute to photochemical smog (Goldstein et al 2007). Methane is a highly explosive gas and has high energy potential of about 55.7 KJ/g. So, LFG is considered either as a significant source of pollution if migrating uncontrollably to the air and ground, or as a potential eco-friendly renewable power source.

Global warming is a common problem due to increase in greenhouse gases. It creates problem to all nations on the earth. Greenhouse gases trap the thermal radiation of earth and increase atmospheric temperature. Global ocean temperature has increased by 0.10°C in the last 40 years (Roy et al, 2015). For the 20th century increase in sea level was 1.7±0.5 mm/yr due to melting of the ice cap as well as volume expansion (Bindoff et al., 2007). It is expected that the rise in the global surface temperatures for the period 2081–2100 with respect to 1986–2005 will be in the ranges between 0.3°C to1.7°C (IPCC, 2013).If necessary actions are not taken to reduce this effect, earth temperature may increase to a value beyond the atmospheric carrying capacity. As a result existence of life on earth will not be possible. So, all nations should take necessary actions against the effect, as per as possible. As LFG is one of the major source of GHGs, so one of action include management of LFG.

There are two possible solutions for management of LFG emissions. One is LFG collection and flared or oxidized in bio-filters. Another is LFG collection and used as a valuable energy source since calorific value of CH_4 is 55.7 KJ/g.

To minimize the greenhouse gas emission from landfill, to protect the environment from different undesirable problems arise from landfill gas emission, to reduce carbon credit to the atmosphere and to establish economically feasible landfill gas recovery project, it is necessary to know the amount of gas generate from the landfill. So, quantification of landfill gas generation is necessary.

1.2 Objective of the work

The objective of the work is the estimation of landfill gas generation and energy recovery potential by using available landfill gas estimation model from an uncontrolled open dump site. The work is demonstrated with reference to Dhapa landfill site, Kolkata Municipal Corporation (KMC) Area in West Bengal, India, as a case study.

1.3 Scope of the study

- Selection of landfill gas emission models for estimation of LFG from available models.
- Selection of landfill site for the study.
- Collection of statistical data on functional elements of solid waste management of the study area
    - Total MSW generated (Gg/yr),
    - Fraction of MSW disposed to solid waste disposal sites
    - Composition of MSW
    - Age of the waste.
- Collection of meteorological data for the landfill site
    - Annual average rainfall (mm),
    - Temperature (°c)
    - Relative humidity (%)
- Collection and estimation of model parameters
    - Methane generation rate constant (year^{-1}),
    - Potential methane generation capacity (m^3/Mg),
    - Methane correction factor (MCF),
    - Degradable organic carbon (DOC) (kg C/ kg SW),
    - Fraction DOC dissimilated (DOC_F),
    - Fraction of CH_4 in landfill gas
    - Oxidation factor.
- Fitting the data in the model.
- Estimation of landfill gas emission.
- Estimation of energy generation potential of estimated LFG
- Preparation of sustainable management plan for Dhapa to minimize generation of LFG and management of generated LFG

Chapter -2
Literature Review

2.1 Municipal solid waste

Solid wastes are wastes that are not liquid or gaseous, such as durable goods, non-durable goods, containers and packaging, food scraps, yard trimmings and miscellaneous inorganic wastes arising from human and animal activities that are discarded as useless or unwanted. Solid wastes are generated from agricultural, industrial, residential, institutional and commercial activities in a given area. Solid waste can be categorized based on its materials content such as plastic, paper, glass, metal, and organic waste. Categorization may also be based on hazard potential, including reactive, corrosive, radioactive, flammable, infectious, toxic, or non-toxic. Categories may also pertain to the origin of waste, such as agricultural, industrial, domestic, commercial, institutional, construction and demolition or municipal services.

Municipal solid waste (MSW) is defined as the solid waste materials generating from residential, commercial, institutional sources, but it does not include such things as construction waste, automobiles bodies, combustion ash and industrial process wastes. Municipal solid waste (MSW) generally includes degradable materials (paper, food waste, textiles, and straw and yard waste), partially degradable materials (wood, disposable napkins and sludge) and non-degradable materials (rubbers, leather, plastics, metals, glass, ash from fuel burning, briquettes or woods, dust). The degradable portion of MSW is called garbage. This waste is largely putrescible organic matter and contains high moisture content, cellulose, hemicellulose, protein and lipid (Jash et al 2016). Home kitchen, restaurants, markets are source of garbage. Biodegradable food materials and yard wastes normally dominate in MSW of developing countries while paper and hardboard dominate in developed countries (Joseph et al., 2003; Vishwanathan and Trakler, 2003). On the other hand, Rubbish consists of old tin cans, newspaper, tires, packaging materials, bottles, plastics etc. which may be combustible or non-combustible in nature.

2.2 Generation of Municipal Solid Waste

Per capita generation of municipal solid waste depends on various factors like climate, food habits, season, recycling and cultural practices, existing rules and regulations etc. but the total quantity of generation is directly proportional to the population of the city (Gunaseelan, 1997). Global population increases rapidly by a rate of about1-1.2% per year (U S census bureau, 2018). In developing country like India, the rate of increase in population is nearly 1.5-1.8% per year (U S census bureau, 2018). Present population in India is 1.32 billion and expected to reach 1.53 billion by the year 2030 (http://www.indiapopulation2019.in/). Urban population also increases rapidly. In India, urban population has increased from 27.8% to 31.16% from 2001 to 2011 (Census of India, 2011).There are three megacities —Kolkata, Greater Mumbai and Delhi, which have a population more than 10 million, 53 cities which have population exceeding 1 million and 415 cities whose population exceeds 100,000 (Census, 2011; Singh et al., 2011; Joshi and Ahmed, 2016). Growth of population, increasing urbanisation, rising standards of living due to technological innovations have contributed to increase both in the quantity and variety of solid wastes, generated by industrial, mining, domestic and agricultural activities.

Globally about 3 billion urban residents generated 1.3 billion tonnes of solid waste per year, at a rate of 1.2 kg per person per day and it is expected to reach 2.2 billion tonnes per year with a rate of 1.42 kg/capita/day of municipal solid waste (World Bank, 2012). High income countries produce more waste than low income countries. Australia generates waste at a rate of about 2.23 kg/capita/day, Austria at 2.4 kg/capita/day, Bangladesh at 0.43 kg/capita/day, Belgium at 1.33 kg/capita/day, Brazil at 1.03 kg/capita/day, Canada at 2.33 kg/capita/day, China at 1.02 kg/capita/day, Finland at 2.13 kg/capita/day, Japan at 1.71 kg/capita/day, Netherlands at 2.12 kg/capita/day, Pakistan 0.84 kg/capita/day, South Africa 2 kg/capita/day, Switzerland at 2.61 kg/capita/day, UK at 1.78 kg/capita/day, US at 2.58 kg/capita/day (World bank 2012). Asian countries are the largest generator of MSW due to their high population densities. The generation of MSW in Asia is1 million tons/day and expected to increase up to 1.8 million tons/day by the year 2025 (Hoornweg et al 2012).

In India, Municipal solid waste generation increases with socio-economic development of urban population (Chakraborty et al 2013). Indian cities now produce eight times more MSW than they generated in1947 (Kaushal et al., 2012). The urban population in India generated about 114576 TPD of MSW in 1996; 127486 TPD during 2011-12 and 144165 TPD during 2013-14 (CPCB, 2012; CPCB, 2015).Total MSW generation increased almost 50% between the years 2001 to 2011. The rate of solid waste generation in cities varies from 0.2 kg to 0.6 kg per day, depending upon the size of population (Dayal, 1994; Ministry of Finance, 2009). Per capita waste generation is increasing by about 1- 1.3% per year (Bhide and Shekdar, 1998; Shekdar, 1999; Imura et al., 2005). The per capita rates of solid waste generation based on population are shown in Table-1.

Table 1: Per capita solid waste generation in different cities

Population size	Waste generation[1] (kg/capita/day)	Waste generation[2] (kg/capita/day)
>2000000	0.43	0.55
1000000–2000000	0.39	0.46
500000–1000000	0.38	0.48
100000–500000	0.39	0.46
<100000	0.36	-

Source: CPCB Report (2000 b)[1] and R.K. Annepu (2012)[2].

In India, urban area generates 62 million tons of MSW per annum currently and it is expected to reach 165 million tons of waste annually by the year 2031 (Planning commission, 2014). By the year 2047, MSW generation in India, is expected to reach 300 MT and land requirement for disposal of this waste would be 169.6 km^2 as against which only 20.2 km^2 were occupied in 1997 for management of 48 MT (Joshi et al .,2016). Fig.1 shows the details on current status of solid waste (non-hazardous and hazardous waste) generation from different sources in India. However, it is reported that about 600 MT of wastes have been generated in India from agricultural sources alone. The major quantity of wastes generated from agricultural sources are sugarcane, paddy and wheat straw and husk, wastes of vegetables, food products, tea, oil production, jute fibre, groundnut shell, wooden mill waste, coconut husk, cotton stalk etc. The major industrial non-hazardous inorganic solid wastes are coal combustion residues, bauxite red mud, tailings from aluminium, iron, copper and zinc extraction

The metropolitan area of Kolkata generates large amount of MSW among Indian cities. It generates about 3000 T/day of MSW of which about 1775 T comes from domestic area and street sweeping, about 941 T from market, commercial area, institutional solid waste etc. and 231 T of silt and debris (Chattopadhyay et al 2007). Among the four geographical regions in India, Northern India generates the highest amount of MSW 30% of all MSW generated in India; and Eastern India, generates the least, only 17% of MSW generated in India.

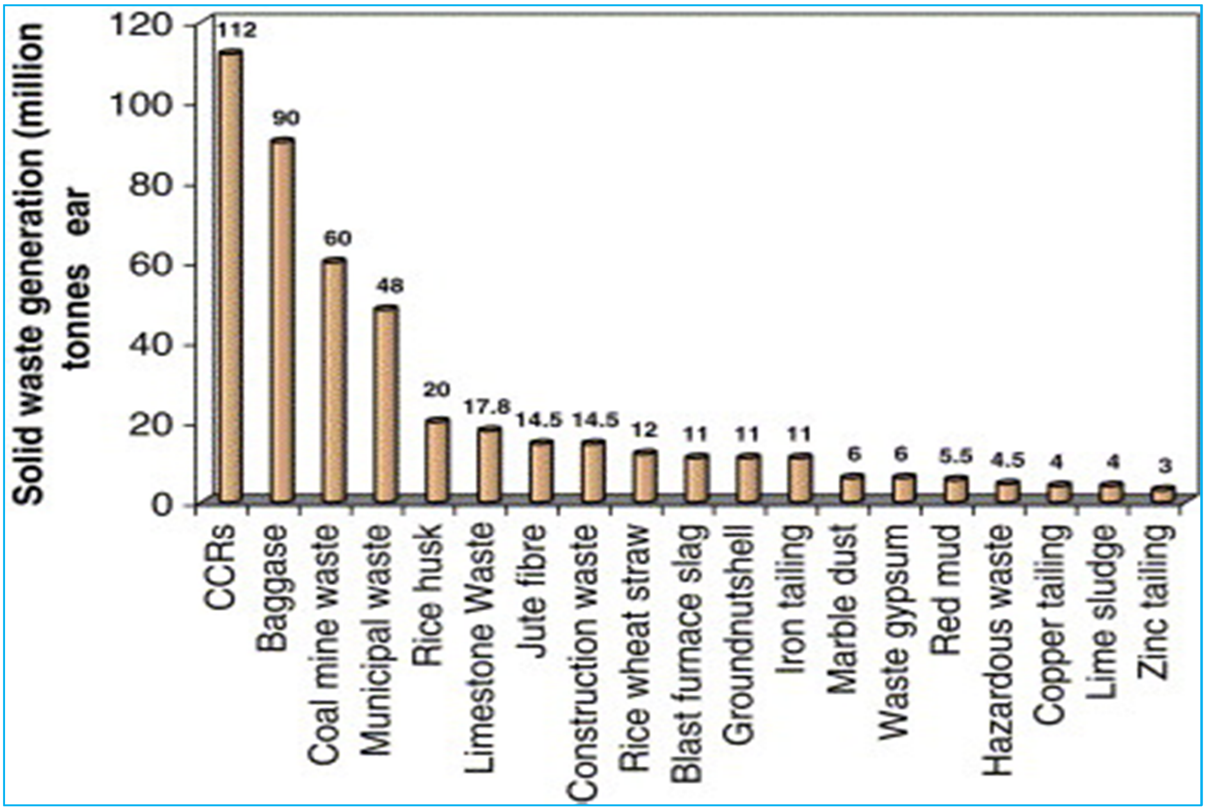

Fig. 1: Generation of solid waste from different source in India (Pappu et al., 2007**)**

Sources of solid waste generation and type of solid waste generation are elaborated in Table 2.

Table 2: Sources and Types of MSW (Tchobanoglous, 1993)

Sources	Typical Waste Generators	Components of MSW
Residential	Single-family and multi-family dwellings	Food wastes, paper, cardboard, yard wastes, plastics, textiles, leather, wood, glass, tin cans, aluminium, other metal, ashes, street leaves, special wastes (including bulky items, consumer electronics, white goods, batteries, oil and tires).
Commercial	Stores, restaurants, markets, office buildings, hotels, motels, service stations.	Paper, cardboard, plastics, wood, metal wastes, food wastes, glass, ashes, special wastes, hazardous wastes, etc.
Institutional	Schools, hospitals, prisons, governmental centres, etc.	Paper, cardboard, plastics, wood, metal wastes, food wastes, glass, ashes, special wastes, hazardous wastes, etc.
Industrial	Construction, fabrication, light and heavy manufacturing, refineries, chemical plants, power plants, demolition, etc.	Paper, cardboard, plastics, wood, food wastes, glass, metal wastes, ashes, Industrial process wastes, scrap materials, etc. special wastes, and hazardous waste.
Municipal services	Street cleaning, landscaping, parks, beaches, recreational Areas.	Street sweepings, inert, automobile parts, construction and demolition wastes, dead Animal carcass, tree trimmings and yard waste, general wastes from parks, beaches.
Treatment facilities	Water, wastewater, industrial treatment processes, etc.	Treatment plant wastes, principally composed of residual sludge and other residual materials.

7 Literature Review

Solid waste generation of different states are different due to economic condition, culture, location, food habits, season and climate. Solid waste generation from different cities also vary. Among states, Maharashtra generates the highest amount of MSW followed by West Bengal, Uttar Pradesh, Tamil Nadu and Andhra Pradesh. Among Union Territories, Delhi generates the highest and Chandigarh generates the second highest amount of waste. Table 3 presents the solid waste generation in different states and union territories in India and Fig. 2 presents solid waste generation in different cities.

Table 3: Municipal solid waste generation, collection and treatment rates in different states in India (CPCB, 2012; CPCB, 2015**)**

Sl. No	Name of state / UT	MSW generated(Tons/day) 1999-2000[1]	MSW generation (Tons/day) 2009-2012	MSW generated (Tons/day) 2014	MSW collected (Tons/day) 2014	MSW treated (Tons/day) 2014
1	Andaman & Nicobar	-	50	70	70	5
2	Andhra Pradesh	4376	11500	11500	10656	9418
3	Arunachal Pradesh	-	93.802	110	80	74
4	Assam	285	1146.28	650	350	100
5	Bihar	1819	1670	1670	-	-
6	Chandigarh	200	380	340	330	240
7	Chhattisgarh	-	1167	1896	1704	168
8	Daman Diu & Dadra	-	41	85	85	-
9	Delhi	4000	7384	8390	7000	4150
10	Goa	-	193	183	182	182
11	Gujarat	-	7378.775	9227	9227	1354
12	Haryana	4232	536.8	3490	3440	570
13	Himachal Pradesh	725	304.3	300	240	150
14	Jammu & Kashmir	35	1792	1792	1322	65
15	Jharkhand	-	1710	3570	3570	65
16	Karnataka	3278	6500	9500	5700	2000
17	Kerala	1298	8338	1576	776	470
18	Lakshadweep	-	21	21	-	-
19	Madhya Pradesh	2684	4500	5079	4298	802
20	Maharashtra	9099	19204	26820	14900	4700
21	Manipur	40	112.9	176	125	-
22	Meghalaya	35	284.6	268	199	98
23	Mizoram	46	4742	552	276	-
24	Nagaland	-	187.6	270	186	18
25	Orissa	655	2239.2	2460	2107	30
26	Pondichery	69	380	495	495	-
27	Punjab	1266	2793.5	3900	3853	32
28	Rajasthan	1966	5037.3	5037	2491	490
29	Tamil Nadu	5403	12504	14234	14234	1607
30	Uttar Pradesh	5960	11585	19180	19180	5197
31	West Bengal	4621	12557	8674	7196	1414

1 includes Class I cities and Class II towns;

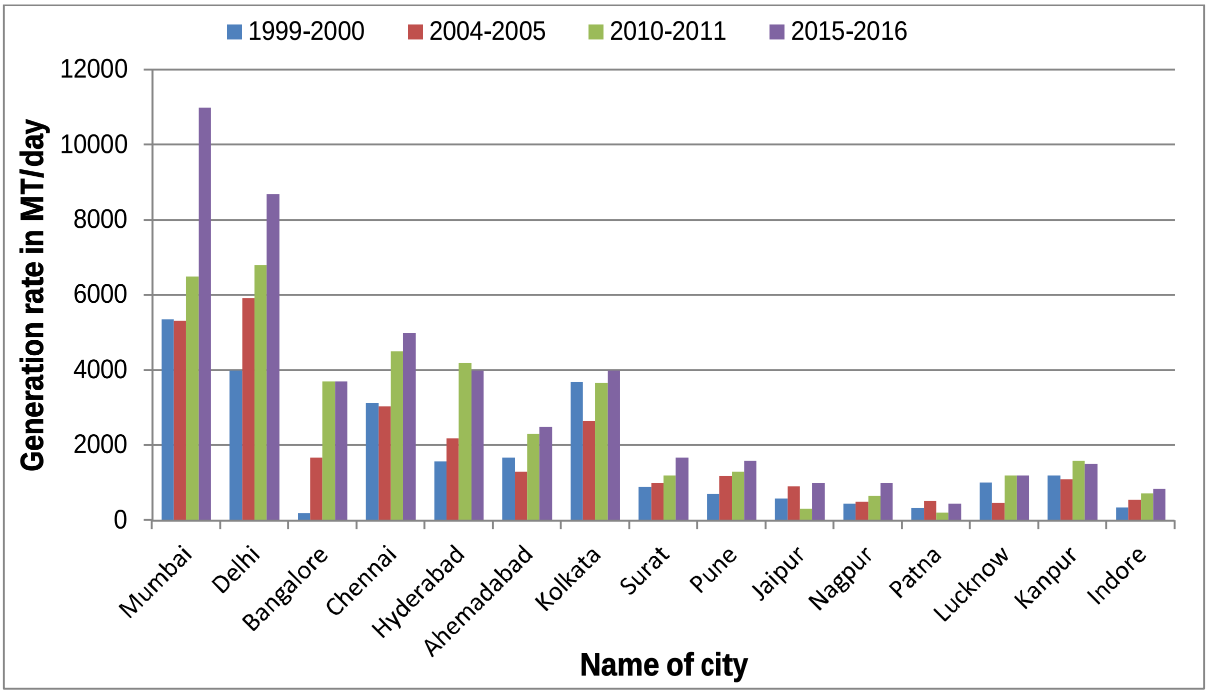

Figure 2: Municipal solid waste generations in a few Indian cities (CPCB, 2012**).**

2.3 Composition and characteristics of Municipal Solid Waste

Municipal solid waste is heterogeneous in nature and consists of different materials derived from various types of activities. The characteristics of municipal solid wastes vary from country to country. Even in the same country, it may vary from one city to another city. The variation of composition depends on number various factors such as social customs, size of population, income levels, standard of living, lifestyle of the community, geographical location, climate, principal activities in the city or town etc. The composition of municipal solid waste also varies from time to time depending on the advancement of technologies, urbanisation, change in life style and change in climate etc.

Waste composition studies are essential tools for solid waste management, though often the lack of consistent procedure and underfunding cause data to be inaccurate and imprecise. The nature of the deposited waste in a landfill will affect gas and leachate production (Chattopadhyay et. al., 2018). Waste characteristics and composition may be of three types viz. physical, chemical and biological. Physical and chemical compositions and characteristics of solid wastes vary depending on sources and types of solid wastes. The physical and chemical characteristics aid in deciding the capacity of waste management facilities, desired frequency of collection, precaution to be taken during transportation and method of processing and disposal.

Physical composition and characteristics

Physical compositions of solid wastes are important in the selection and operation of equipment and facilities, in assessing the feasibility and resources and energy recovery and in the analysis and design of disposal facilities. Domestic municipal solid waste contains 45.1% fruit and vegetable waste and 8.8% paper, waste from the markets contains 32.4% leaves and straw and 25.7% fruit and vegetable, and waste from the commercial area contains about 51% recyclable waste (KEIP, 2003). MSW in India has approximate 40–60% compostable matter, 30–50% inert waste and 10% to 30% recyclable (Ahmed et al 2016). In developing country, the amount of paper, plastics, food containers and wrapping materials is much lower than developed countries; such as USA (65%) and Western Europe (48%) (IGES 2001). Waste in developing cities generally has a high organic matter and low energy value. So it is suitable for biological treatment (IGES 2001). Waste compositions indifferent countries are shown in Table 4.

Table 4: Composition of MSW for different income group countries (Central Public Health & Environmental Engineering Organisation (CPHEEO), 2000)

Composition (% by weight)	**Low income countries**	**Middle income countries**	**High income countries**
Food & garden waste	40-65	20-60	20-50
Paper	1-10	15-40	15-40
Textiles	1-5	2-10	2-10
Plastics/Rubber	1-5	2-6	2-10
Metal	0.2-2.5	1-5	3-13
Glass, Ceramics	0.5-3.5	1-10	4-10
Misc. Combustible	1-8	-	-
Inert	20-50	1-30	1-20
Density (kg/m^3)	250-500	170-330	100-170
Moisture content (%)	40-80	40-60	20-30
Waste generation (kg/capita/day)	0.4-0.6	0.5-0.9	0.7-1.8

Earlier stated that waste composition changes from time to time, here the change in the physical and chemical composition of Indian MSW with time is shown in Table 5.

Table 5: Change in composition of municipal solid waste with time (%)

Parameter	**1996**	**2005**	**2011**
Biodegradables	42.21	47.43	42.51
Paper	3.63	8.13	9.63
Plastic/rubber	0.60	9.22	10.11
Metal	0.49	0.50	0.63
Glass	0.60	1.01	0.96
Rags	-	4.49	-
Inert	45.13	25.16	17.00
Others	-	4.02	-

Source: Planning commission report, 2014.

The physical characteristics of solid waste include moisture content, waste particle size, waste density, temperature and pH, which are important as these affect the extent and rate of degradation of waste. The average density of solid waste is around 450-500 kg/m^3 and moisture content is about 25-45% (GOI manual, 2016).Again, waste characteristics and composition varies from place to place, as stated earlier. Table 6 show the variation of physical composition and characteristic of MSW in different cities of India.

Table 6: Physical characteristic of MSW in some Indian cities (CPCB, 2000)

Name of city	paper	Textile	Leather	Plastic	Metals	Glass	Ash, fine earth	Compostable matter
Ahmedabad	6.0	1.0	-	3.0	-	-	50.0	40.0
Bangalore	8.0	5.0	-	6.0	3.0	6.0	27.0	45.0
Bhopal	10.0	5.0	2.0	2.0	-	1.0	35.0	45.0
Mumbai	10.0	3.6	0.2	2.0	-	0.2	44.0	40.0
Kolkata	10.0	3.0	1.0	8.0	-	3.0	35.0	40.0
Coimbatore	5.0	9.0	-	-	-	1.0	50.0	35.0
Delhi	6.5	4.0	0.6	1.5	2.5	1.2	51.5	31.78
Hyderabad	7.0	1.7	-	1.3	-	-	50.0	40.0
Indore	5.0	2.0	-	1.0	-	-	49.0	43.0
Jaipur	6.0	2.0	-	1.0	-	2.0	47.0	42.0
Kanpur	5.0	1.0	5.0	1.5	-	-	52.5	40.0
Kochi	4.9	-	-	1.1	-	-	36.0	58.0
Lucknow	4.0	2.0	-	4.0	1.0	-	49.0	40.0
Ludhiana	3.0	5.0	-	3.0	-	-	30.0	40.0
Chennai	10.0	5.0	5.0	3.0	-	-	33.0	44.0
Madurai	5.0	1.0	-	3.0	-	-	46.0	45.0
Nagpur	4.5	7.0	1.9	1.25	0.35	1.2	53.4	30.4
Patna	4.0	5.0	2.0	6.0	1.0	2.0	35.0	45.0
Pune	5.0	-	-	5.0	-	10.0	15.0	55.0
Surat	4.0	5.0	-	3.0	-	3.0	45.0	40.0
Vadodara	4.0	-	-	7.0	-	-	49.0	40.0
Varanasi	3.0	4.0	-	10.0	-	-	35.0	48.0
Vishakhapatnam	3.0	2.0	-	5.0	-	5.0	50.0	35.0
Average	5.7	3.5	0.8	3.9	1.9	2.1	40.3	41.8

Chemical composition and characteristics

Chemical characteristics of solid wastes are important in evaluating alternative processing and recovery options. Typically, wastes can be thought of as a combination of semi-moist combustible and non-combustible materials. Chemical properties of the waste show that the C/N ratio is highest (22.0) in market waste and lowest (9.3) in hotel waste (Hazra and Goel 2009). Indian waste consists of Nitrogen content (0.64 ± 0.8) %, Phosphorus (0.67 ± 0.15) %, Potassium (0.68 ± 0.15) %, and C/N ration (26 ± 5) % (NEERI, 2005). Chemical composition helps in determining treatment option for a particular type of waste. If solid wastes are to be used as fuel, the four most important properties to be known are: Proximate properties [moisture (loss at 105°C for 1 h), volatile matter (additional loss on ignition at 950°C), ash (residue after burning) and fixed carbon (remainder)], Fusing point of ash, Ultimate properties [percentage of C (carbon), H (hydrogen), O (oxygen), N (nitrogen), S (Sulphur) and ash] and Heating value. If waste is used for composting, C/N ratio and moisture content are important. The carbon/nitrogen ratio should be within the range 26-31 for composting (CPHEEO, 2000). Table 7 presents chemical characteristics of MSW in Indian cities based on population range.

Knowledge of chemical characteristics of waste is essential in determining the efficiency of any treatment process. Chemical characteristics include (i) chemical; (ii) bio-chemical; and (iii) toxic.

Chemical: Chemical characteristics include pH, Nitrogen, Phosphorus and Potassium (N-P-K), total Carbon, C/N ratio, calorific value etc.

Bio-Chemical: Bio-Chemical characteristics include carbohydrates, proteins, natural fibre, and biodegradable factor.

Toxic: Toxicity characteristics include heavy metals, pesticides, insecticides, etc. Toxicity test for Leachates (TCLP) can be used to determine the toxicity.

Table 7: Chemical characteristic of MSW in Indian cities

Population Range (million)	Number Of Cities Surveyed	Moisture (%)	Organic matter (%)	Total nitrogen (%)	Phosphorous as P_2O_5 (%)	Calorific value Kcal/kg	C/N Ratio (%)
0.1 to 0.5	12	25.81	37.09	0.71	0.63	1009.89	30.94
0.5 to 1.0	15	19.52	25.14	0.66	0.56	900.61	21.13
1.0 to 2.0	9	26.89	26.89	0.64	0.82	980.05	23.68
2.0 to 5.0	3	21.03	25.60	0.56	0.69	907.18	22.45
>5	4	38.72	39.07	0.56	0.52	800.70	30.11

All values are in % by dry weight basis except PH, C/N ratio and calorific value ((www.slideshare.net))

Chemical characteristics of waste also vary from time to time. Table 8 show the variation of chemical composition of MSW at Kolkata with time.

Table 8: Variation of chemical characteristics of MSW at Kolkata (NEERI, 2005)

Parameters	1970	1995	2005
Moisture	42.84	61.57	46
pH	7.31	6.33	0.3-8.07
Loss on ignition	35.24	46.78	38.53
Carbon	19.58	25.98	22.35
Nitrogen as N	0.55	0.88	0.76
Phosphorous as P_2O_5	0.57	0.58	0.77
Potassium as K_2O	0.40	0.93	0.52
C/N ratio	35.60	29.53	31.81
Calorific value kj/kg	2300	2717	5028

All values are in % by dry weight basis except PH, C/N ratio and calorific value

Biological properties

Biodegradable waste includes any organic matter in waste which can be broken down into CO_2, CH_4, H_2O or simple organic molecules by micro-organism and other living things by the processes like composting, aerobic digestion, anaerobic digestion etc.

The organic fraction of MSW can be classified as-

- Water soluble elements – sugars, starches, amino acids and organic acids found in food wastes.
- Hemicellulose – green wastes.
- Cellulose – waste paper, green wastes.

- Fats , oils and waxes - food wastes
- Lignin – waste paper, yard waste
- Lignocellulose – combination of lignin and cellulose
- Proteins – food wastes

2.4 Management of Municipal Solid Waste

Municipal Solid Waste Management (MSWM) is defined as the discipline associated with control of generation, storage, collection, transport or transfer, processing and disposal of solid waste materials in a way that best addresses the range of public health, conservation, economics, aesthetic, engineering and other environmental considerations. With the increase of generation of solid waste, management of solid waste is going to be an important issue. The ineffective management of MSW has severe problem, not only in the area of environmental and aesthetic concerns but also in the area of human health and welfare. To ensure effective management of MSW, GOI published several rules and regulation. As per Municipal Solid Waste (Management & Handling) Rules, 2000, it is mandatory for all municipal bodies to prohibit dumping of solid waste anywhere in the city and it is mandatory for the generators to segregate and store waste at source and the municipal bodies collect such segregated waste directly from the households, public places and transport it to designated places. Then the dry waste should be recycled and the organic matter should transfer for treatment. The remaining waste that cannot be processed and the residue after processing send to the engineered landfill site. As per the Solid Waste Management Rules, 2016, the ULB should create public awareness for minimising waste generation and reusing waste to the extent possible.

Solid waste management includes planning, administrative, financial, engineering and legal functions in the process of solving problems arising from waste materials. The solutions might include complex inter-disciplinary relations among fields such as public health, city and regional planning, political science, geography, sociology, economics, communication and conservation, demography, engineering and material sciences. Solid waste management practices can differ for residential and industrial producers, for urban and rural areas, and for developed and developing nations.

Objectives of waste management

The primary goal of solid waste management is reducing and eliminating adverse impacts of waste materials on human health and environment to support economic development and superior quality of life and to reduce the quantity of solid waste disposed-off on land by recovery of materials and energy from solid waste. In other word Waste reduction, prevention and minimization: Waste prevention is at the top of the waste hierarchy and number one priority for the integrated approach to solid waste management. Recycling can reduce waste to landfill but also provide economic, environmental and social positives.

An effective system of solid waste management can ensure better human health and safety. It must be both economically and environmentally sustainable i.e. it must reduce the environmental impacts as much as possible and at the same time it must operate at an acceptable cost to the community. Although it is difficult to minimise the two variables cost and environmental impact simultaneously. However, a balance between them should be ensured to reduce the environmental impacts of waste management within an acceptable level of cost. A sustainable solid waste management system is effective if it follows an integrated approach i.e. it deals with all types and all sources of solid waste. A multilateral, multi-source management approach is usually effective in environmental and economic terms than a material specific and source specific approach (CPHEEO Manual, 2000).

Functional Elements of Municipal Solid Waste Management:

There are six functional components of the waste management system as-

A. Waste generation– It refers to activities involved in generating materials which are no longer usable and are either gathered for systematic disposal or thrown away. It is discussed in details in section 2.2.

B. Waste Handling, Sorting, Storage, and Processing at the Source- Waste handling and sorting involve the activities associated with management of wastes until they are placed in storage containers for collection. Sorting of waste components is an important step in the handling and storage of solid waste at the source. As per SWM Rules, 2016, sorting and separate storage of various components of solid waste such as biodegradable wastes, non-biodegradable wastes, sanitary waste , non-recyclable inert waste, domestic hazardous wastes, and construction and demolition wastes should be done. Because of segregating waste at source ensures less contamination and can be collected and transported for further processing. Segregation of waste also minimizes waste processing and treatment cost. On-site storage is of primary importance because of public health concerns and aesthetic consideration. At the household level wet waste, dry waste and domestic hazardous waste should be stored in separate bins of appropriate capacity and colour as per SWM rules 2016.Storage bins should be placed in public places for collecting and storage of different wastes. Fig. 3 shows the different type of bins for storage and collection of waste. Horticulture waste from park sand gardens should be collected separately and treated on-site to minimise the cost of its collection and transportation (The SWM Rules, 2016).Processing at the source involves activities such as backyard waste composting.

Figure 3: Bins for Collection of Dry, Wet and Domestic Hazardous Waste at Household

C. Collection– The functional element of collection includes not only the gathering of solid wastes and recyclable materials but also the transport of these materials to the location where the collection vehicle is emptied. This location may be a material's processing facility, a transfer station, or a landfill disposal site. Fig. 4 shows the primary collection and secondary storage.

SWM Rules, 2016 suggest that it is duty of local authorities to arrange door to door collection of segregated solid waste from all households and public places, collect separately waste from sweeping of streets, lanes and by-lanes. This primary collection of segregated MSW from individual households and public places is accomplished through the use of containerised pushcarts, tricycles, small mechanised vehicles, compactors, or tipping vehicles depending on the terrain of the locality, width of streets, and building density. The waste collected by primary collection is directly transferred to secondary collection vehicles or secondary storage points which later transported. Secondary collection vehicles are parked at specific locations for the entire time during primary collection.

Figure 4: Primary Collection and Secondary Storage

D. Sorting, Processing and Transformation of Solid Waste- Sorting of mixed wastes usually occurs at a materials recovery facility, transfer stations, combustion facilities, and disposal sites. Sorting often includes the separation of bulky items, separation of waste components by size using screens, manual separation of waste components, and separation of ferrous and non-ferrous metals. Waste processing is undertaken to recover conversion products and energy. The organic fraction of Municipal Solid Waste (MSW) can be transformed by a variety of biological and thermal processes. The most commonly used biological transformation process is aerobic composting. The most commonly used thermal transformation process is incineration. Waste transformation is undertaken to reduce the volume, weight, size or toxicity of waste without resource recovery. Transformation may be done by a variety of mechanical, thermal or chemical techniques.

E Transfer and Transport- Transfer and transport involve two steps: (i) the transfer of wastes from the smaller collection vehicle to the larger transport equipment and (ii) the subsequent transport of the wastes to a processing or disposal site.

F. Disposal- The final functional element in the solid waste management system is disposal. The non-decomposable, non-combustible, non-recyclable inert portion of the solid waste is disposed to a safe disposal site. Figure 5: presents the flow chart of different functional elements of solid waste managements and their options.

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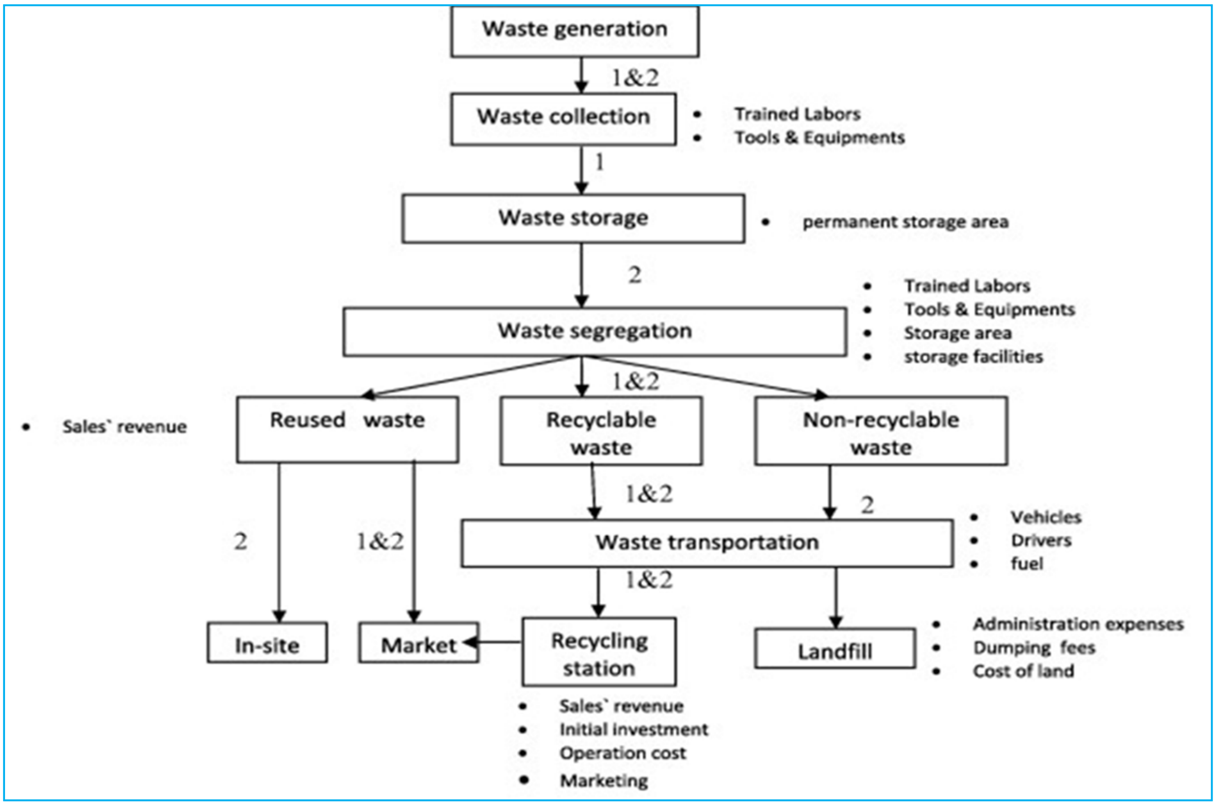


Figure 5: Flow chart of solid waste management

Principle of solid waste management

Each component of solid waste management may have different options, but we have to choose the best option to achieve environmental sustainability, economic viability, and social acceptability i.e. effective solid waste management. This can be achieved by considering solid waste management system as a whole called Integrated Solid Waste Management (ISWM). Proper municipal solid waste management (MSWM) involves the application of the principle of Integrated Solid Waste Management (ISWM) (Beukering et al., 1999; Klundert and Anschutz, 1999; CPHEEO, 2000; UNEP, 2009; UNHABITAT, 2010; ISWA, 2012).

Integrated Solid Waste Management

Integrated solid waste management (ISWM) can be defined as the selection and application of suitable techniques, technologies, and management programs to achieve specific waste management objectives and goals. The Integrated Solid Waste Management (ISWM) proposes a waste management hierarchy which help to reduce the amount of waste being disposed, while maximizing resource conservation and resource efficiency. Integrated Solid Waste Management (ISWM) is a program of waste prevention, recycling, processing and disposal. ISWM evaluate local needs and conditions, and then select the most appropriate waste management activities for those conditions. An effective ISWM system considers management of solid waste without disturbance of human health and the environment. An effective integrated solid waste management (ISWM) system depends upon the correlation between functional elements (generation, storage, collection, transportation, processing and disposal) and strategic aspects (social awareness, participation, technology, governance and financial resources). ISWM considers technical and non –technical element together. The hierarchy of ISWM is shown in fig. 6.

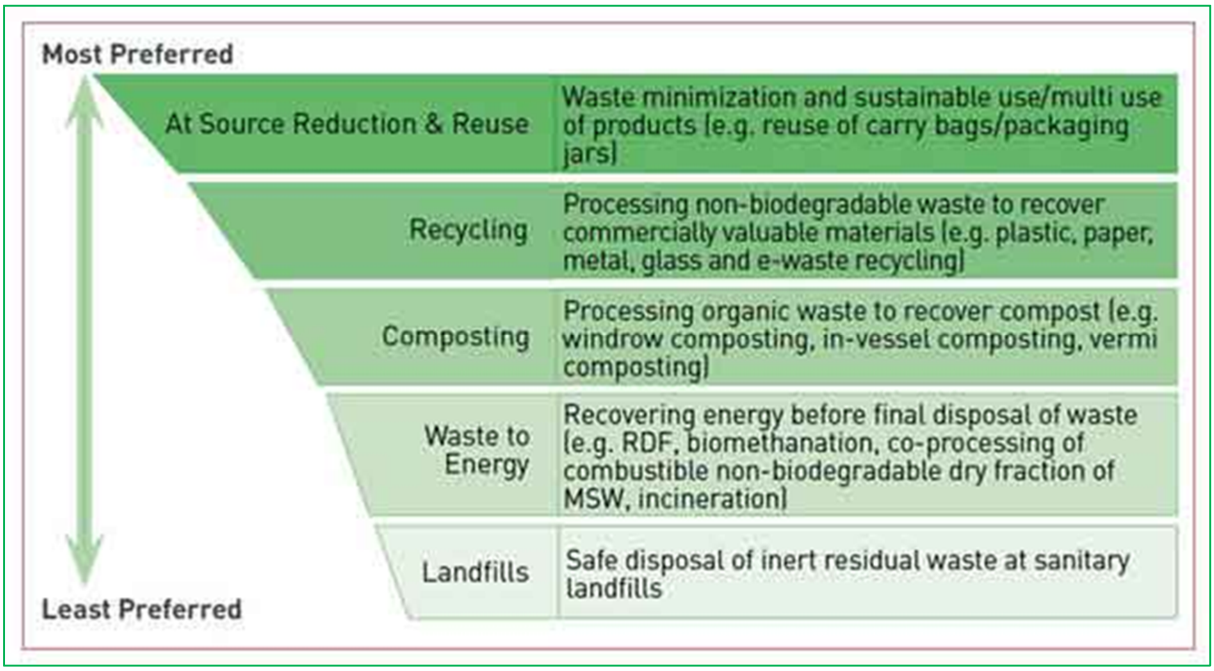


Figure 6: Waste management hierarchy (GOI manual 2016**)**

A. Source reduction and reuse: The most preferred option for waste management in the ISWM hierarchy is to prevent the generation of waste at various stages including in the design, production, packaging, use, and reuse of products. Source reduction helps on reducing the volume and/or toxicity of generated waste. Source reduction can be practiced by everybody. Waste prevention helps to reduce handling, treatment, and disposal costs and various environmental impacts such as leachate, air emissions, and generation of greenhouse gases (GHG). Minimisation of waste generation at source and reuse of products are the most preferred waste prevention strategies.

B. Waste recycling: The next preferred option for waste management in the ISWM hierarchy is recycling of waste to recover material resources through segregation, collection, and re-processing to create new products. Recycling will return raw materials to market by separating reusable products from the rest of the municipal waste stream. Recycling saves precious finite resources and reduces the need for mining of virgin materials which lowers the environmental impact for mining and processing and reduces the amount of energy consumed. Recycling can help to increase landfill capacity. Recycling can also improve the efficiency of incinerators and composting facilities by removing non-combustible materials such as metals and glass. Recycling also supports the economic condition.

C. Recovery (materials and energy): The next preferred option for waste management in the ISWM hierarchy is recovery of valuable materials through segregation and collection. Where material recovery from waste is not possible, energy recovery from waste through production of heat, electricity, or fuel is preferred. Bio-methanation, waste incineration, production of refuse derived fuel (RDF), co-processing of combustible non-biodegradable dry fraction from MSW in cement kilns and pyrolysis or gasification are some waste-to-energy technologies.

D. Waste disposal: The Residual inert wastes at the end of the hierarchy are to be disposed in sanitary lined landfills, which are constructed in accordance with stipulations prescribed in SWM Rules, 2016. As per the hierarchy, the least preferred option is the disposal of waste in open dumpsites. However, Indian laws and rules do not permit disposal of organic matter into sanitary landfills and mandate that only inert rejects from the processing facilities, inert street sweepings, etc. can be landfilled.

Rules for solid waste management

Human and animal activities lead to generation of solid waste. So, solid waste generation is a historical problem. In earlier days, the disposal of human and other wastes did not create any significant problem because the population was small and the amount of land available for assimilation of wastes was large. With the advancement of time, solid waste generation was going to increase and it create disposal problem. Requirement of proper management under suitable law was going to be essential.

Indian Penal Code, 1860, under Chapter XIV says that of offences affecting the public health, safety, convenience, decency and morals'. Since, solid waste gives rise to various form of diseases and is dangerous to public health, it has been treated as 'public nuisance' and has been made punishable. But there is no direct section in the Code which deals with the problem of solid waste (shastri et al, 2016).

Water (Prevention & Control of Pollution) Act, 1974, Air (Prevention and Control of Pollution) Act, 1981 and **Environment Protection Act, 1986** was introduced but the subject of MSW was neglected legislatively. Certain rules **like Hazardous Wastes (Management and Handling) Rules, 1989** and **Biomedical Waste (Management and handling) Rules, 1998** dealt with the solid waste management problem only tangentially.

Until 2000, India didn't even have any law concentrating on how to deal with MSW. In 1996, Supreme Court observed that "The authorities, responsible for pollution control and environment protection, have not been able to provide the clean and healthy environment to the residents of Delhi" (The capital of India is one of the most polluted cities in the world).By Supreme Court's order in the year 1998, a Committee was formed to look into all aspects of urban solid waste management. On submission of its report, the Government came up with the MSW rules and **published Municipal Solid Wastes (Management and Handling) Rules, 2000** rules under Section 5 **of Environment Protection Act, 1986.**These rules finally provided a uniform framework for the local authorities around the country on MSW management. These rules were superseded and published **Solid Waste Management Rules, 2016** in the year 2016**.** After that many rules are published for management of different type of waste.

The Batteries (Management and Handling) Rules, 2001(amended in 2010) apply to every manufacturer, importer, re-conditioner, assembler, dealer, auctioneer, consumer, and bulk consumer who involved in the manufacture, processing, sale, purchase, and use of batteries or its components to regulate and ensure the environmentally safe disposal of used batteries (http://www.moef.nic.in/legis/hsm/leadbat.html).

Plastic Waste (Management and Handling) Rules, 2011 mainly specify the minimum thickness of plastic bags as to be of 40 microns as opposed to the previous 20 microns specified by Plastics Rules, 1999. These rules do not allow the carry bags for consumers, co-retailers at free of cost. As per these rules, use of recycled or compostable plastics for storing, carrying or packing foodstuffs is prohibited (http://www.moef.nic.in/legis/hsm/plastic.html). In the year 2016, **Plastic Waste Management Rules, 2016** was published (supersession of 2011 rules).

E-waste (Management and Handling) Rules, 2011was published for management of electronics wastes and after supersession it published as E-Waste (Management) Rules, 2016.

Hazardous and Other Wastes (Management and Trans-boundary Movement) Rules, 2016 for management of hazardous waste was published in supersession of **Hazardous Wastes (Management, Handling, and Trans-boundary Movement) Rules, 2008** (amended on 21st July 2009, 23rd September 2009, 30th March 2010 and 13th August 2010)).

Construction & Demolition Waste Management Rules, 2016was published for management of construction and demolition waste.

Bio-medical Waste Management Rules, 2016was published for management of bio-medical waste in supersession of **Biomedical Waste (Management and handling) Rules, 1998.**

2.5 Disposal of municipal solid waste

The safe and reliable disposal of municipal solid waste (MSW) and solid waste residues is an important component of integrated solid waste management. Landfill is a best option for disposal of the waste and waste residues. Engineered landfill is most preferred option from environmental consideration.

Landfill is a physical facilities used for the disposal of solid wastes and solid waste residuals in the surface soils of the earth. Solid waste residues are waste components that are not recycled, that remain after processing at a materials recovery facility, or that remain after the recovery of conversion products or that remain after the recovery of energy, are required to dispose in a landfill. The use of landfills has been the most economical and environmentally acceptable method for the disposal of solid wastes throughout the world.

2.5.1 Components of engineered landfill

The essential components of a landfill are –

1. **A liner system at the base and sides of the landfill –** It prevents migration of leachate or gas to the surrounding. Liners usually consist of successive layers of compacted clay or geo-synthetic materials or both.

2. A leachate collection and control facility- It collects and extracts leachate from the base of the landfill and from within the landfill and then treats the leachate.

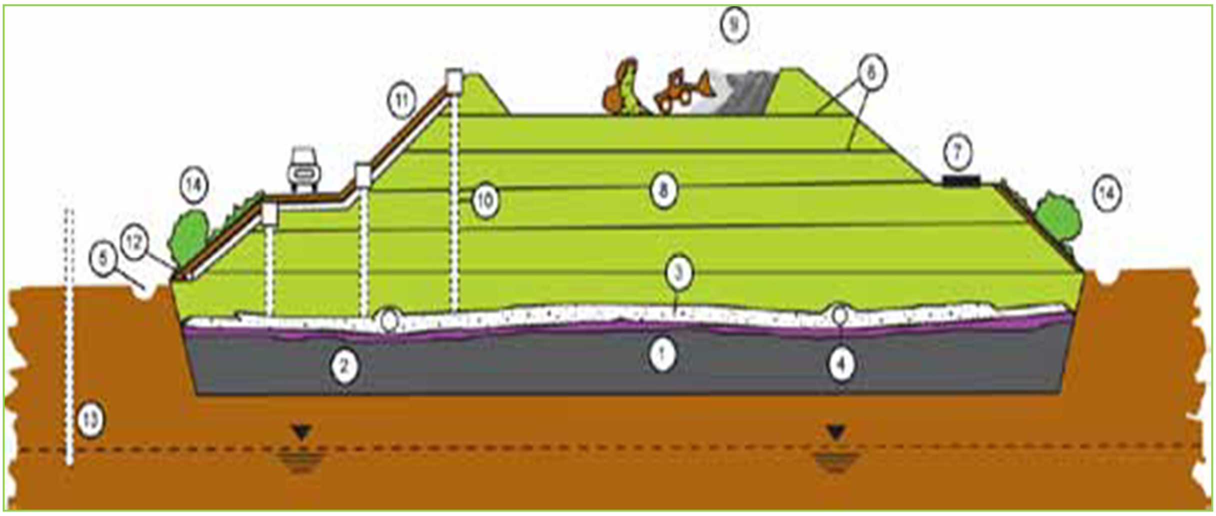
3. **A gas collection and control facility -** It collects and extracts gas from the top of the landfill and from within the landfill and then treats it or use it for energy recovery.

4. **A final cover system** – It is provided at the top of the landfill to enhance surface drainage, to prevent infiltration of rain water and supports surface vegetation. It consists of successive layers of compacted clay or geo-synthetic materials.

5. A **surface water drainage system -** It collects and removes all surface runoff from the landfill site.

6. **An environmental monitoring system-** It periodically collects and analyses air, surface water, ground water and soil-gas around the landfill.

A closure and post-closure plan must be taken to close and secure a landfill site once the filling operation has been completed and the activities for long term monitoring, operation and maintenance of the completed landfill. Figure 7: presents a typical section of an engineered landfill.



1. Geological barrier
2. Impermeable base liner
3. Drainage layer
4. Leachate collection system
5. Storm - water drain ditch
6. Bordering dams
7. Circulation roads
8. Landfill body
9. Filling and compacting in layers
10. Gas venting system
11. Protective cover system
12. Gas collectors
13. Groundwater control
14. Re-planting

Figure 7: Section of Typical Engineered Landfill

2.5.2 Layout of an engineered landfill

A landfill site will comprise of the area in which the waste will be filled as well as additional area for support facilities. It is recommended that for each landfill site, a layout be designed incorporating all the facilities given below. Figure 8 shows the layout of an engineered landfill.

1. Access roads
2. Equipment and employee shelters
3. Platform Scales
4. Office space
5. Location of convenience transfer station and recycling area
6. Storage and disposal sites for special wastes
7. Identification of areas to be used for waste processing (e.g., composting)
8. Definition of the landfill areas and areas for stockpiling cover material
9. Drainage facilities
10. Location of landfill gas management facilities
11. Location of leachate treatment facilities
14. Location of monitoring wells
13. Placement of barrier berms or structures to limit sight lines into the landfill
14. Plantings

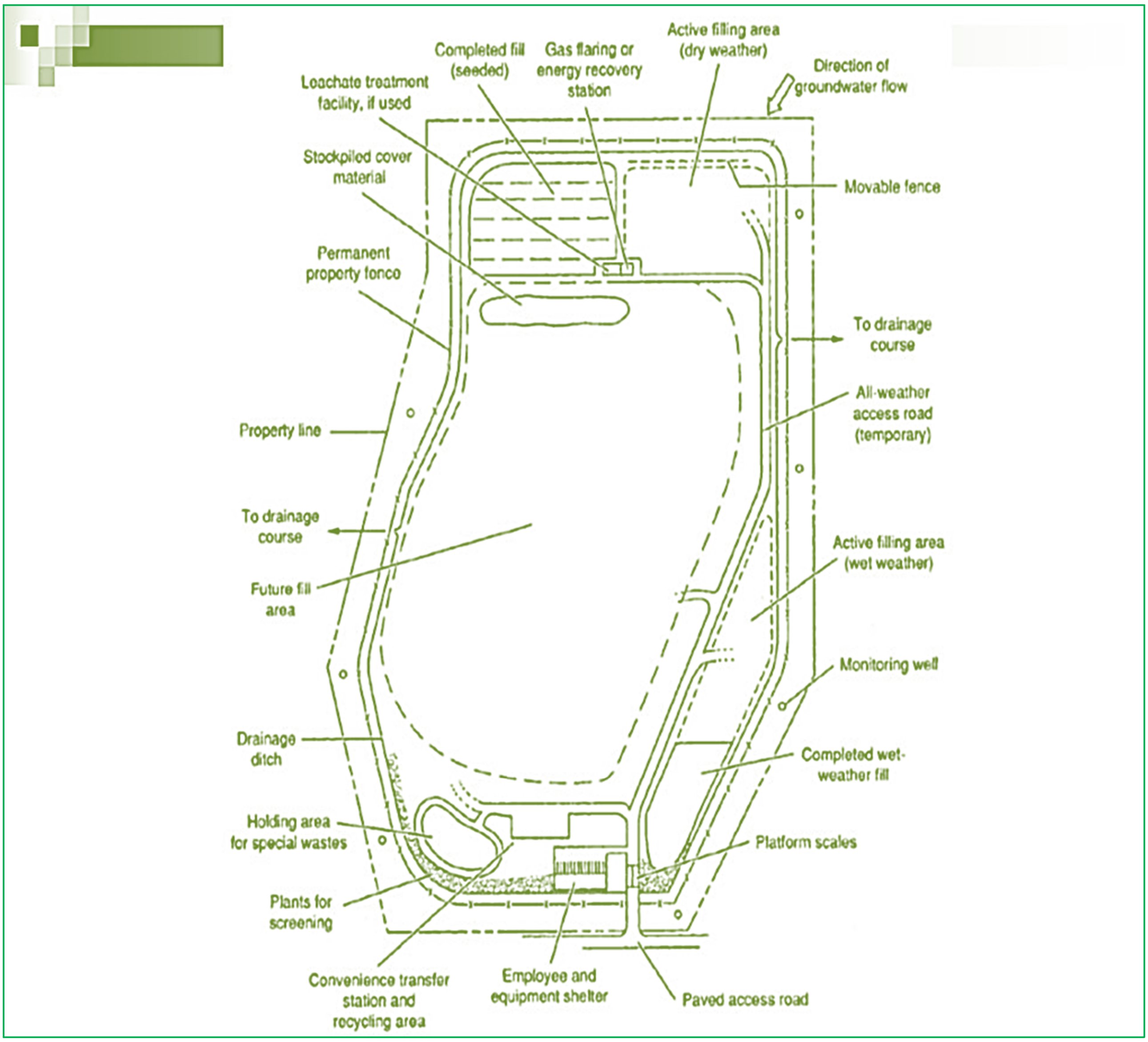


Figure 8: Typical layout of landfill site

2.5.3 Landfilling methods

The principal methods used for the landfilling of MSW may be classified as

1) Area landfill
2) Trench landfill
3) Slope landfill
4) Valley landfill

Area landfill: The area method is used when the terrain is unsuitable for the excavation of cells or trenches in which to place the solid wastes due to high groundwater conditions. Site preparation includes the installation of a liner and leachate management system. The filling operation usually is started by building an earthen levee against which wastes are placed in thin layers and compacted. At the end of each day's operation a layer of cover material is placed over the compacted fill. Cover material must be hauled in by truck or earthmoving equipment from adjacent land or from borrow-pit areas. A final layer of cover materials is used when the fill reaches the final design height.

Trench landfill: The trench method of landfilling is ideally suited to areas where an adequate depth of cover material is available at the site and where the water table is not near the surface. Typically, solid wastes are placed in cells or trenches excavated in the soil. The soil excavated from the site is used for daily and final cover. The excavated cells or trenches are lined with synthetic membrane liners, low-permeability clay, or a combination of the two to limit the movement of both landfill gases and leachate. These landfills are constructed below the naturally occurring groundwater table surface. Drainage systems control the entry of groundwater into the landfill cell.

Valley landfill: In this method the waste is placed in Canyons, ravines, dry borrow pits, and quarries. The techniques to place and compact solid wastes in canyon/depression landfills vary with the geometry of the site, the characteristics of the available cover material, the hydrology and geology of the site, the type of leachate and gas control facilities to be used, and the access to the site. Control of surface drainage often is a critical factor in the development of canyon/depression sites. Typically, filling starts at the head end of the canyon and ends at the mouth, so as to prevent the accumulation of water behind the landfill.

Slope landfill: In hilly regions it is usually not possible to find flat ground for landfilling. Slope landfills and valley landfills have to be adopted. In a slope landfill, waste is placed along the sides of existing hill slope. Control of inflowing water from hillside slopes is a critical factor in design of such landfills.

2.5.4 Phases of landfill

A landfill is operated in phases because it allows the progressive use of the landfill area, such that at any given time a part of the site may have a final cover, a part being actively filled, a part being prepared to receive waste, and a part undisturbed. A phase is a sub-area of landfill. A phase consists of cells, lifts, daily cover, intermediate cover, liner and leachate collection facility, gas control facility and final cover over the sub-area. Each phase is typically designed for a period of 12 months. Phases are generally filled from the base to the final or intermediate cover. It must be ensured that each phase reaches the final cover level at the end of its construction period and it must be capped. The final cover layer is applied to the entire landfill surface of the phase after all landfilling operations are complete.

Figure 9: Different phases of a landfill site

2.5.5 Daily, Intermediate and final landfill cover

Daily cover is given to the layer of compressed soil or earth which is laid on top of a day's deposition of solid waste on an operational landfill site. The cover helps to prevent the interaction between the waste and the air. Thus it prevents windblown litter and odours, pest attraction, fire hazard and improves the site’s visual appearance. It also helps in leachate management by reducing infiltration.

Intermediate cover layers are used to cover the wastes placed each day to enhance the aesthetic appearance of the landfill site, to limit the amount of surface infiltration. The greatest amount of water that enters a landfill and ultimately becomes leachate enters during the period when the landfill is being filled. Some of the water, in the form of rain and snow, enters while the wastes are being placed in the landfill. Water also enters the landfill by first infiltrating and subsequently percolating through the intermediate landfill cover. Thus, the materials and method of placement of the intermediate cover can limit the amount of surface water that enters the landfill. The types of materials that have been used as intermediate landfill cover include a variety of native soils, composted MSW, composted yard waste, yard waste mulch, agricultural residues, old carpets, synthetic foam, geo-membranes and construction and demolition waste.

The primary purposes of the final landfill cover are-
(1) To minimize the infiltration of water from rainfall and snowfall after the landfill has been completed.
(2) To limit the uncontrolled release of landfill gases.
(3) To suppress the proliferation of vectors.
(4) To limit the potential for fires.
(5) To provide a suitable surface for the re-vegetation of the site
(6) To serve as the central element in the reclamation of the site.

A landfill cover is made up of a series of layers, each of which has a special function. The sub-base soil layer is used to contour the surface of the landfill and to serve as a sub-base for the barrier layer. A gas collection layer is placed below the soil layer to transport landfill gas to gas management facilities. The barrier layer is used to restrict the movement of liquids into the landfill and the release of landfill gas through the cover. The drainage layer is used to transport rainwater and snowmelt that percolates through the cover material away from the barrier layer and to reduce the water pressure on the barrier layer. The protective layer is used to protect the drainage and barrier layers. The surface layer is used to contour the surface of the landfill and to support the plants that will be used in the long-term closure design of the landfill.

If the cover materials are saturated, a thin layer of water is maintained on the surface and there is no resistance to flow below the cover layer then certain amount of water enter the landfill. The amount of water entering the landfill will depend on local hydrological conditions, design of the landfill cover, and final slope of the cover and whether vegetation has been planted. Landfill cover designs consist of a flexible membrane liner which is designed to eliminate the percolation of rainwater or snowmelt into the waste below the landfill cover. The cover materials should resist water percolation as maximum as possible. Because, the percolating water convert to leachate and contaminate ground water, land and environment. Figure 10 shows the typical cover and liner system.

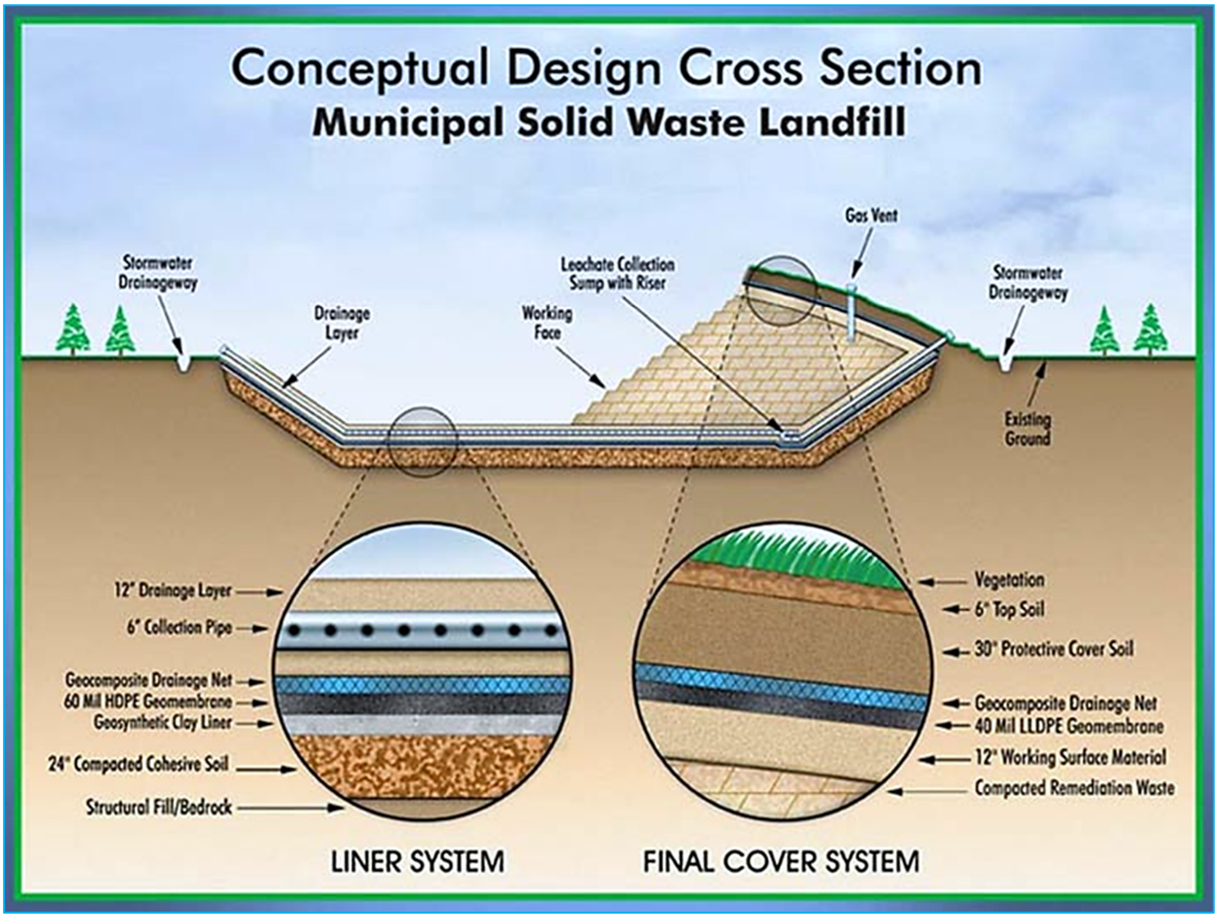


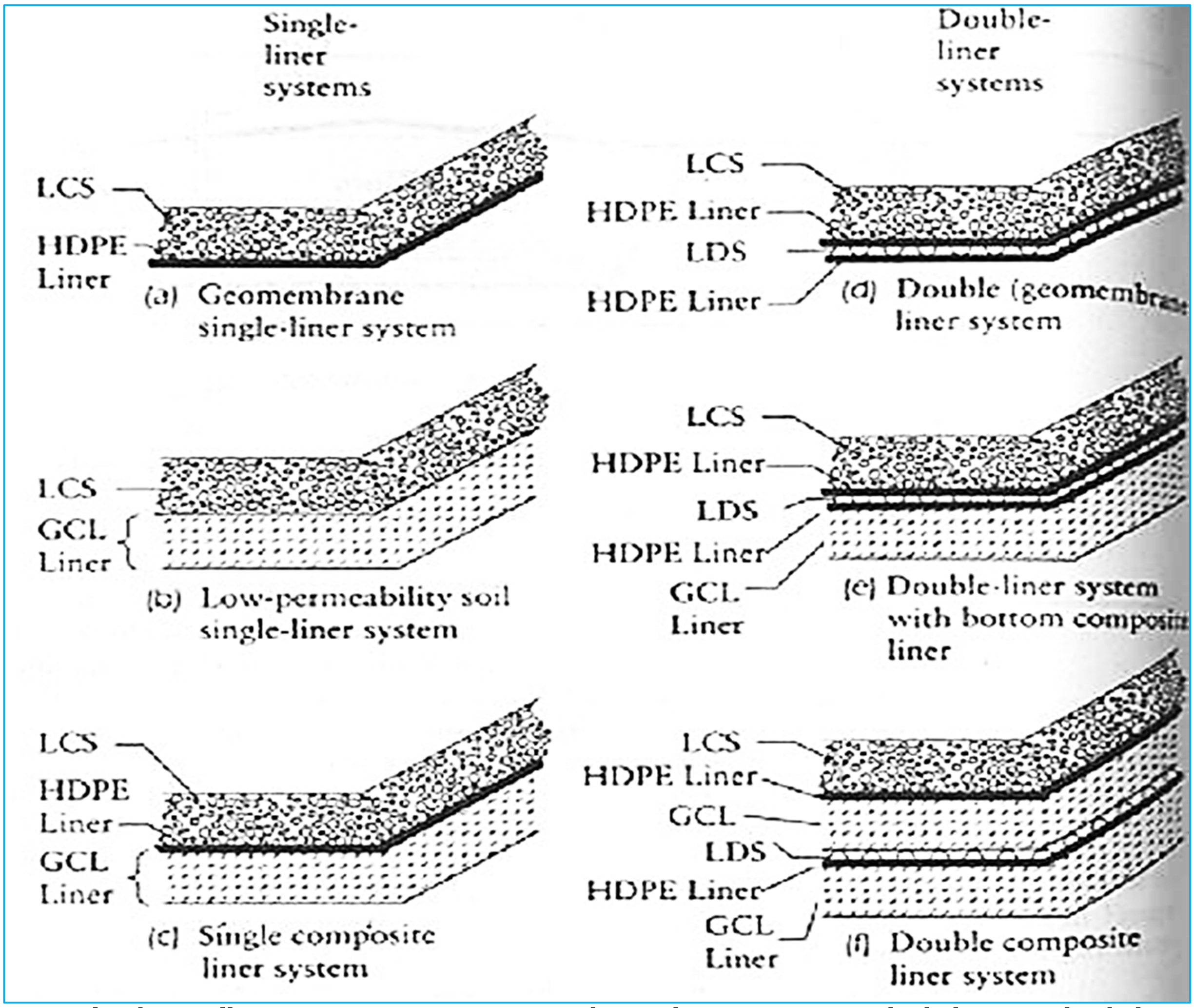
Figure 10: Typical Cover and linear system of a landfill

2.5.6 Liner system of a landfill site

The objective in the design of landfill liners is to minimize the infiltration of leachate into the subsurface soils below the landfill to substantially reduce the potential for groundwater contamination. A number of liner designs have been developed to minimize the movement of leachate into the subsurface below the landfill. In the multilayer landfill liner designs, each of the various layers has a specific function.

The clay layer and the geo-membrane serve as a composite barrier to the movement of leachate and landfill gas. The sand layer serves as a collection and drainage layer for any leachate that may be generated within the landfill. The geotextile layer is used to minimize the intermixing of the soil and sand layers. The final soil layer is used to protect the drainage and barrier layers. A liner system should have low permeability, should be strong and durable and should be resistant to chemical attack, puncture and rupture. Three types of liner systems are usually adopted (Figure 11), they are-

1. Single liner system
2. Single composite liner system
3. Double liner system



LCS: leachate collection system, GCL : Geo-synthetic Clay Liner, HDPE : high density polyethylene

Figure 11: Typical components of a liner system

2.5.7 Reactions occurring in a landfill

A solid waste landfill can be conceptualized as a biochemical reactor, with solid waste and water as the major inputs, and with landfill gas and leachate as the principal outputs. Material stored in the landfill includes partially biodegraded organic material and the other inorganic waste materials originally placed in the landfill. Solid wastes placed in a sanitary landfill undergo a number of simultaneous and interrelated biological, chemical, and physical changes.

The most important biological reactions occurring in landfills are those related to the conversion of the organic material in MSW, leading to the evolution of landfill gases and leachate.

The important chemical reactions that occur within the landfill include-

- Dissolution and suspension of landfill materials and biological conversion products in the liquid, percolating through the waste.
- Evaporation and vaporization of chemical compounds and water into the evolving landfill gas.
- Sorption of volatile and semi-volatile organic compounds into the landfilled material.

- De-halogenation and decomposition of organic compounds.
- Oxidation-reduction reactions affecting metals and the solubility of metal salts.

The important physical changes in landfills are-

- The settlement caused by consolidation and decomposition of landfilled material.
- Escape of gases from the fill.
- Movement of liquids caused by differential heads.

2.5.7.1 Biological conversion of wastes

In landfill, bacterial decomposition initially occurs under aerobic conditions because a certain amount of air is trapped within the landfill. However, the oxygen in the trapped air is soon exhausted and long term decomposition occurs under anaerobic condition.

The anaerobic conversion of organic compounds is thought to occur in three steps-

1. The first involves the enzyme-mediated transformation (liquefaction) of higher weight molecular compounds into simple compounds.
2. The second is associated with the bacterial conversion of compounds resulting from the first step into identifiable lower molecular weight compounds.
3. The third step involves the bacterial conversion of intermediate compounds into simpler end products such as CO_2 and CH_4.

The general anaerobic transformation of the organic portion of the solid waste placed in a landfill can be described by the following equation.

Organic matter + H2O + nutrients

↓ Micro-organism

New cells + resistant organic matter + CO2 + CH4 + NH3 + H2S + heat

If we assume the principal gases are CH_4, CO_2 and NH_3, the equations becomes

$$C_aH_bO_cN_d \longrightarrow nC_wH_xO_yN_z + mCH_4 + sCO_2 + rH_2O + (d - nz)NH_3$$

Where, s = (a -nw-m) and r = (c -ny- 2s). The terms $C_aH_bO_cN_d$ and $C_wH_xO_yN_z$ are used to represent the composition of the organic material present at the start and the end of the process, respectively. If it is assumed that the biodegradable portion of the organic waste is stabilized completely, the corresponding expression is

$$C_aH_bO_cN_d + \frac{4a-b-2c+3d}{4}H_2O \longrightarrow \frac{4a+b-2c-3d}{4}CH_4 + \frac{4a-b+2c+3d}{8}CO_2 + dNH_3$$

The important observation is that the reactions occur in presence of water. Landfills lacking sufficient moisture content have been found in a “mummified” condition. Hence, although the total amount of gas that will be produced from solid waste derives straight forwardly from the reaction stoichiometry, the rate and the period of time over which that gas production takes place will vary significantly with local hydrologic conditions and landfill operating procedures.

2.6 Consequences of disposal of MSW in a Landfill

The main conversion products of wastes in landfill which create hazard are –

1. Leachate
2. Landfill gas

2.6.1 Leachate

Leachate is composed of the liquid that has entered the landfill from external sources, such as surface drainage and rainfall and the liquid produced from the decomposition of the wastes. So leachate is a contaminated liquid that contains a number of dissolved and suspended materials.

Composition of leachate

The chemical composition of leachate will vary greatly depending on the age of landfill, waste composition, elapsed time, temperature, moisture, available oxygen etc. A typical data on characteristics of leachate reported by Oweis and Khera(1990),), Tchobanoglous et al. (1993) and Bagchi (1994) are presented in Table 9.

Table 9: Characteristics of leachate

Parameter	Range (mg/l)
pH	3.7-8.9
Turbidity (JTU)	30-500
Conductivity (mho/cm)	480-72500
Total suspended solids	2-170900
Total dissolved solids	725-55000
Chlorine	2-11375
Sulphate	0-1850
Hardness	300-225000
Alkalinity	0-20350
Total kjedahl nitrogen	2-3320
Sodium	2-6010
Potassium	0-3200
Calcium	3-3000
Magnesium	4-1500
Lead	0-17.2
Copper	0-9
Arsenic	0-70.2
Mercury	0-3
Cyanide	0-6
COD	50-99000
TOC	0-45000
Acetone	170-11000
Benzene	2-410
Toluene	1-1600
Chloroform	2-1300
BOD	0-195000
Total coliform bacteria	0-100
Fecal coliform bacteria	0-10
Phenol	10-28800

2.7 Landfill gas

Landfill gas is generated as a product of waste biodegradation. Initially the reactions takes place in aerobic condition but after sometime it becomes in anaerobic condition.

Generation of landfill gas

The generation of principal landfill gases is thought to takes place in five sequential phases.

- **Phase 1: Initial adjustment -** In this phase the organic biodegradable components present in municipal solid waste begin to undergo bacterial decomposition as soon as after they are placed in a landfill. Biological decomposition occurs under aerobic conditions because a certain amount of air is trapped within the landfill during landfilling operation. The principal source of both the aerobic and the anaerobic organisms responsible for waste decomposition is the soil material that is used as a daily, intermediate and final cover. If the digested wastewater treatment plant sludge is disposed of in MSW landfills, it gives the major source of microorganism. The recycled leachate is also a source of organisms.
- **Phase 2: Transition phase** - In Phase II, oxygen is depleted and the environmental condition in the landfill turn into anoxic and ultimately reach to anaerobic conditions. As the landfill becomes anaerobic, the anaerobic micro-organism participates in the decomposition of organic matter and nitrate and sulphate serve as electron acceptors in biological conversion reactions. These electron acceptors are often reduced to nitrogen gas and hydrogen sulphide. By measuring the oxidation-reduction potential, one can monitor the onset of anaerobic conditions. Reduction of nitrate and sulphate occur when the oxidation-reduction potential value near about -50 to −100 mV. The production of methane occurs when the oxidation/reduction potential values are in the range from −150 to −300 mV. As the oxidation/reduction potential continues to decrease, the organic material in MSW convert to methane and carbon dioxide with the help of microorganism through three step process. The pH of the leachate in this phase starts to drop due to the presence of organic acids and the effect of the elevated concentrations of CO_2 within the landfill.
- **Phase 3: Acid phase -**The bacterial activity initiated in Phase II is accelerated with the production of significant amounts of organic acids and lesser amounts of hydrogen gas. The first step in the three-step process involves the enzyme-mediated transformation (hydrolysis) of higher-molecular-mass compounds into compounds suitable for use by microorganisms as a source of energy and cell carbon. The second step in the process (acidogenesis) involves the bacterial conversion of the compounds resulting from the first step into lower- molecular weight intermediate compounds by fermentation such as acetic acid (CH_3COOH) and other volatile acids. In this step, very little stabilisation of BOD or COD is realised. CO_2 is the principal gas generated in this phase. Smaller amounts of hydrogen gas (H_2) will also be produced. The microorganisms involved in this conversion consist of facultative and obligate anaerobic bacteria are known as acid formers. Because of the acids produced during this phase, the pH of the liquids held within the landfill will drop. The pH of the leachate will often drop to a value of 5 or lower because of the presence of the organic acids and the effect of the elevated concentrations of CO_2 within the landfill. The biochemical oxygen demand (BOD_5), the chemical oxygen demand (COD) and the conductivity of the leachate will increase significantly during this Phase due to the dissolution of the organic acids in the leachate. Also, some inorganic constituents such as heavy metals will be solubilized during this Phase.

- **Phase 4: Methane Fermentation Phase-**In this Phase a second group of microorganisms converts the acetic acid and hydrogen gas formed by the acid formers in the acid phase to methane (CH_4) and CO_2. The bacteria responsible for this conversion are strict anaerobes and are called methanogens methane formers. In this Phase both methane and acid fermentation proceed simultaneously although the rate of acid fermentation is considerably reduced. As the acids and the hydrogen gas produced by the acid formers in phase III are converted to CH_4 and CO_2 in Phase IV, the pH within the landfill will rise to more neutral values in the range of 6.8 to 8. Hence the pH of the leachate will rise and the concentration of BOD_5 and COD and the conductivity value of the leachate will be reduced.
- **Phase 5: Maturation phase -** The maturation phase occurs after the readily available biodegradable organic material has been converted to CH_4 and CO_2 in Phase IV. The rate of landfill gas generation diminishes significantly in Phase V, because most of the available nutrients have been removed with the leachate during the previous phases and the substrates that remain in the landfill are slowly biodegradable. The principal landfill gases evolved in Phase V are CH_4 and CO_2. Depending on the landfill closure measures, small amounts of nitrogen and oxygen may also be found in the landfill gas. During the maturation phase, the leachate will often contain higher concentrations of humic and fulvic acids, which are difficult to process further biologically.

Duration of phases

The duration of the individual phases in the production of landfill gas will vary depending on the distribution of the organic components in landfill, the availability of nutrients, the moisture content of waste, moisture routing through the waste material and the degree of initial compaction (Tchobanoglous et al., 1993). The generation of landfill gas will be retarded if sufficient moisture is not available.

Increasing the density of the material placed in the landfill will decrease the availability of moisture to some parts of the waste and thus reduce the rate of bioconversion and gas production.

Variation of gas production with time

The overall rate of degradation of the organic material in a landfill also depend on the distribution of the organic components in landfill, the availability of nutrients, the moisture content of waste, the path of moisture percolate through the fill, the degree of initial compaction and the duration of phases. The rate of decomposition of mixed organic wastes deposited in a landfill is measured by gas production. The rate of gas production depends upon the rate of decomposition of organic materials. If the solid wastes consist of rapidly biodegradable organic matter, the rate of gas production is high in yearly period. If the solid wastes consist of slowly decomposable organic materials, the rate of gas production is low and the gas production continues over number of years. The variation in rate of gas production depends upon the order of reaction. The order of reaction depends upon the type of organic materials present in MSW. Generally, for mixed organic matter of MSW, the gas production in a landfill reaches a peak within the first 2 years and then slowly tapers off and continuing in many cases for periods up to 25 years or more.

Typical data on the percentage distribution of principal gases found in a newly completed landfill as a function of time are reported in Table 10 as investigated by Merz and Stone (1970) and Figure 12 shows Gas production in different phases.

Table 10: Percentage distribution of principal gases found in a newly completed landfill as a function of time

Time interval after cell completion months	Averaged percentage by volume		
	Nitrogen N_2	Carbon-di-oxide CO_2	Methane CH_4
0-3	5.2	88	5
3-6	3.8	76	21
6-12	0.4	65	29
12-18	1.1	52	40
18-24	0.4	53	47
24-30	0.2	52	48
30-36	1.3	46	51
36-42	0.9	50	47
42-48	0.4	51	48

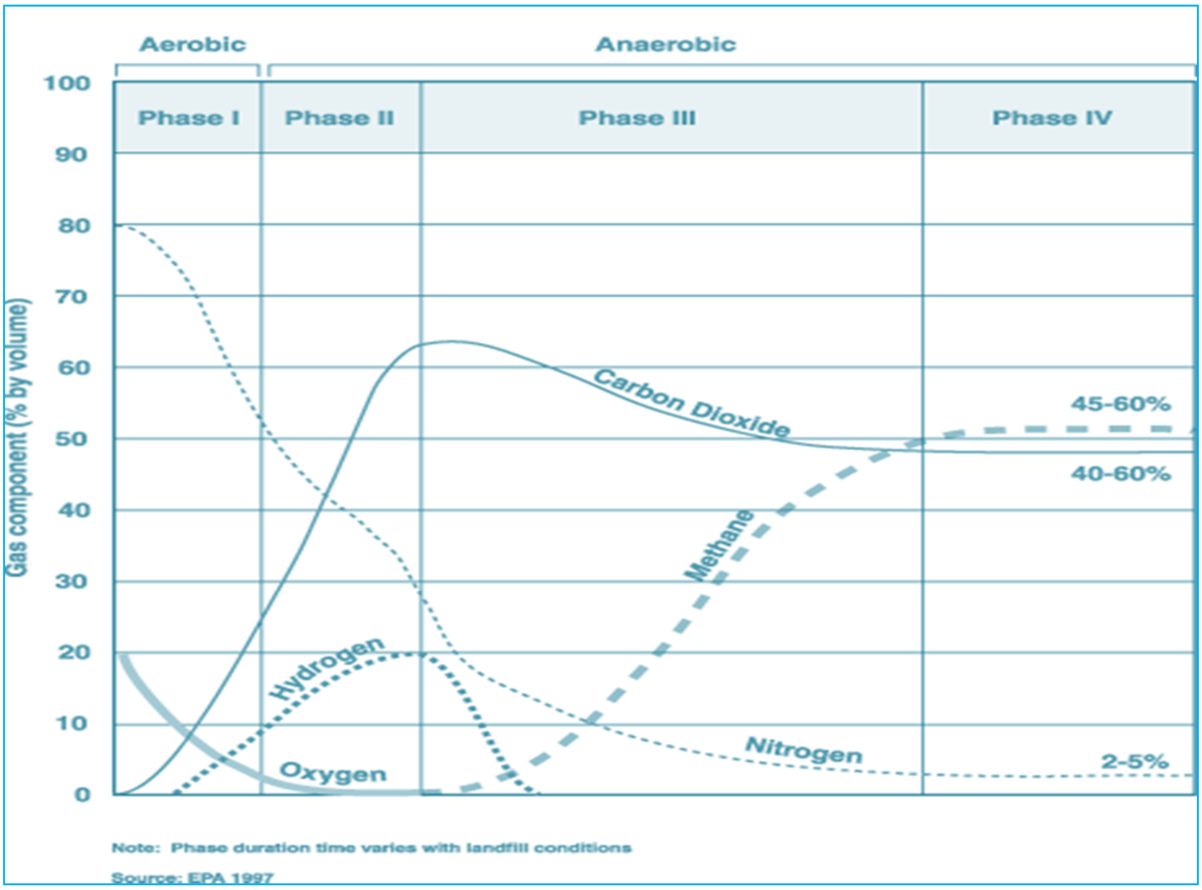


Figure 12: Generation of landfill gases in different phases

Factors affecting landfill gas production

- **Waste composition-** The more organic waste present in a landfill, the more landfill gas is produced by bacterial decomposition. If the organic waste contains all the elements required for decomposition, the landfill gas production increases. Alternatively, some wastes contain compounds that harm bacteria, causing less gas to be produced.
- **Oxygen in the Landfill-** The more oxygen present in a landfill, the longer aerobic bacteria can decompose wastes in Phase I. If waste is loosely buried or frequently disturbed more oxygen is available so that oxygen-dependent bacteria live longer and produce carbon dioxide and water for longer periods. If the waste is highly compacted methane production will begin earlier as the aerobic bacteria are replaced by methane-producing anaerobic bacteria in Phase III. Methane gas starts to be produced by the anaerobic bacteria only when the oxygen in the landfill is used up by the aerobic bacteria. Therefore any oxygen remaining in the landfill will slow methane production.
- **Temperature-** Temperature is one of the important factors that affect the decomposition of the organic materials. The activity of microorganism mostly depends on temperature. With the increase in temperature, the microbial activities also increase and increase the gas production and decrease with the decrease in temperature. Hence weather changes have a greater effect on gas production in shallow landfills.
- **Moisture Content-**The decomposition of organic materials also depends upon the moisture content in the landfill. In many landfills the available moisture is insufficient to allow for the complete conversion of the biodegradable organic constituents in the MSW. The optimum moisture content for the conversion of the biodegradable organic matter in MSW is on the order of 45 to 60 %. Also, in many landfills, the moisture that is present is not distributed uniformly. When the moisture content of the landfill is limited, the gas production curve is more flattened out and is extended over a greater period of time. The production of landfill gas over extended periods of time is of great significance with respect to the management strategy to be adopted for post-closure maintenance. The goal of leachate recirculation is to enhance the rate of gas production and thus reduce the time required to stabilize the biodegradable organic matter in the landfill. Variations in temperature, landfill cell depth, and waste density also will influence the amount of gas and timing of gas generation. Figure 13 presents the effect of moisture content on the production of the landfill gas. Figure 13 depicts more moisture content means high peak of LFG generation within small duration where less moisture means low peak of gas generation and duration of generation is more.

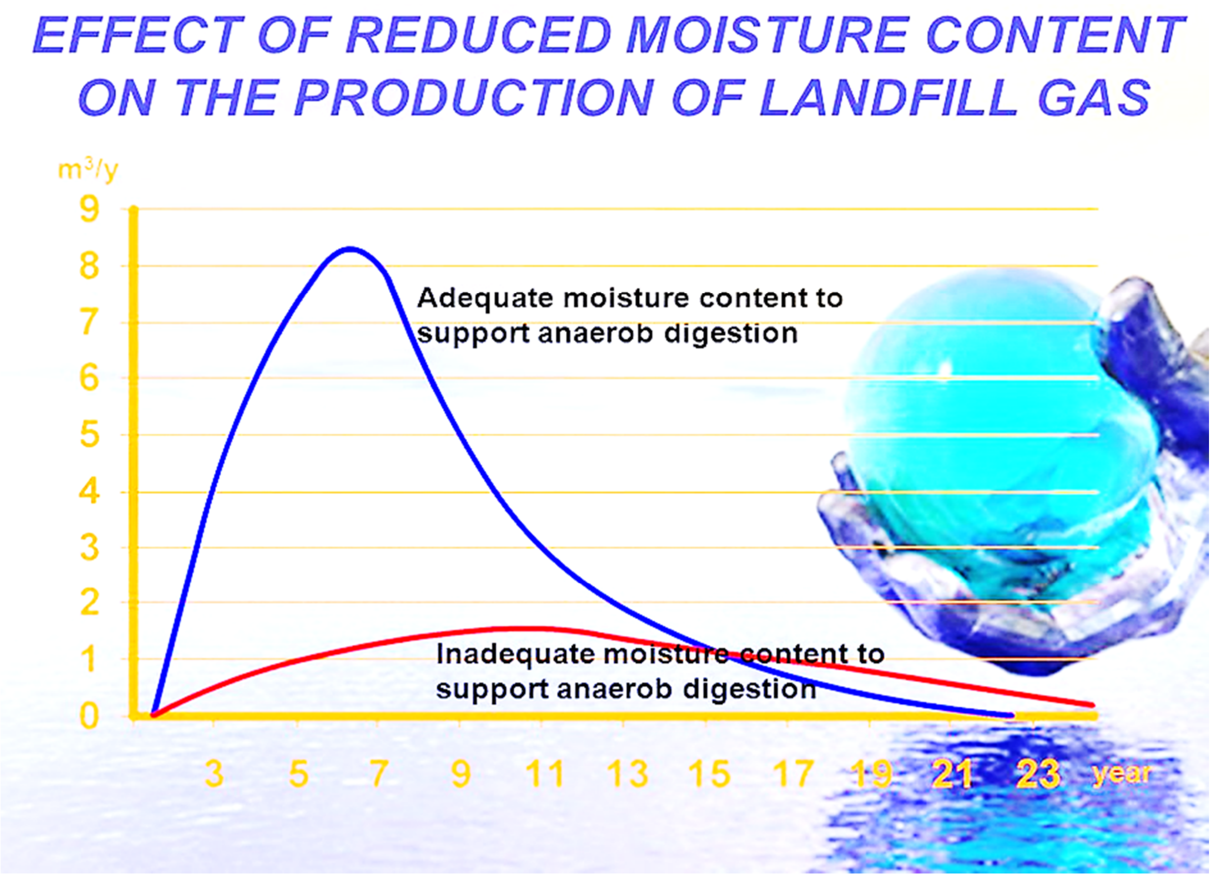


Figure 13: Effect of moisture content on production of landfill gas

2.8 Composition of landfill gas

Landfill gas comprises a number of gases. The gases that are present in large amounts are called principal gases and that are present in very small amounts are called trace gases. The principal gases are produced from the decomposition of the biodegradable organic fraction of MSW. Traces gases may be brought to the landfill with the incoming waste or they may be produced by biotic and abiotic conversion reactions occurring within the landfill.

Principal landfill gas constituents

Landfill Gases include ammonia (NH_3), carbon dioxide (CO_2), carbon monoxide (CO), hydrogen (H_2), hydrogen sulphide (H_2S), methane (CH_4), nitrogen (N_2), and oxygen (O_2). Methane and carbon dioxide are the principal gases produced from the anaerobic decomposition of the biodegradable organic waste components in MSW, because of limited amounts of oxygen are present in a landfill. Methane is a naturally occurring gas. It is colourless and odourless. Landfills are the largest source of man-made methane emissions. Carbon dioxide is naturally found at small concentrations in the atmosphere (0.03%). It is colourless, odourless and slightly acidic gas. Nitrogen comprises approximately 79% of the atmosphere. It is odourless, tasteless and colourless gas. Ammonia is a colourless gas with a pungent odour. Oxygen comprises approximately 21% of the atmosphere. It is odourless, tasteless and colourless. Hydrogen is an odourless and colourless gas. Carbon monoxide is an odourless and colourless gas.

Trace landfill gas constituents

Landfill gases contain certain amount of Volatile Organic Carbons (VOCs) which include chloroform, Benzene, Chloro-benzene, Acetone, Di-chloroethane, Di-chloromethane, Di-ethylene chloride, Ethylene bromide, Ethylene di-chloride, Ethylene oxide, Ethyl benzene, Toluene, Vinyl chloride, Tetra-chloro-ethylene, methyl ethyl ketone, Styrenes, Vinyl acetate etc. These Landfill gases can be created when certain wastes particularly organic compounds change from a liquid or a solid into a vapour. This process is known as volatilization. Table11: presents the typical composition of landfill gases.

Table 11: Typical constituents of municipal landfill gas (SWM of GOI, 2000**)**

Constituents	Range (% or concentration)
Major constituents	
Methane	30-60 %
Carbon-di-oxide	34-60 %
Nitrogen	1-21 %
Oxygen	0.1-2 %
Hydrogen sulphide	0-1 %
Carbon mono-oxide	0-0.2 %
Hydrogen	0-0.2 %
Ammonia	0.1-1 %
Trace constituents	
Acetone	0-240 ppm
Benzene	0-39 ppm
Vinyl chloride	0-44 ppm
Toluene	8-280 ppm
Chloroform	0-12 ppm
Di-chloromethane	1-620 ppm
Di-ethylene chloride	0-20 ppm
Vinyl acetate	0-240 ppm
Tri-chloro-ethane	0-13 ppm
Perchloro-ethane	0-19 ppm
Others	Variable

2.9 Movement of landfill gases

The gases produced in the landfill move in all direction i.e. upward, downward and horizontal direction. Once gases are produced under the landfill surface, they generally move away from the landfill. Gases tend to expand and fill the available space, so that they can move through the limited pore spaces within the refuse and soils covering of the landfill. The natural tendency of landfill gases that are lighter than air such as methane is to move upward through the landfill surface. Upward movement of landfill gas can be inhibited by densely compacted waste or landfill cover materials. When upward movement is inhibited, the gas tends to migrate horizontally to other areas within the landfill or to areas outside the landfill. The horizontal movement of landfill gases can transport the gases over a distance 100 to 500 m from the edge of the landfill with significant concentration. Basically the gases follow the path of least resistance. The movement of landfill gases also include the sorption of the gases into liquid or solid components and move with this liquids or solids. Three main factors influence the migration of landfill gases:

- **Diffusion (concentration) -** The natural tendency of a gas is to reach a uniform concentration in a given space. This phenomenon is known as diffusion. Due to this, gases in a landfill move from areas of high gas concentrations to areas with lower gas concentrations. Due to gas concentrations higher in the landfill than in the surrounding areas, the landfill gases diffuse out of the landfill to the surrounding areas with lower gas concentrations.
- **Pressure-** The generated gases get accumulated in a landfill and create areas of high pressure. The variation in pressure throughout the landfill results in gases moving from areas of high pressure to areas of low pressure. Movement of gases from areas of high pressure to areas of lower pressure is known as convection. With increasing the anaerobic decomposition, the gas production also increases which lead to increase in gas pressure in the landfill. As a result the movement of gas takes place over a long distance.
- **Permeability-** Gases will also migrate through the pore space available in the landfill cover and bottom of the landfill. Permeability is a measure of how well gases and liquids flow through connected spaces or pores in refuse and soils. Dry sandy soils are highly permeable while moist clay is less permeable. Gases have tendency to move through areas of high permeability rather than through areas of low permeability. Landfill covers are often made of low-permeability soils such as clay. Gases in a covered landfill move horizontally than vertically.

Due to density of CO_2, It can accumulate in the bottom of a landfill. If a clay or soil liner is used, the carbon dioxide can move downward primarily by diffusive transport through the liner and the underlying formation until it reaches the groundwater, as carbon dioxide is readily soluble in water. It usually lowers the pH of ground water and increase the hardness and mineral content in the groundwater through solubilisation.

The traces organic compounds present in the landfill gases can move through the non-saturated zone of the soil profile and may go into solution when they contact with water. This could occur either by infiltration of rainfall through the soil profile or increase in groundwater table. The trace organics from landfill gas is a source of significant groundwater contamination. This complicates the monitoring of groundwater quality.

2.10 Scenario of landfill gas emission

Global scenario

In a span of 260 years, from 1750 (beginning of urbanization) to 2010, the concentration of GHG CH_4 in the environment has increased from 700 ppb to 1808 ppb (Stocker, T. (Ed.) Climate change 2013) and atmospheric methane concentration has been increasing in the range of 1–2% per year (IPCC, 2007a). The CH_4 emissions from MSW landfill increase from 16.50 Tg in 1970 to 29.50 Tg in 2008 (JRC and PBL, 2012). Global greenhouse gas emissions in 2005 from waste based on reported emissions from national inventories and national communications, and on 1996 inventory guidelines and extrapolations was 750 Mt CO_2-eq (US EPA, 2006). According to the IPCC Fourth Assessment Report (IPCC, 2007b), the total CH_4 emissions accounted for 14.3% of the global GHG emissions in 2004. Methane emission from landfill is estimated to account for 3–19% of the anthropogenic sources in the world (IPCC, 1996). Figure 14 shows the global participation in increasing CH_4 concentration from many sources in 2000. Of these activities, solid waste landfilling is recognized as one of the major sources of anthropogenic CH_4 emissions. Landfills worldwide are responsible for more than

10% of the total anthropogenic methane emissions (Al-Ghazawi and Abdulla, 2008; Zhu et al., 2013; Tercan et al.,2015).

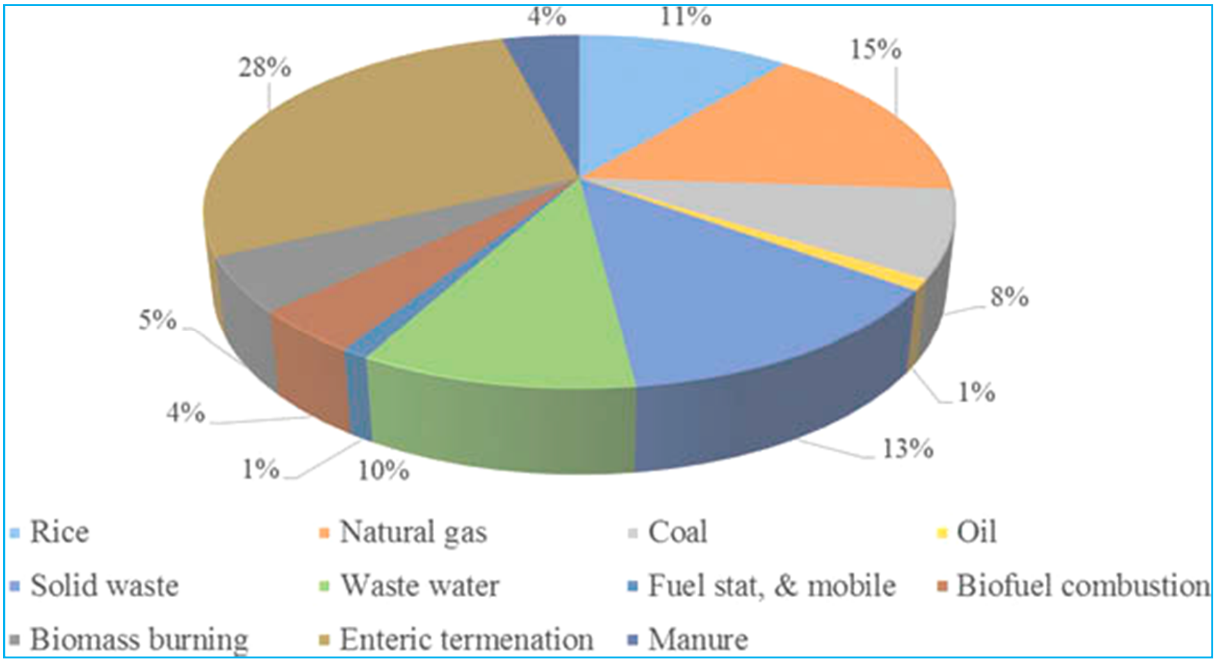


Figure 14: Global anthropogenic CH_4 in 2000 (Themelis and Ulloa, 2007**).**

Global CH_4 emissions estimates from landfill have ranged from 9 to 70 Tg per year (Bingemer and Crutzen, 1987, Richards, 1989).In 2012, U.S landfills emitted around 5 Tg of methane (USEPA, 2014). The greenhouse gas emissions from paper in Australia in 1999/2000 were estimated to be 12.1 million tonnes (Mt) of CO_2 equivalent. In 2005, CH_4 and CO_2 emission from Kahrizak, Karaj and Shiraz (Iran) landfill sites were 7.66×10^4 Ton/year and 1.34×10^5 Ton/year, 1.34×10^5 Ton/year and 2.36×10^5 Ton/year, and 7.358×10^3 Ton/year and 3.81×10^4 ton/year, respectively (Atabi et al 2014). Heijo Scharff et al. show that GHG emission from MSW landfill systems are 1000 kg CO_2-eq. tone^{-1} for open dump and 300 kg CO_2-eq. tone^{-1} for conventional landfill. The atmospheric CH_4 burden grew by a rate of 25–40 Tg/yr in the 1980s (1 Tg = 10^{12} g) and at a slower rate of less than 20 Tg/yr during the 1990s (Dlugokencky et al., 2001). Results from a limited number of whole landfill CH_4 emissions measurements in Europe, the United States and South Africa exhibit CH_4 emission vary from 0.1 to1.0 tonnes CH_4 /ha/d (equivalent to 0.03 to 0.3 g CH_4/m^2 /d) (Nozhevnikova et al., 1993; Hovde et al., 1995; Borjesson, 1996; Czepiel et al., 1996b; Mosher et al., 1999; Tregoures et al., 1999; Galle et al., 2001; Morris, 2001). The maximum and minimum global CH_4emissions are 30–70 Tg CH_4/yr (Bingemer and Crutzen, 1987) and 9–18 Tg CH_4/yr (Richards, 1989) respectively. In 1990, Nakicenovic et al. estimated that combined emission for landfill and sewage sources vary from 51-62 Tg (Special Report on Emissions Scenarios, Intergovernmental Panel on Climate Change (IPCC)). In 1994, global CH_4 emission was 40.3 Tg (Stern and Kaufmann, 1998). According to an estimate by Global Methane Initiative, the concentration of CH_4 is expected to be 8.59 Gt CO_2-eq by 2020 and was recorded as 6.88 Gt CO_2-eq in 2010 (GMI, 2012). In 1995, CH_4 emission was 43 Tg (Meadows etal.1996). Figure 15: shows the global landfill methane emission trend.

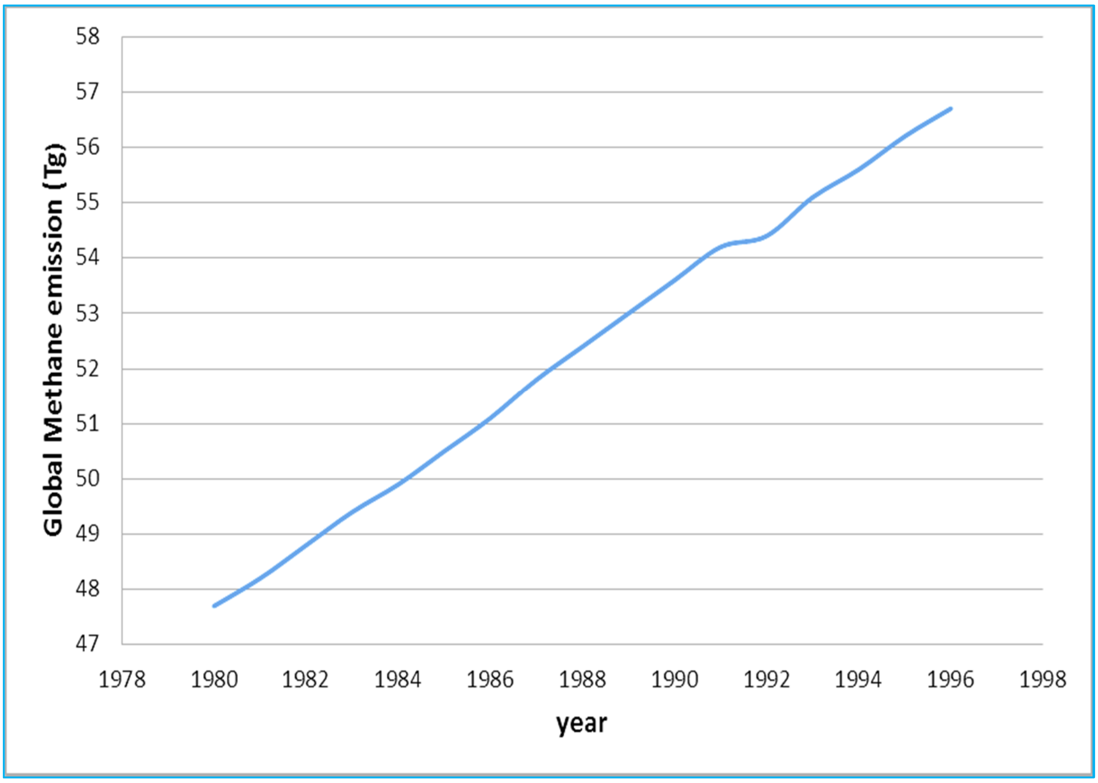


Figure 15: Global landfill CH_4 emissions trend (Tg) (Matthews et al, 2003)

Indian scenario

India is one of the world's largest emitter of CH_4 from landfills, currently produces about 16 tons of CO_2 equivalent per year which is predicted to increase to almost 20 tons of CO_2 equivalent per year by 2020 (Singh and Singh,1998). CH_4 alone constitutes about 29% of the total GHG emissions in India which is nearly twice the worldwide average of 15%. The total methane emissions from Indian landfills carried out by National Environmental Engineering Research Institute (NEERI), worked out to be 0.334 Tg /yr during 1990–1991 (Bhattacharya and Mitra, 1998). In 2000, methane emission from Kodungaiyur and Perungudi (Chennai) landfill sites were 8.1 Gg and 9.8 Gg respectively (Singh et al., 2008). In 2014, landfill gas emission from Ghazipur, Bhalswa and Okhla (Delhi) landfill sites were 123Gg, 110 Gg and 86 Gg respectively (Chakraborty et al 2013). The CH_4 emission from the same landfill sites was 31.06 Gg/yr and 65.16 Gg/yr in the year 2000 and 2015 respectively (Singh et al., 2017). CH_4 emission rate from Punki open dump site, Kanpur was 25.14 Gg/year (Kushal et al., 2015). In 2016, CH_4 emission rate from landfills of north east India was 68 mg/min/m^2 (Gollapalli et al, 2018). Figure 16 shows the methane emission from landfill sites of India in different year. Table 12 shows the CH_4 emission from different metro city of India during 2001- 2020. Table13 represent status of LFG emission at different state of India.

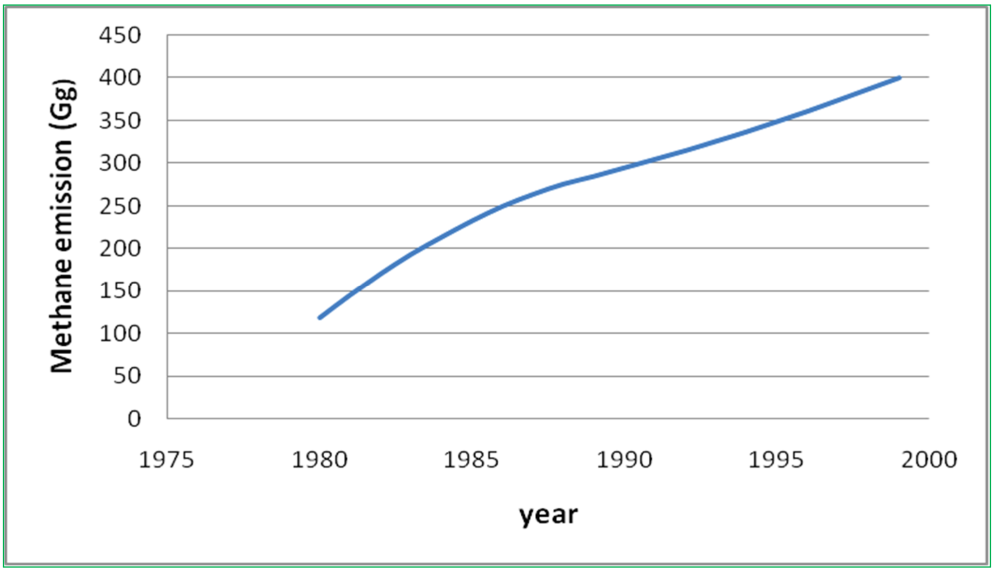


Figure 16: Landfill CH_4 emission from Indian landfill sites (Kumar et al 2004)

Table 12: CH_4 emission from different metro city through dumping of MSW in 20 year duration (2001-2020**)** (Kumar and Sharma 2014)

Name of metro city	**CH_4 emission (Gg)**
Ahmedabad	155.21
Bengaluru	163.78
Bhopal	47.61
Mumbai	6049.25
Kolkata	406.12
Coimbatore	17.08
Delhi	197.40
Hyderabad	93.61
Indore	24.66
Jaipur	37.47
Kanpur	54.49
Kochi	42.74
Lucknow	69.66
Ludhiana	22.58
Chennai	361.45
Madurai	23.96
Nagpur	26
Patna	27.9
Pune	56.18
Surat	55.41
Vadodara	18.96
Varanasi	33.32
Visakhapatnam	16.71

Table 13: Greenhouse gas emission from landfill in India from different states

Year 1999-2000		Year 2009-10		Year 2014-15	
States	CH_4 Emission Gg	States	CH_4 Emission Gg	States	CH_4 Emission Gg
Maharashtra	70.67	Maharashtra	149.16	Maharashtra	208.32
Uttar Pradesh	46.29	Uttar Pradesh	97.53	Uttar Pradesh	148.97
Tamil Nadu	41.97	Tamil Nadu	97.12	Tamil Nadu	112.87
West Bengal	35.89	West Bengal	89.98	West Bengal	89.32
Andhra Pradesh	33.99	Andhra Pradesh	89.32	Andhra Pradesh	71.67

Source: (Singh et al. 2017**)**

From Table 13, it is seen that methane emission increases for all the states except Andhra Pradesh. Presently, in India almost entire amount of methane generated in disposal site is directly entered into the atmosphere. As methane is a GHG of high global warming potential (GWP), it traps more amount of thermal radiation emitted from earth surface. As a result atmospheric temperature increases rapidly and different undesirable effect of global warming takes place. If necessary mitigation measures are not taken against the increasing trends of methane emission, it may destroy the environment. So management of LFG is necessary. Again management system should be sustainable with respect to environment and economy. To develop sustainable management, it is necessary to know the amount of methane generated from the disposal site. The amount of methane generation can be calculated either experimentally or by using any suitable model.

2.11 Review of available models on GHG emission from MSW

The rate of gas production in landfill can be estimated by modelling. The gas production in landfill depends on the rate of decomposition of the organic matter. The decomposition of the organic materials depends on the order of the reaction takes place in the landfill. As the MSW consist of different types of organic materials, the order of the reaction in the landfill is difficult to identify. Based on the order of the reaction, different types of models are developed. The models are-

1. Zero order models
    - Germany EPER model (Jash et al. 2016; Das et al. 2016)
    - SWANA zero order model (SWANA, 1998)
    - IPCC Default Methodology (Kumar et al. 2004; Chakrabarty et al. 2011)
2. First order models
    - TNO model (Jash et al. 2016; Das et al. 2016)
    - IPCC model (Kushal et al. 2016;Chattopadhyay et al. 2018)
    - LandGEM model (Kumar et al. 2014; jash et al. 2016)
    - GasSim Multiphase model (Scheepers and van Zanten, 1994)
    - Afvalzorg Multiphase model (Shariatmadari et al. 2007; Jash et al. 2016)
    - EPER France model (Scharff and Jacob, 2006)
    - Mexico model (Stege and Murray, 2003)
    - LFGGEN model (Reinhart and Faour, 2004)
    - Tabasaran & Rettenberger model (Sarptaş et al. 2012)
    - SWANA model (SWANA, 1998)

- Modified Triangular Method (Mor et al 2006; Gollapalli et al. 2018)

3. Complex mathematical models
    - Halvadakis model (El-Fadel et al. 1989)
4. Numerical method (Afshar, 2002)

Many Indian researchers (Kumar et al.2004, Mor et al., 2006, Jha et al.2007, Chakraborty et al., 2011, 2013, Kumar and Sharma 2013, Kumar and Sharma 2014, Singh et al. 2016, Das et al., 2016, Kushal et al., 2016, Jash et al., 2016, Chander et al. 2017, Chattopadhyay et al. 2018, Gollapalli et al. 2018) used IPCC DM, IPCC FOD, LandGEM, MTM, TM, EPER Germany, TNO, Multiphase model to estimate landfill gas emission from MSW landfill sites and the results obtained from the models compared with the result obtained from the Flux chamber method. It is concluded that IPCC FOD and LandGEM give more realistic result in Indian condition than other models. Kumar el al. 2004 concluded that triangular method is more realistic method than default method.

FOD models are widely used models. FOD models require different parameters like methane generation rate constant (k) of MSW, potential methane generation capacity (L_0) of MSW, degradable organic carbon (DOC) present in the waste, physical and chemical composition of the waste, amount of waste generated and age of the waste etc. For application of FOD models, it is required to determine the value of the following parameters. Methane generation rate constant depends on mainly rainfall, temperature, type of waste, pH of waste etc. L_0 and DOC values mainly depend on type of waste and composition of waste. The details description about the model parameters are given in methodology section.

2.12 Review of works on GHG emission from MSW

Sl. No	Reference	Methodology Adopted	Paper Title	Main Findings
1	De La cruz and Barlaz 2010	linear regression	Estimation of Waste Component-Specific Landfill Decay Rates Using Laboratory-Scale Decomposition Data	• Estimation of field-scale decay rates (k_{field}) for each waste component using laboratory-scale rate constants (k_{lab}) for the major biodegradable MSW components and the assumption that the average of the field-scale decay rates for each waste component, weighted by its composition, is equal to the bulk MSW decay rate.
2	Weitz et al. 2012	IPCC FOD And DM	Estimated National Landfill Methane Emissions: An Application of the 2006 Intergovernmental Panel on Climate Change Waste Model in Panama	• Estimation of national methane emissions from solid waste disposal sites in Panama over the time period 1990–2020 using both the IPCC (2006) FOD Waste Model and the default emissions estimate approach resented in the 1996 IPCC DM Guidelines.
3	Amini et al. 2012	linear regression	Determination of first-order landfill gas modelling parameters and uncertainties	• Evaluation of LFG generation model parameters (k, L_0) using (1) fixed AP-42 default parameters, (2) calculated L_0-variable k, and (3) simultaneously variable L_0 and k approaches. • It is concluded that the k value can be

				selected by model fitting and regression using the first-order model if LFG collection data are available. When such data are not available, k can be selected from technical literature, based on site conditions.
4	Mou et al. 2014	Experimental method	Evaluating the methane generation rate constant (k) of low-organic waste at Danish landfills	• Recorded methane generation from different waste samples under anaerobic degradation in experimental set up • Applying gas generation data and FOD equations calculated half-life time values and k values of various waste categories • k values obtained from the experiment are compared with the default k values in FOD models and it is seen that experimental k values are lower than model k values.
5	Karanjekar et al. 2015	Experimental method	Estimating methane emissions from landfills based on rainfall, ambient temperature, and waste composition	• Methane generation was measured from 27 laboratory scale landfill reactors, with varying waste compositions (ranging from 0% to 100%); average rainfall rates of 2, 6, and 12 mm/day; and temperatures of 20, 30, and 37 ºC. • Based on the data collected, a multiple linear regression equation was developed to predict first-order methane generation rate constant values k as functions of waste composition, annual rainfall, and temperature. • The Capturing Landfill Emissions for Energy Needs (CLEEN) model was developed by incorporating both regression equations into the first-order decay based model for estimating methane generation rates from landfills.
6	Wang and Barlaz 2016	Experimental method	Decomposition and carbon storage of hardwood and softwood branches in laboratory-scale landfills	• Measurement of methane (CH_4) yields, decay rates, the decomposition of cellulose, hemicellulose and organic carbon, as well as carbon storage factors (CSFs). • Characterization of anaerobic biodegradability of hardwood (HW) and softwood (SW) branches under simulated but optimized landfill conditions
7	Lee et al. 2018		Methods for determining the methane generation potential and ethane generation rate	• Summarize the literature on the measurement of L_0 and k values, including the dynamics and decomposition of bulk MSW and individual waste components within

			constant for the FOD model: a review	landfills. • k value has been determined by precipitation rates, laboratory simulations, aged-defined waste sample, and model fitting or regression analysis using actual gas data. • L_0 values have been derived from theoretical stoichiometric calculations, laboratory experiments, or actual field measurements.
8	Hazra et al. 2009		Solid waste management in Kolkata, India: Practices and challenges	• Overview of current solid waste management (SWM) practices in Kolkata, India and suggests solutions to some of the major problems.
9	Chattopadhyay et al. 2009		Municipal solid waste management in Kolkata, India – a review	• Overview of current solid waste management (SWM) practices in Kolkata, India and suggests solutions to some of the major problems.

2.13 Review of works on GHG emission from MSW in India

Sl. No	Reference	Methodology Adopted	Paper Title	Main Findings
1	Kumar et al. 2004	DM and TM	Estimation of CH_4 emission from MSW landfills of India	• Estimation of CH_4 emission from landfill sites of India using DM and TM • Results obtained using DM and TM are compared and it is found that TM is more realistic
2	Mor et al. 2006	FOD and MTM	Estimation of CH_4 emission from Ghazipur landfill, Delhi	• The waste composition data obtained by drilling the landfill site up to 9 m is used to estimate CH_4 generation potential by FOD and MTM. • Comparison of results from both the model showed that both can be used for such estimation.
3	Jha et al. 2007	IPCC, FOD and Chamber method	Estimation of GHG emission from landfill sites of Chennai	• Estimation of GHG emission potential using chamber method and FOD model for landfill sites of Chennai • It is found that MSW generation rate is over-riding the population growth rate in Chennai.
4	Akolkar et al. 2008	Stoichiometric method and chamber method	Estimation of CH_4 emission from Bhandewadi dumping site, Nagpur and Amrabati dumping site, Amrabati	• Estimation of methane emission from dumping sites of Nagpur and Amravati • The study concludes that LFG emission depends on physical condition, depth, age of dumping and chemical composition of the waste.

5	US EPA 2009	LandGEM version 3.02	Assessment of landfill gas from Okhla landfill, Delhi	• Preliminary site investigation suggested that direct use of LFG as domestic fuel of flaring may be feasible option for Okhla landfill
6	Chakraborty et al. 2011	DM. FOD, MTM and chamber method	Estimation of CH_4 emission from three landfill sites of Delhi	• Based on comprehensive analysis by DM, FOD, MTM and chamber method, methane emission factors were developed to reduce the uncertainty in CH_4 emission estimates • The study suggested that FOD method can give comparable result to that of in-situ chamber method.
7	Chakraborty et al. 2013	LandGEM version 3.02	Assessment of energy generation potentials of MSW in Delhi under different technological options	• Composition analysis of MSW in Delhi • Estimation of CH_4 generation from Delhi's landfill sites using LandGEM • Assessment of energy generation potentials using biomethanation, incineration, gasification/pyrolysis, refused derived fuel (RDF) and plasma arc gasification methods of segregated and without segregated MSW • It is found that higher values are obtained for bulk waste and Plasma arc gasification process yield high energy potential.
8	Kumar and Sharma 2013	LandGEM version 3.02	Estimation of GHG emission and energy recovery potential from three landfill sites of Delhi	• Estimation of GHG emission energy recovery potential using LandGEM from three landfill sites of Delhi • Results are compared with the results obtained using different methodology like DM, FOD, MTM and chamber method on same landfill sites. • The work concludes that LandGEM is relatively better model for estimation of GHG emission of landfills
9	Kumar and Sharma 2014	LandGEM version 3.02	Estimation of GHG emission and carbon sequestration potential from MSW landfills of Indian metro cities	• Estimation of GHG emission from MSW landfill sites of 23 metro cities • Computation of methane yield and methane generation rate constant for MSW of 23 metro cities
10	Jash et al. 2016	TNO, Multiphase model, LandGEM, DM, FOD and EPER Germany model	Estimation of Landfill Gas Generation From Dhapa Landfill in Kolkata	• Landfill gas emission estimation in Dhapa landfill site using different models • Comparison of results obtained from these models. • It is show that DM method gave highest result.
11	Singh et al. 2016	IPCC, DM and IPCC FOD	Greenhouse gas emissions from landfill sites, Delhi	• Estimation of GHG emission potential using DM and FOD model for three landfill sites of Delhi • Results obtained using DM and FOD are compared and it is found that DM

				gave higher result than FOD
12	Das et al. 2016	TNO, LandGEM, EPER and Afvalzorg	Estimation of land-fill gas generation from MSW in Six Indian Cities	• Estimation of LFG emission from six Indian metro cities using four different model and comparison of results obtained by different method
13	Kushal et al. 2016	IPCC DM , IPCC FOD and LandGEM version 3.02	Methane Emission from Panki Open Dump Site of Kanpur, India	• Estimation of CH_4 emission from Panki landfill site of Kanpur, India using DM, FOD and LandGEM method • Results obtained using DM, FOD and LandGEM are compared and it is found that LandGEM is more realistic
14	Chander et al. 2017	DM, MTM and FOD model	Quantitative analysis of the methane gas emissions from municipal solid waste in India	• Estimation of CH_4 emission from MSW in India using DM, MTM and FOD method • It is seen that the estimated CH_4 emission was higher for the DM than the other methods.
15	Chattopadhyay et al. 2018	LandGEM, IPCC FOD and TM	Gas Management and Energy recovery from Municipal Solid Waste Landfill	• Methane estimation from MSW landfill site of Kolkata using TM, FOD and LandGEM model and variation of results with changing of model parameter • Energy generation from LFG and loss/profit analysis for installation of power generation plant
16	Gollapalli et al. 2018	Flux chamber method, LandGEM, IPCC, MTM	Methane emission from a landfill in North-east India: Performance of various landfill gas emission model	• Estimation of CH_4 emission from MSW disposal sites using the following methods. • Analysis of performance of LandGEM, IPCC and MTM method and it is found that IPCC model gave better prediction.

. 2.14 Critical literature review

MSW consist of biodegradable, partially biodegradable and non-biodegradable materials. These wastes are generally disposed to a landfill site as final disposal without any treatment or with negligible degree of treatment. At landfill site, these wastes are subjected to physical, chemical and biological decomposition and landfill gases are produced. The landfill gases consist of GHGs, toxic gases and different VOCs. The GHGs obtained from landfill, mainly composed of methane (45-60%) and carbon dioxide (40-50%) (US EPA, 2014). If these gases are released to the atmosphere, they cause greenhouse effect (**has the highest climate change impact (5.94 kg CO_2 eq / KWh_e))** and lead to global warming and other adverse effect. Again the landfill gas also consist of air pollutants like carbon monoxide, hydrogen sulphide, ammonia, benzene, toluene, chloroform, toxic gases, VOCs and other gases, they cause air pollution and lead to adverse environmental and health effect and explosive hazard. So landfill gas emission is a threat to environment for protection of life in the earth. Hence, it is necessary to collect and treat the landfill gases before released to the atmosphere or prepare sustainable management plan. Since landfill gas mainly consists of CH_4, has high energy potential (55.7 KJ/g), it can be used as an alternate source of energy. The rate of CH_4 generations depends on moisture content, temperature, waste composition and characteristics etc. To minimize the greenhouse gas emission from landfill, to protect the environment from different undesirable problems arise from landfill gas emission, to reduce carbon credit to the atmosphere and to establish economically feasible landfill gas recovery project, it is necessary to know the amount of gas generate from the landfill. The gas generation should be such that it can meet the requirement of the project for the self-sustainability in terms of economy. To achieve this goal, quantification of landfill gas generation is necessary. Quantification of landfill gas may be done by modelling. Different models have been developed so far for the estimation of landfill gas generation.

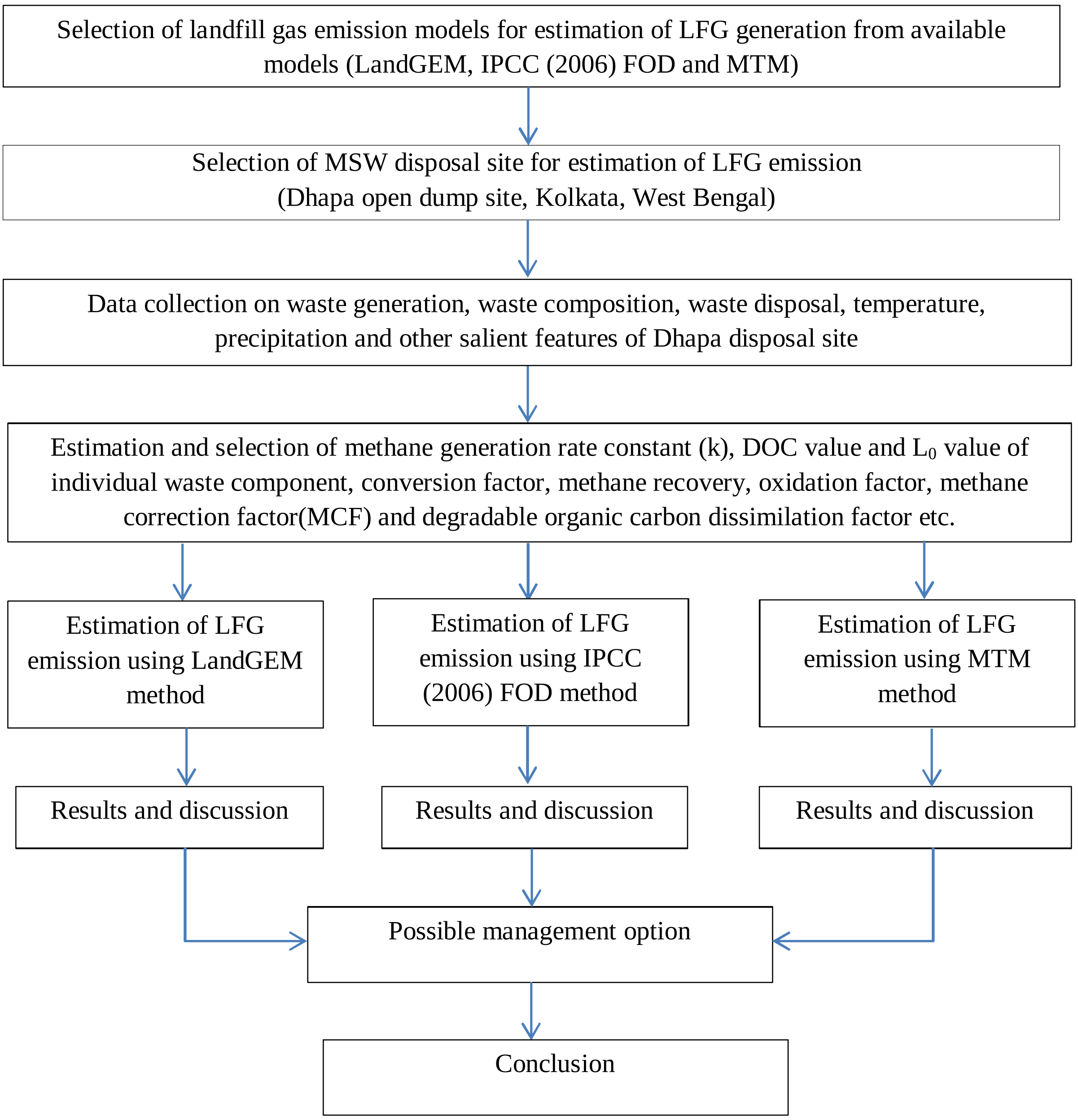
Literature reveals that several researchers have estimated GHG emission potential of landfills and open dump sites using different methodologies. Kumar et al. (2004) used default method & modified triangular method and found that total CH_4 generation is approximately the same by both the methods. Mor et al. (2006) used FOD for Ghazipur landfill site and compared the results with Modified triangular method. The CH_4 generation potential was found within the range of existing estimates by both models, and suggested that atmospheric CH_4 emission could be reduced if the MSW site is properly planned and landfill gas recovery is taken into account. LandGEM adopted by USEPA (2005) has been used to prepare prefeasibility report for Deonar and Okhla landfill sites, India. Stoichiometric approach was adopted by Akolkar et al. (2008) to assess GHG emissions and control the GHG fluxes at different depths of in metro cities, state capital cities, towns in India. Chalvatzaki and Lazaridis (2010) used Triangular, Stoichiometric and LandGEM model for Akrotiri landfill site, Greece and found the LandGEM as the most reliable model for quantification of emission rates. Ecuador LFG model was further adopted by Siddiqui and Khan (2011) for evaluation of CH_4 recovery potential from Okhla (Delhi), Gazipur (Delhi), Deonar (Mumbai), Gorai (Mumbai), Pirana (Ahmadabad) and Autonagar (Hyderabaad) landfill sites. Chakraborty et al. (2011) used in-situ CH_4 measurement, FOD, default and modified triangular method for three landfills of Delhi. LandGEM, version 3.02 was adopted by Yang et al. (2012) to estimate total landfill gas and CO_2 emission from Tanjulangstat MSW landfill site in Malaysia. Kumar & Sharma (2012) used the same version to estimate GHG Emission and energy recovery potential from Ghazipur, Okhla and Bhalswa landfills of Delhi, India and compared the results with that obtained using DM, FOD, MTM and chamber methods on the same sites. Jash et al (2016) used TNO, Multiphase model, LandGEM, DM, FOD and EPER Germany model to estimate landfill gas generation from Dhapa landfill site, Kolkata. Chattopadhyay et al. 2018 used LandGEM, IPCC FOD and TM model to estimate LFG emission and energy recovery potential from MSW landfill site. Most of the researcher used model predefined default values of the parameters. In India there is no experimental data on methane generation rate constant, methane yield, degradable organic carbon and gas emission. To obtain realistic result from the models, the site specific value of the parameters should be determined.

From the above literature, it is found that a very little work present on the estimation of landfill gas emission in Kolkata region. The researchers used model predefined default values for the estimation. Locality specific parameter like methane generation rate constant, methane yield and fraction of degradable organic carbon of waste have yet to be calculated for Kolkata region. The parameters are very important for accurate determination of landfill gas emission. The Estimation of the possible threat of global warming through GHGs emission by open dumping of MSW in Kolkata and energy generation potential are also required to make decision about developing any sustainable management plan.

Chapter -3
Methodology

Landfill gas emission from a solid waste disposal site can be estimated either by conducting field experiment or by using a suitable model which is developed for estimation of landfill gas emission. The present study use modelling method for estimation of landfill gas emission from a solid waste disposal site. The schematic diagram of the work is shown below.

Schematic diagram of the work



3.1 Selection of landfill Gas emission models for estimation of FLG generation from available models

For estimation of greenhouse emission from MSW landfill sites, many researcher developed different models based on waste generation data, waste composition data, methane generation rate constant, methane generation capacity of the waste and climatic condition of the disposal site. Available landfill gas emission models are shown in section 2.11. Based on order of biochemical reaction, the models are either zero order, first order or second order model. Most of the models are first order models because of bacteriological reactions are generally first order reaction. Among the first order models, LandGEM and IPCC FOD model are widely used models. These models allow site specific data of model parameters. If site specific data are not available, these models give default value of the parameters based on location and climatic condition of the disposal site. Most of researcher obtained satisfactory result on GHGs emission for landfill sites by using these models. Many researchers found that the results obtained from these models are close to the result obtained from flux chamber method (an experimental method). Most of Indian researcher also use these models and obtained satisfactory results. Modified triangular method (MTM) is a graphical method of landfill gas estimation. In absence of any suitable data on MSW, this method gives satisfactory result. Many Indian researchers also recommend this method in absence of suitable data on MSW.

The present paper selects three models viz. LandGEM, IPCC FOD and MTM for estimation of landfill gas emission and energy recovery potential from a MSW open dump site situated at Dhapa, Kolkata, India.

3.1.1 LandGEM method

USEPA landfill gas emission model (LandGEM) is widely used for the estimation of methane from degradation of solid wastes in the waste disposal site with time. LandGEM is a single phase automated tool for estimating total LFG, CH_4, CO_2 and other non-methane organic compounds (NMOCs) and individual air pollutants emitted from MSW landfills using the total annual disposed waste during the operation of site. LandGEM is based on a first-order decomposition rate equation for quantifying emissions from the decomposition of waste in MSW landfills. It assumes that the CH_4 generation rate reaches its peak shortly after the initial waste is placed and decrease exponentially after that. The LandGEM model also assumes that the volume emission rate of CO_2 and CH_4 are same, with trace amount of non-methane organic compounds (NMOCs) and other air pollutants. Field test data can also be used in this model. LandGEM is considered a screening tool and the better the input data, the better the estimates. However it doesn't include the categorization of wastes. Equation (1) shows the first order decay equation used to estimate methane generation rate (Q, in m^3/year) (USEPA, 2005).

$$Q_{CH_4} = \sum_{i=1}^{n} \sum_{j=0.1}^{1} k L_0 (\frac{M_i}{10}) e^{-kt_{ij}} \tag{1}$$

Where,

Q_{CH4} = annual methane generation in the year of the calculation (m^3/year).
i = 1 year time increment.
n = (year of the calculation) - (initial year of waste acceptance).
j = 0.1 year time increment.
k = 1st order methane generation rate ($year^{-1}$)

L_0 = Potential methane generation capacity (m^3/Mg).
M_i = Mass of waste accepted in the i^{th} year (Mg).
t_{ij} = Age of the j^{th} section of waste mass M_i accepted in the i^{th} year.

The usual composition of landfill gas (% by volume) consists of about 47.7% methane, about 47.7% carbon dioxide, 0.1% carbon monoxide, 0.01% hydrogen sulphide, 0.5% trace components, 3.1% nitrogen, 0.8% oxygen and 0.1% hydrogen (Tchobanoglous et al., 1993). This percentage differs spatially due to waste composition, age, quantity, moisture content and ratio of hydrogen/oxygen availability at the time of decomposition. The model assumes 50% CH_4 and 50% CO_2 with additional traces of NMOCs and other air pollutants. Further, there is a facility to input user specified CH_4 content within a range of 40-60 % while the concentration falling outside the range is not recommended. In present study, it is assumed to be 55 % methane and 45 % carbon-dioxide, with additional, trace constituents of NMOCs and other air pollutants. In developing country, the biodegradable portion in the solid waste is generally high compared to developed country. The production of methane is determined using the first-order decomposition rate equation and is not affected by the concentration of methane. However, the concentration of methane affects the production of carbon dioxide. The production of carbon dioxide (Q_{CO2}) is calculated from the production of methane (Q_{CH4}) and the methane content percentage (P_{CH4}) using the equation (2).

$$Q_{CO_2} = Q_{CH_4}\left[\left\{\frac{1}{\frac{P_{CH4}}{100}}\right\} - 1\right] \qquad (2)$$

To estimate LFG emission from a disposal site requires input parameters like landfill open year, landfill closure year, methane generation rate, k ($year^{-1}$), methane yield, L_0 (m^3/Mg) and waste acceptance rates (Mg/year) (US EPA, 2005).

3.1.2 IPCC method

Decomposition of Municipal, industrial and other solid waste disposed in a landfill, produces a significant amounts of methane(CH_4), carbon dioxide(CO_2) and non-methane volatile organic compounds (NMVOCs) and small amounts of nitrogen oxides (NO_x) , carbon monoxide (CO). They are collectively called landfill gas (LFG) as already defined earlier. For estimation of LFG, IPCC Guidelines described two main methods:

A) The default IPCC methodology (1996).
B) First order decay model (FOD) (2006).

Default IPCC Methodology

It is the simplest one for the estimation of methane emissions from landfills, based on mass balance approach. This method was developed by Bingemer and Crutzen (1987) and is being used in the Revised IPCC (1996) guidelines as the default methodology for estimating methane emissions from solid waste disposal sites. A number of empirical constants, like methane correction factor (MCF), degradable organic carbon (DOC), dissimilated organic fraction converted into LFG, have been considered while developing the default methodology and accordingly the emissions are calculated using equation 3.

CH_4 Emissions (Gg/yr) = (MSW_T ● MSW_F ● MCF ● DOC ● DOC_F ● F ● 16/12-R) ● (1-OX)   (3)

MSW_T : total MSW generated (Gg/yr)
MSW_F : fraction of MSW disposed to solid waste disposal sites
MCF : methane correction factor (fraction)
DOC : degradable organic carbon (fraction) (kg C/ kg SW)
DOC_F : fraction DOC dissimilated
F : fraction of CH_4 in landfill gas (IPCC default is 0.5)
16/12 : conversion of C to CH_4
R : recovered CH_4 (Gg/yr)
OX : oxidation factor (fraction – IPCC default is 0)

The method assumes that all the potential CH_4 emissions are released from waste disposed of in a given year to that year in which the waste is disposed. But, the CH_4 emissions can continue to occur for several decades after waste disposal and CH_4 generation from wastes is highest for the first few years after deposition and then decreases as the available carbon is consumed. However, this method does not reflect the time variation in solid waste disposal, composition and degradation profile of wastes over time. These lead to inaccuracies in emissions estimates in situations where waste quantity, composition, and conditions are not the same every year. Due to these reasons, default IPCC model (1996) has been avoided and adopted FOD model which produces more accurate estimates of annual emissions.

First order decay model (FOD) (2006)

IPCC developed a multiphase model in the year 2006 for estimation of CH_4 generation from all the countries in the world. It can be used either with default values or site specific data pertaining to waste generation rates, composition of waste, degradable organic carbon (DOC), fraction of degradable organic carbon dissimilated (DOC_f), waste decay rate (k), methane correction factor (MCF), LFG collection efficiency and oxidation factors. FOD method assumes that the degradable organic component (DOC) in waste decays slowly throughout a few decades, during which CH_4 and CO_2 are formed and follow the first order decomposition rate for degradation of waste i.e. the rate of CH_4 production depends solely on the amount of carbon remaining in the waste. This method provides a time-dependent emission profile that reflects the true pattern of degradation process over a period of time. This method requires data on current and historic waste quantities, composition and disposal practices over the decades. . Equation (4) shows the first order decay equation used to estimate methane generation rate (Q, in Gg/year) (Weitz et al., 2012).

CH_4 Emissions from the landfill at any year T (Gg/yr)

$$Q_{CH4,T} = [\sum_{x=S}^{T-1}\{MSW_{T,x}\bullet MSW_{F,x}\bullet L_{0,x}\bullet\left(e^{-k(T-x-1)} - e^{-k(t-x)}\right)\} - R]\bullet(1 - OX) \quad (4)$$

Where,

$L_{0,x}$: DOC ● DOC_F ● MCF ● F ● 16/12
$MSW_{T,x}$: total MSW generated in the year x (Gg/yr)
$MSW_{F,x}$: fraction of MSW disposed to solid waste disposal sites in the year x
k : 1^{st} order methane generation rate ($year^{-1}$)
x : year in which waste was disposed
s : Start year of inventory calculation
T : The year for which emissions are calculated

MCF : methane correction factor for aerobic decomposition in the year of deposition (fraction)
DOC : degradable organic carbon (fraction) (kg C/ kg SW)
DOC_F : fraction DOC dissimilated
F : fraction of CH_4 in landfill gas (IPCC default is 0.5)
16/12 : conversion of C to CH_4
R : recovered CH_4 (Gg/yr)
OX : oxidation factor (fraction – IPCC default is 0)
L_o : CH_4 generation potential, Gg CH_4/Gg SW .

3.1.3 Modified triangular method (MTM)

Triangular method (TM) is based on the first order decay methodology with the modification, the total amount of LFG generated from the waste is represented by the area of triangle for a particular period of time i.e. the rate of gas emission is linear rather than exponential. This model was developed by Tchobanoglous et al. (1993). The yield of LFG is computed using mass balance equation (Tchobanoglous et al., 1993). To make the mass balance equation, detailed characterization and quantification of the solid waste is required. In this model, the organic materials present in MSW are divided into two parts, (1) rapidly biodegradable waste (RBW) (2) slowly biodegradable waste (SBW) (Tchobanoglous et al., 1993). The rapidly degradable wastes of MSW consist of food waste, paper and a portion of yard wastes and the slowly degradable wastes of MSW consist of rubber, leather, woody portions of yard waste and wood (Tchobanoglous et al). In Triangular method, the chemical formula of RBW and SBW are determined by using ultimate analysis. After that applying mass balance equation to the biochemical reaction of the waste, LFG emissions are calculated. It is assumed that the MSW starts gas production after one year of deposition. Gas emission from the RBW reach maximum in the second year after waste deposition and gradually decrease to zero at the end of sixth year i.e. gas emission from RBW takes place over a period of five year. For the SBW, gas generation starts at the end of first year and reach to the peak after six years of waste deposition, then gradually decreases to zero after the sixteenth year i.e. gas emission for SBW takes place over a period of fifteen year. The peak value of LFG emission can be calculated by knowing the total volume of the gas production from the MSW. The total quantity of landfill gas produced from MSW placed in a year can be expressed with the following formula:

Total LFG produced (m^3/ kg) = ½ ×(years of gas emission)×(peak rate of gas production (m^3/ kg. yr)).

The total rate of gas generation from a landfill in which wastes were placed is obtained graphically by summing the amount of gas generation from RBW and SBW portions of MSW deposited each year.

FOD models which use site specific data, relies on in-situ waste composition, are more realistic to estimate the LFG emission rates (Gollapalli et. al, 2018). The FOD models also consider the effect of age of waste (Hoeks, 1983; Van Amstel et al., 1993; Oonk and Boom, 1995). But the data required for the model must be well representative of the wastes and landfill conditions. To determine the model parameters such as methane generation rate constant (k), methane generation potential (L_0), degradable organic carbon (DOC) etc. accurately, information like historical waste quantities, composition, disposal practices, temperature variation, rainfall variation, distribution of waste, compaction and density of waste, moisture content , pH, gas management facilities, leachate management facilities, availability of nutrients etc. are required. The effect of all the factors on the model parameters should be well investigated. The model should be well flexible to take the variation of parameters from year to year.

Modified triangular method is slight modification to the triangular method. This method assumed that the total landfill gas production is equal to the gas estimated by the Default Methodology and the peak rate of gas generation is calculated by equating the area of triangle to the gas estimate in IPCC default methodology (Mali S.T. et al.2011). Using the peak value, other ordinates are calculated as Triangular method. In this model, the biogas release is based on FOD in a triangular form distribution but the biogas generation is based on IPCC DM method. In absence of detailed data about the waste composition, distribution, characteristics, disposal practices and statistical data on temperature, rainfall, waste generation and information about landfill management practice, this method of gas estimation can be adopted (Kumar et al. 2004). Since the historical data on waste composition, characteristics, quantities, disposal and management practices are not available for Indian conditions, the FOD model does not give better estimation of methane emissions. Hence in the present work MTM model has been selected for the estimation of LFG generation.

The rate and amount of gas generation at the end of each year from one kilogram rapidly biodegradable and slowly biodegradable organic matter are shown in Figure 17 and 18 and Table 14 shows composition of biodegradable MSW in Kolkata. Table 15 shows gas generation from 1 kg of RBW, SBW and MSW for Kolkata.

Table 14: Composition of biodegradable MSW in Kolkata

Component	% by wet weight	
Food waste	50.56	RBW
Paper	1.07	
Rubber and leather	0.68	SBW
Wooden matter	1.15	
Coconut	4.5	
Rags	1.87	

Source: (Chattopadhyay et al.,2009)

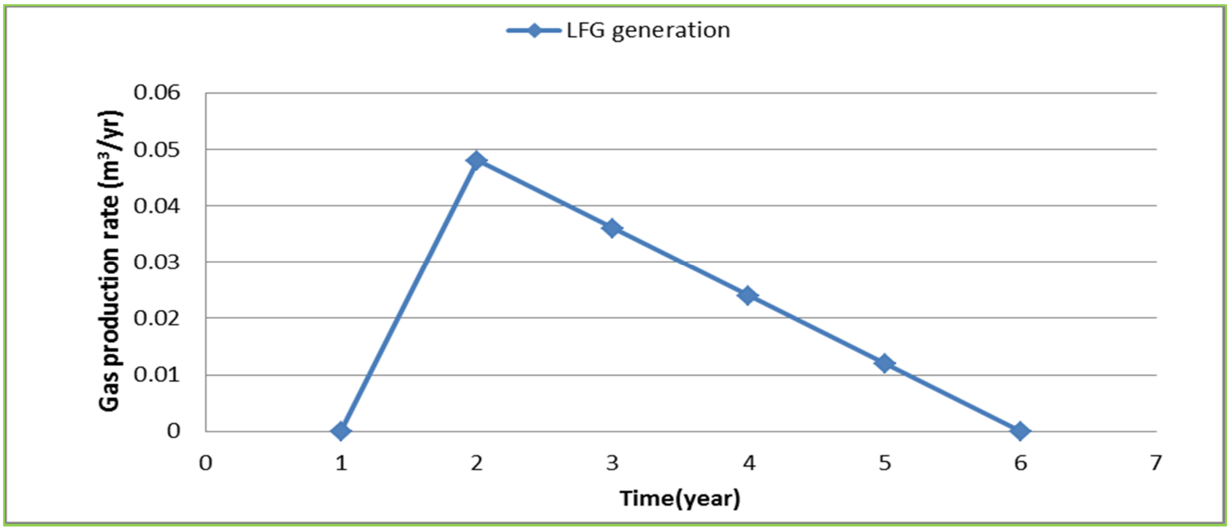


Figure 17: Triangular gas production for rapidly biodegradable waste for Kolkata

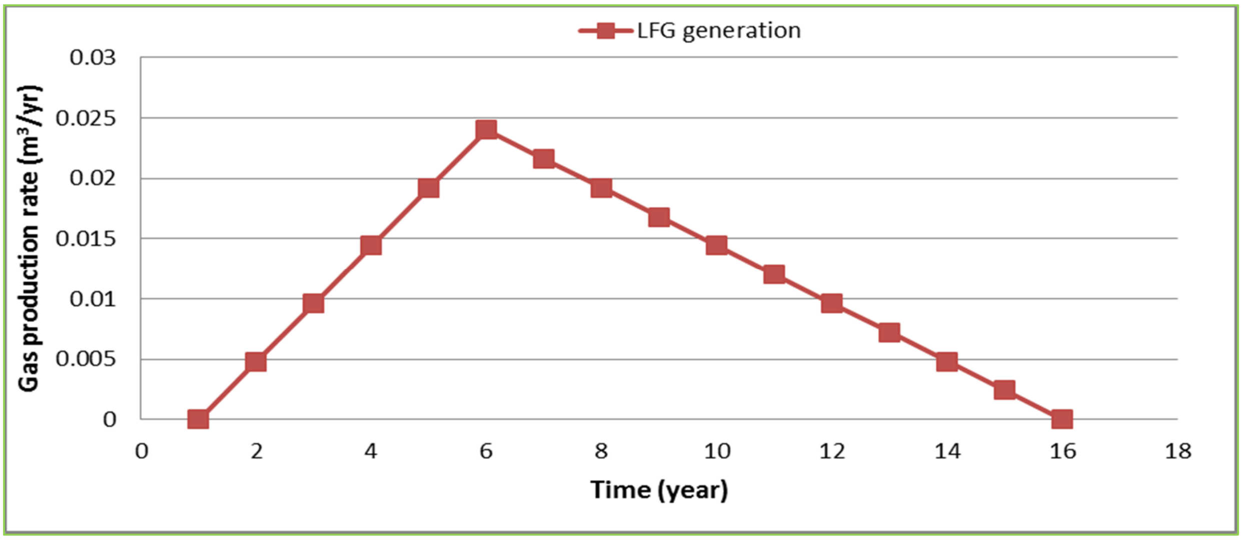


Figure 18: Triangular gas production for slowly biodegradable waste for Kolkata

Table 15: Gas generation from 1 kg of RBW, SBW and MSW for Kolkata

Year	Rate of gas production from RBW(m^3/yr)	Rate of gas production from SBW(m^3/yr)	Rate of gas production from MSW(m^3/yr)
0	0	0	0
1	0	0	0
2	0.048	0.0048	0.025176
3	0.036	0.0096	0.019374
4	0.024	0.0144	0.013572
5	0.012	0.0192	0.00777
6	0	0.024	0.001968
7		0.0216	0.001771
8		0.0192	0.001574
9		0.0168	0.001378
10		0.0144	0.001181
11		0.012	0.000984
12		0.0096	0.000787
13		0.0072	0.00059
14		0.0048	0.000394
15		0.0024	0.000197
16		0	0

3.2 Study area

3.2.1 Geographical location

This study has been conducted in the Capital of West Bengal, Kolkata, which is a metropolitan city of India. It is situated in eastern India on the east bank of River Hooghly and 30 km from the Bay of Bengal. The city is situated on latitude 22º34′North and longitude 88º24′ East and an average elevation of 17 feet above the sea level. The city is more than 300 years old and it served as the capital of India during the British governance until 1911. Kolkata covers an area of about 205sq. km. (Census 2011). Kolkata has a population of 4.49 million with a population density of 24270 persons per km^2 and a floating population of approximately 3.4 million (Census 2011). As per census report of the Institute of Local Government and Urban Studies, the growth of population of Kolkata city from 1981 to 1991 as 6.61% and from 1991 to 2001 as 4.00% and from 2001 to 2011 as -1.69%.

3.2.2 Solid waste generation, management and disposal facility at Kolkata

The MSW generation rate is about 470 g per capita per day for the resident population and 250 g per capita per day for the floating population, and the total generation is about 3520 t d^{-1} (Ali et al., 2016). It has been predicting that KMC will generate about 8805 t d^{-1}solidwaste per day in 2035 (Ali et al., 2016). Kolkata Municipal Corporation (KMC) is responsible for the management of solid waste generated in the city. The city is divided into 16 boroughs and 144 electoral wards.

Major sources of MSW in the KMC area are residential houses, commercial and market areas, offices, institutions and street sweeping etc. The quantity and sources of solid waste generation in the KMC area are shown in Table 16 and Figure 19 respectively.

Table 16: Quantity of Solid Waste Generation (KMC, 2011)

Sources of solid waste	Weight (kg)
Household waste	3110091
Market waste	674450
Institutional and office	64973
Playground and park	13974
Hospital	51351
Factory	21160

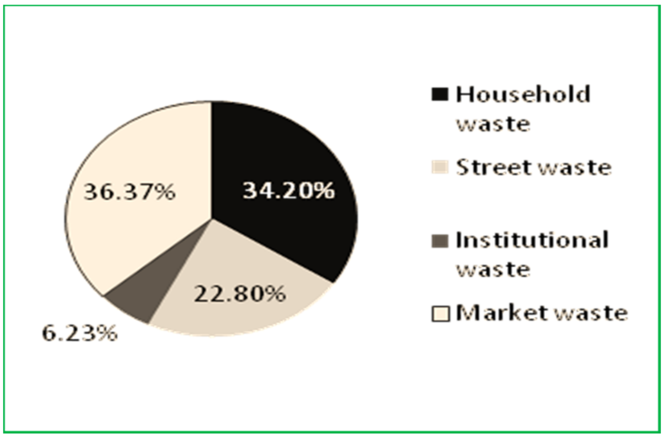


Figure 19: Source of solid waste generation in KMC

Solid waste management in KMC area are performed under-

- Garbage sweeping
- Garbage collection
- Transportation of garbage and
- Disposal of garbage as waste

Due to climatic factors like humidity and high temperature along with high organic matter content, MSW decomposes rapidly and resulting in unhygienic conditions. Hence in most areas, collection has to be done on a daily basis. Different collection methods are being used in KMC, they are house-to-house collection (primary collection), collection from roadside storage areas and collection from community bins. For garbage collection around 250 persons are engaged. They sweep the roads and collect garbage and transfer the waste into bins. KMC has 664 waste bins around the area and garbage is accumulated in these bins from adjacent area. It is seen that, a large percentage about 19% to 21% waste remain uncollected either in the place of originates or around the bins. KMC has 664 storage places in the form of large masonry storage enclosures, trash bins, and dumpers for temporary storage of MSW which is collected from the city during secondary collection. The available storage capacity of the areas in KMC is around 23,400 m^3. The mixed waste (biodegradable and recyclable) that is collected from residential, commercial and market areas and brought to collection points is directly loaded into trucks or trailers manually or using pay loaders for transportation. This is known as secondary collection. KMC has a total no of 245 conservancy vehicles for transporting and collecting solid waste. These vehicles include trucks, dumper placer vehicles, tractor-trailers, refuse collectors, tipper trucks and pay loaders. KMC transports around 40%of the total waste using dumper placers and the remaining portion by tipper trucks. An estimation show that private agencies are collecting 55% of the total waste and KMC is collecting only 45% (KEIP, 2003). Figure 20 shows primary collection of municipal solid waste.

Figure 20: Road Sweeping (a), regular handcarts (b) and containerized handcarts (c).

(Hazra et al. 2009)

Collection and transportation of solid waste in the KMC area is conducted in an ad hoc manner, without any scientific approach. Solid waste collection vehicles are assigned without any serious demand analysis. The responsibility of route selection is on the drivers and every vehicle collects solid waste along its route until its maximum capacity, at which time it goes to the available disposal site to depose its load. The empty vehicle then returns back to its route and continues collection for the next load. The present approach is neither economical nor efficient. GIS based analysis and optimization techniques can be used to determine optimal ways of utilizing scarce manpower and resources for waste collection and transfer. Figure 21 shows transportation of waste to disposal site.

Figure 21: Transfer and transport of collected waste from bins to disposal site (Hazra et al. 2009)

Currently, there is no incinerator or RDF plant in Kolkata. The wastes are disposed to an open dumping site without any sorting or segregation. A mechanized compost plant was installed at Dhapa by KMC in April 2000 with a 700 t/d capacity. The waste carried by vehicles is received at the compost plant. Larger sized materials, particularly construction and demolition wastes are separated manually. The remaining solid wastes are placed in the position as windrows.

Worldwide about 95% of MSW is landfilled or dumped on land, on riverbanks or into the sea (Hogland and Marques, 2007). For techno-economic reasons, landfilling is the most suitable option for management of solid waste. Open dumping is mostly practiced in India and other developing country. There are three disposal sites in the KMC area viz. at Dhapa, GardenReach and Naopara of which Dhapa is the major one. About 95% of the total waste generated in the KMC area is disposed at the Dhapa disposal site and the rest is disposed at the Garden Reach disposal site (Hazra and Goel, 2009). Dhapa receives about 3000-3200 T of solid waste per day. Another site at Garden Reach receives about 100-150 T of solid waste per day. The present study selects Dhapa MSW disposal site for estimation of landfill gas emission from MSW.

3.2.3 Dhapa MSW open dump site in Kolkata

Dhapa is major MSW dumping site in Kolkata. It is situated at the eastern extreme of the city with all collection points within a distance of 20 km. The total area of Dhapa MSW disposal site is 24.47 hectares. This part of the city has been used for waste dumping for over 100 years. The Dhapa Disposal Site is owned by the KMC. It is an Open dump site without any liner or leachate management facility or gas management system and accepts waste from both KMC's public waste haulers and private haulers. Waste disposal method in Dhapa disposal site is unscientific and uncontrolled that has resulted in steep, unstable slopes, leachate accumulation within the waste mass, and leachate runoff into nearby water bodies (Figure 23). It creates environmental hazards and affects to the LFG generation. The disposal site is divided into two parts, eastern mound which receives waste from KMC's waste haulers, and a western Mound, which receives waste from private haulers. An Asian Development Bank (ADB) survey showed that about 21.5 ha of land under zone-III is developed up to 17 m height from its original level (13 m above road level) (Fig 24), and only a very small area is now available for waste disposal (CEIP, 2000). There is an expansion area of 10×10^4 m^2 near the eastern mound. A composting facility is located between the two disposal areas and receives selected waste loads from organics-rich sources. It covers 12.2 ha of the disposal site land. A schematic diagram of the disposal site is shown in Figure 22. The main features of this site are given in Table 17.

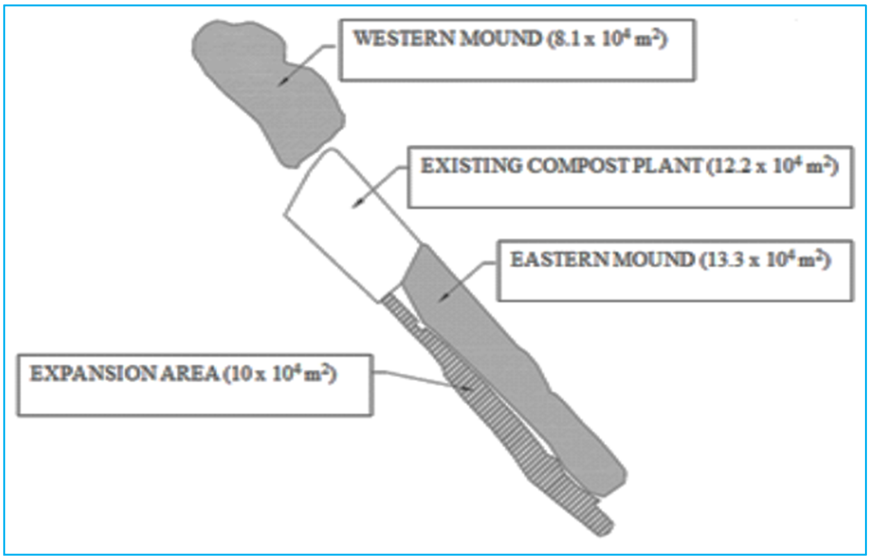


Figure 22: Layout of Dhapa disposal site in Kolkata (Jash et al., 2016**)**

Figure 23: Leachate ponding at Dhapa Disposal site (Assessment report, KMC, 2010**)**

Fig. 24: Dhapa Dumping Site, waste piles are 17 m high from ground level.
(Hazra et al., 2009)

Table 17: Salient features of Dhapa open dump site, Kolkata, India

Characteristics	Dhapa landfill site
Starting year	1980
Year of closure	2020
Location	22°34′N, 88°24′E
Elevation	17 feet above the sea level
Waste management facility	Daily spreading and compaction
Area (Hectare)	34.2
Climate	Tropical and rainy
humidity	52%-82%
Average height (m)	30
Dumping quantity (TPD)	3500
Annual precipitation (mm/year)	1770
Temperature(°c)	26.1
LFG collection system	No gas collection system
Soil cover	Little or no
Density (tones/m^3)	1.2

Source: Assessment report, Dhapa disposal site, Kolkata, 2010)

3.3 Data collection for estimation of LFG emission

For estimation of landfill gas emission, waste disposal data and waste composition data are required. The information about waste disposal and waste composition are taken from the work of Chattopadhyay et al., 2009 and “Assessment Report” of Dhapa disposal site, KMC, 2010.

3.3.1 Waste composition of MSW disposed at Dhapa

Waste composition, waste particle size, waste density, moisture content, temperature and pH are important due to influence on rate of degradation of waste. The physical and chemical characteristics help in deciding the frequency of collection, precaution to be taken during transportation and methods of processing and disposal. The physical composition and chemical properties of waste in KMC during 2010 are shown in Table 18.

Table 18: Physical composition and chemical characteristics of MSW in Kolkata

Physical composition of MSW [a]		Chemical composition of MSW [b,*]	
Parameters	% by wet weight	parameters	value
Biodegradable matter	50.56	Moisture	46
Green coconut shells	4.5	pH	0.3-8.07
Paper	6.07	Loss of ignition	38.53
Plastic	4.88	Carbon	22.35
Glass	0.34	Nitrogen as N	0.76
Metal	0.19	Phosphorous as P_2O_5	0.77
Rubber and leather	0.68	Potassium as K_2O	0.52
Rags	1.87	C/N ratio	31.81
Wooden matter	1.15	Calorific value kJ/kg^{-1}	5028
Bones	0.16		
Inert	29.6		
Total	100		

a) source: (Chattopadhyay et al.,2009), b) source: (NEERI, 2005)

*All values are in % by dry weight basis except pH, C/N ratio and calorific value.

3.3.2 Annual waste disposal rates for Dhapa disposal site

. To estimate LFG emission using any model from any models/methods, the waste composition data and waste generation from several past years is very important. The waste disposal data for Dhapa open dump site for the year 1981-2012 was obtained from " Assessment report”, Dhapa disposal site Kolkata, SCS engineers 2010. As per report of KMC, annual waste disposal rate of Dhapa open dump site goes on increasing. The amount of waste disposed of in the open dump site is expressed as Mg/yr. The values are listed in Table 19.

Table 19: Waste acceptance rates for Dhapa open dump site, Kolkata

year	Annual disposal (Mg)	Waste in place (Mg)	year	Annual disposal (Mg)	Waste in place (Mg)
1981	18000	18000	1997	168400	1170900
1982	20700	38700	1998	193700	1364600
1983	23800	62500	1999	222800	1587400
1984	27400	89900	2000	256200	1843600
1985	31500	121400	2001	294600	2138200
1986	36200	157600	2002	338800	2477000
1987	41600	199200	2003	389600	2866600
1988	47800	247000	2004	448000	3314600
1989	55000	302000	2005	515200	3829800
1990	63300	365300	2006	592500	4422300
1991	72800	438100	2007	681400	5103700
1992	83700	521800	2008	912000	6015700
1993	96300	618100	2009	1277500	7293200
1994	110700	728800	2010	1303100	8596300
1995	127300	856100	2011	1329200	9925500
1996	146400	1002500	2012	1042100	10967600

3.4 Selection and estimation of model parameter's value

Methane generation rate constant (k), DOC value and L_0 value of individual waste component, conversion factor, methane recovery, oxidation factor, degradable organic carbon dissimilation factor, and Methane correction factor (MCF) are most important model parameters. Proper determination of these parameters gives more realistic estimates. Before use of the models, these parameters are required to determine properly.

3.4.1 Evaluation of Methane Generation Rate Constant (k)

The Methane Generation Rate constant (k) determines the rate of methane generation and decay of waste in the landfill. The higher the value of k, the faster the methane generation rate increases and then decays over time. The k value is found to increase with higher moisture content and higher temperature (Balwin et al. 1998; Ishii and Furuchi, 2013). The value of k is reported as 0.1, 0.03 and 0.009 $year^{-1}$ for rapid decaying (food and garden waste), medium decaying (paper, wood, textiles) and slow decaying organic waste (leather, rubber), respectively (US EPA, 2009). The k value controls the predicted time over which CH_4 is generated from the specified waste stream (Amini et al., 2012). The value of k is primarily a function of four factors:

- Moisture content of the waste mass.
- pH of the waste mass.
- Temperature of the waste mass.
- Availability of the nutrients for microorganisms that break down the waste to form methane and carbon dioxide.

The organic part of each waste type is considered to have different decay rates (Thompson et al., 2009), so it is required to determine a single overall value of k for a landfill, to determine the landfill emission by using available models. There are different methods for evaluation of k value. They are-

a) **Precipitation rate method** (US EPA, 2004; Chalvatzaki and Lazaridis, 2010)
b) **Laboratory simulations method** (De la Cruz and Barlaz, 2010; Wang and Barlaz, 2016)
c) **Method 2E** (Experimental method)
d) **Aged-defined waste samples and regression** (Kim and Townsend, 2012; Ishii and Furuichi, 2013) (Experimental method)
e) **Model fitting or regression analysis using actual gas data** (Sormunen et al., 2013)

The present study use precipitation rate method and laboratory simulation method for computation of k value.

Precipitation rate method

Precipitation is the most important parameter to estimate the k value of a landfill (Garg.et al.2006). Thus, US EPA provides an empirical equation to calculate the k value of a landfill based on precipitation on the area.

$$k = (3.2 \times 10^{-5} \times average\ annual\ precipitation\ in\ mm) + 0.01 \qquad (5)$$

Laboratory simulation method

Each waste component has different decay rate. As different type of waste present in a landfill, the k value of the landfill is affected by the waste components. For calculation of k value of a landfill, it is assumed that the weighted average decay rate for a waste mixture is equal to the bulk MSW decay rate ($k_{field,MSW}$). First k values of individual waste component are determined in laboratory condition by experiment, after that the k value of waste mix is calculated by taking weighted average of k values of individual waste component. Several studies have presented CH_4 yield measurements for individual components of MSW to determine their k values (De la Cruz and Barlaz, 2010; Mou et. al., 2015; Wang and Barlaz, 2016). Laboratory k values are generally higher in magnitude than field k values because laboratory conditions are more ideal (Lamborn, 2012; Fei et al., 2016). So it is necessary to develop a correction factor for converting laboratory k value to field k value. Karanjekar et al. (2015) presented a correction factor (f) based on annual average precipitation and average temperature to translate the laboratory-scale decay rates of MSW components into field-scale decay rates ($k_{field,\ i}$).

$$k_{field,MSW} = f\{\sum k_{lab,i} \times (wt.fraction)_i\} \qquad (6)$$

$$k_{field,i} = f \times k_{lab,i} \qquad (7)$$

$$f = -0.00758\,T + 0.0135\,R + 0.137 \qquad (8)$$

Where i: i^{th} waste component, T: ambient temperature (^oC), R: average annual precipitation (mm/day) Laboratory scale decay rates of different waste component are shown in Table 20 and waste composition of MSW of different Indian cities are shown in Table 21. For determination of k value of MSW, it is assumed that k value of green waste is average of k values of leaves and grass, k value of branches is same as k value of wood, k value of textiles is same as k value of office paper, k value of paper is average of k value of office paper and newspaper, k value of other organics is average of k value of food, wood, grass, leaves and branches (De la Cruz and Barlaz, 2010).

Table 20: Laboratory-Scale Decay Rates, Methane Yields for MSW Constituents

Component	K value(year^{-1})	Methane yield (L_0)(m^3/dry Mg)
Office paper	3.08	217.3
Grass	31.13	144.4
Branches	1.56	62.6
Newspaper	3.45	74.3
Corrugated containers	2.05	152.3
Food	15.02	300.7
Leaves	17.82	30.6
Coated paper	12.86	84.4

Source: De la Cruz and Barlaz, 2010.

Table 21: Waste composition of MSW of different cities in India

k_{lab} (year^{-1})	15.02	1.56	24.5	3.08	3.27	13.68
Name of city	**Food waste (%)**	**Branches /wood (%)**	**Green waste (leaves + grass)(%)**	**Textile (%)**	**Paper (%)**	**Other organics (%)**
Chennai [1]	8	6.99	32.25	3.14	6.45	3
Ahmedabad [2]	35	0.5	15	3	23	4
Kolkata [3]	45.5	1.2	5	4	4	3.4
Mumbai [4]	47.57	0.95	10.34	5	10	3.79
Bengaluru [5]	47.4	0.35	15.2	4.6	8.76	3.3
Dehradun [6]	26	1.1	18.76	4	3	4
Srinagar [7]	45	2.8	10.58	2.2	7.5	3
Shimla [8]	46.93	4.55	7.83	4.22	7.31	3.9
Hyderabad [4]	48.22	2.7	3.06	5.7	7.26	2

Source:1) sujatha et al 2012, 2) Joshi et al 2015, 3) Dhapa assessment report, KMC, 4) Sastry et al, 2012, 5) www. BBMP.gov.in, 6) Naveen et al 2018, 7) Zareena et al 2016, 8) Verma et al 2016.

3.4.2 Computation of Methane yield (L_0)

L_0 is the amount of CH_4 (m^3) generated per Mg of MSW decomposition, under idealized conditions for methane generation (Krause et. al.,2016a) and is also known as Potential Methane Generation Capacity (PMGC), Landfill Gas Generation Potential or Methane Generation Potential. The value of L_0 indicates, the maximum amount of methane produced per unit mass of waste under anaerobic conditions. It does not refer to methane generation potential at the landfill (Wang et al., 2013a). The methane generation potentials in field are lower, because landfills does not works as efficiently as anaerobic digesters or laboratory experiments (Bogner and Matthews, 2003; Fei et. al., 2016;).

The Potential Methane Generation Capacity (L_0) depends only on the type and composition of waste placed in the landfill. Hence it is not possible to predict L_0 for landfills without accurate waste composition data (Amini et al., 2013). A waste with higher cellulose content would have higher L_0, while the waste having higher lignin content would have lower L_0 value. Food waste with high moisture content has a low L_0, whereas paper wastes have a high L_0. Over the lifetime of the landfill, the slowly degrading components, especially paper and card waste, make the most significant overall contribution to CH_4 emissions (Donovan et al., 2011).

There are various methods to measure L_0 of the solid waste. They are-

- Stoichiometric method (Mor et al., 2006; Sanderson et al., 2008; Machado et al., 2009)
- Experimental methods (jeon et al., 2007; Tolaymat et al., 2010; Cho et al., 2012)
- Model fitting or regression analysis using gas data (Amini et al.,2012; Wang et al.,2013a)
- IPCC model (Kumar et al.,2004; Thompson et al.,2009; Govindan and Agamuthu,2014)

For measurement of L_0 value of the landfill, experimental method has been used using secondary data. In the present study, L_0 values of different components of MSW are taken from the work of Staley and Barlaz, (2009) which are obtained after biodegradation of different components of MSW in laboratory-scale landfills. L_0 value is computed on the basis of per Mg of dry waste. Therefore, the moisture content of each component must be subtracted to make the waste dry. In this study, IPCC (2006) data of moisture content has been used for computation of CH_4 yield. IPCC (2006) data of moisture content of different components of MSW is developed in consultation with a group of scientists throughout the world and using the same data, better results are obtained by Kumar and Sharma (2013) under Indian condition. For calculation of L_0 of a landfill, it is assumed that the L_0 value of a waste mix is equal to the weighted average L_0 value of individual waste component. Moisture content and ultimate methane yield of different waste components are shown in Table 22.

Table 22: Moisture content, Ultimate CH_4 yield of different waste components

Waste categories	Moisture content (%) IPCC(2006)	Ultimate CH_4yield (L_0) (m^3/Mg) Staley and Barlaz (2009)
Compostable matter [a]	45	145.1
Paper [b]	10	132.8
textile	20	14.8

a) Average of food waste, Green waste and wood waste.

b) Average of newspaper, office paper, glossy paper and old corrugated containers (OCC)/Kraft bags.

3.4.3 Degradable Organic Carbon (DOC)

Degradable organic carbon (DOC) is the organic carbon in waste that is available for biological decomposition. DOC value is a characteristic of waste and depends on type of waste and fraction of different waste. DOC in MSW ranges from 8% to 30% (Bingemer and Crutzen, 1987).

To measure organic carbon in waste sample, it is necessary to separate organic carbon and inorganic carbon, because organic carbon is degradable carbon. Thus, sample should be acid washed to eliminate inorganic carbon prior to analysis (Wang et al., 2015a). It is important for paper samples, because some paper products contain inorganic carbon in the form of $CaCO_3$ as fillers (Wang et al., 2015a). Mou et al. (2014) used the assumption that 2 mL of sulfurous acid (5% H_2SO_3 solution) was added to approximately 0.5 g of powder to remove inorganic carbon.

The DOC in bulk waste is estimated based on the composition of waste and can be calculated from a weighted average of the degradable carbon content of various components of the waste stream. DOC values of different components wastes are shown in Table 23. Equation 9 estimates DOC content values:

$$DOC = \sum_i (DOC_i \bullet W_i)$$

Where, (9)

DOC = fraction of degradable organic carbon in bulk waste (Gg C/Gg waste)

DOC_i = fraction of degradable organic carbon in waste type i

W_i = fraction of waste type *i* by waste category

Table 23: DOC values for different components of wastes

Composition	DOC value [a] (DOC_i)	% Waste [b] (W_i)
Food waste	0.15	45
Branches /wood	0.43	1.2
Green wastes (leaves +grass)	0.2	5
Textiles	0.24	4
Paper	0.4	4
Other organics	0.2	3.4

Source: a) IPCC 2006, b) Assessment report, Dhapa disposal site, Kolkata, 2010

DOC value of MSW in Kolkata = 0.12 (from Equation 9)
DOC value of MSw for south-east Asia = 0.17 (IPCC 2006)
DOC value of MSW for Gazipur landfill, Delhi, India = 0.0835 (Mor et al. (2006))
DOC value of MSW in India = 0.11-0.16 (Kumar et al. (2004)

3.4.4 Fraction of Degradable Organic Carbon Decomposes (DOC_f)

DOC_f is an estimate of the fraction of carbon that will actually degraded in the landfill. It represents the fact that some degradable organic carbon does not degrade, or degrades very slowly, under anaerobic conditions in the solid waste disposal sites (SWDS). The recommended default value for DOC_f including lignin is 0.5 (IPCC (2006)). From laboratory studies of solid waste decomposition from the United States, Germany, and Italy have shown that the DOC_f ranges 0.17–0.47 (Bogner and Matthews, 2003; Bogner and Spokas, 1993; Lornage et al., 2007). DOC_f factor may vary from 0.42 for 10°C to 0.98 for 50°C (Manna et al. (1999)).

DOC_f value is dependent on many factors like temperature, moisture, pH, composition of waste, etc. Food waste and grass have a high DOC_f value, whereas paper and wood have a low DOC_f value within the landfill. The most critical factor in landfill decomposition is the amount of moisture in the waste; if sufficient moisture is not available, then gas formation will not proceed, and in some cases will not start at all (Hartz and Ham, 1983; Micales and Skog, 1997; Baldwin et al., 1998; Meima et al., 2008;).

For the present work DOC_f value is considered 0.5.

3.4.5 Methane Correction Factor (MCF)

MCF is defined as the portion of organic materials that decompose an-aerobically. This implies that a semi-aerobic landfill emits less amount of CH_4 compare to an equal size anaerobic landfill. MCF accounts for the fact that unmanaged landfill site produce less CH_4 from a given amount of waste than anaerobic managed landfill site, because of a larger fraction of waste decomposes aerobically in the top layer of unmanaged landfill site. Again, unmanaged landfill site with deep disposal produce higher CH_4 than shallow disposal site. The MCF ranges from 0.4 to 1.0, depending on the landfill condition. Wang yao et al. (2010) established that the best fitting values of the CH_4 correction factor are 0.65, 0.20, 0.15, and 0.1 for deep landfills, shallow landfills, deep dumpsites, and shallow dump sites, respectively. Default values of MCF for different dumping sites are shown in Table 24.

Table 24: Default values of MCF for different dumping sites/landfills

Type of site	MCF default values
Managed MSW sites	1.0
Unmanaged deep MSW sites (≥5m)	0.8
Unmanaged shallow MSW sites (<5m)	0.4
Unspecified MSW sites	0.6

Sources: IPCC (2000); Matsufuji *et al*. (1996, Chiemchasri et al. (2008)

As Dhapa landfill site is an unmanaged deep site, MCF is taken as 0.8 for estimation of landfill gas

3.4.6 Oxidation Factor (OX)

The oxidation factor (OX) represents the amount of CH_4 from landfill site that is oxidised in the soil or other material covering the waste. The thickness, physical properties and moisture content of cover soils directly affect CH_4 oxidation (Bogner and Matthews, 2003). Studies show that engineering landfill tend to have higher oxidation rates than open dump sites (IPCC2006). The default value for oxidation factor is zero for open dump site and 0.1 for sanitary landfill (IPCC2006).

3.4.7 Methane Recovery (R)

CH_4 generated at landfill can be recovered and combusted in a flare or energy device. The amount of CH_4 which is recovered is expressed as R. If the recovered gas is used for energy, then the resulting greenhouse gas emissions will be less from the landfill site. The default value for CH_4 recovery is zero (IPCC 2006) for open dump landfill site.

3.4.8 Delay Time

In the landfill sites, waste is deposited continuously throughout the year, usually on a daily basis. But, CH_4 does not produce immediately after deposition of the waste. At first, decomposition is aerobic, which may last for some weeks, until all readily available oxygen has been used up. This is followed by the acidification stage, with production of hydrogen. The acidification stage is often said to last for several months. After which there is a transition period from acidic to neutral conditions, when CH_4 production starts. The period between deposition of the waste and full production of CH_4 is chemically complex and involves successive microbial reactions. It varies with waste composition and climatic condition. Delay may be up to one year (Gregory et al., 2003; Bergman, 1995; Kämpfer and Weissenfels, 2001; Barlaz, 2004). The IPCC provides a default value of six months for the time delay (IPCC, 1997). The present study considers the delay time as 6 months.

3.5 Fitting the data in the model

The value of different parameters used in present study is shown in Table 25.

Table 25: Value of models parameters for Dhapa open dump site

Model parameter		IPCC Default method	IPCC FOD method	LandGEM model
Methane generation rate constant k ($year^{-1}$)	Precipitation method	-	0.04	0.04
	Laboratory simulation method		0.07	0.07
Methane generation potential L_0 (m^3/Mg)		-	-	46.51
Fraction of CH_4 in landfill gas (F)		0.55	0.55	0.55
Degradable organic carbon (DOC) (kg C/kg SW)		0.12	0.12	
Fraction DOC dissimilated (DOC_f)		0.5	0.5	
Methane correction factor (MCF)		0.8	0.8	
Methane recovery (R)		0	0	
Oxidation factor (OX)		0	0	
Conversion factor from C to CH_4		1.33	1.33	

In the present study, different methodologies like LandGEM version 3.02, IPCC First Order Decay (FOD) and Modified Triangular Model (MTM) are used to estimate CH_4 emission from Dhapa MSW open dump site of Kolkata based on the amount of waste dumped at the site and is compared with emission estimates of assumed landfill. The estimation of landfill gas emission depends on mainly methane generation rate constant (k), potential methane generation capacity (L_0), degradable organic carbon (DOC) and waste disposal data. The present study use waste composition data published by KMC. The value of methane generation rate constant is determined by using precipitation method and laboratory simulation method based on waste composition, rainfall and temperature. The obtained k value is used in the estimation rather than using model predefined default value. L_0 and DOC value also determined by using experimental method and IPCC method respectively and used in the estimation. The rate of LFG emission from Dhapa MSW open dump site obtained by using LandGEM, IPCC and MTM methodology are shown in Table 30, Table 31 and Table 32 respectively.

4.1 Description of study area

Dhapa landfill site is one of the major landfill sites in Kolkata metropolitan city. Per day, about 3000 tons of solid wastes are disposed of in Dhapa open dump site. There is a huge generation of landfill gas. Presently, there has been no facility available for the recovery of gases at the Dhapa landfill site in Kolkata. The total area of Dhapa MSW disposal site is 24.47 hectares. The disposal site was opened in the year 1980 and it is expected that the closure year will be 2020. It is situated at 17 feet above the sea level. The climatic condition of the area is tropical and rainy. Average temperature of the area varies from 24-27ºC and humidity varies from 52-82%. Average annual precipitation of the area varies from 1600-1800mm. A composting facility is located between the two disposal areas and receives selected waste loads from organics-rich sources. It covers 12.2 ha of the disposal site land.

4.2 Estimation of methane generation rate constant (k)

Methane generation rate constant is an important factor for FOD models. It controls the emission over a time period. Higher k value indicates most of emission takes place over a specified time period and lower k value indicates emission takes place over long time period i.e. k value controls the distribution of gas emission. It does not affect the total gas emission. Huge emission at a particular time has more environmental impact than low emission over a long time period. So rate of gas generation is important. The value of k of MSW in landfill depends on waste composition, percentage of different waste, k values of individual wastes, rainfall on the landfill, temperature, cover of landfill, gas collection system, leachate collection, pH, density of MSW in landfill etc. Table 26 shows the k value with different rainfall condition calculated by using Equation 5. Table 27 shows the k value of MSW of different cities in India with different waste composition; temperature and precipitation calculated using Equation 6 and 8. Table 28 shows the k value of individual wastes of Kolkata.

From Table 26 and 27, it is obtained that k value of MSW in field for Kolkata is 0.07 y^{-1} based on precipitation only and 0.04 y^{-1} based on both precipitation and temperature. Kumar et al 2014 used k value as .0.07 y^{-1} for estimation of methane emission from Kolkata. Chattopadhyay et al., 2018 used k value as 0.05 y^{-1} for estimation of methane emission from Kolkata MSW disposal site. From Table 28, it is seen that k value for food waste is maximum (0.07 y^{-1}) and k value for wood is minimum (0.007 y^{-1}). The present study used both the k value obtained from Table 26 and 27. Presently in Kolkata, there is no experimental data on k value of MSW disposal site. So, there is no opportunity to validate the k values, obtained by using different methodology. Some researchers recommend precipitation method and some researchers recommend laboratory simulation method for determination of k value of MSW disposal sites. The present study use both the method for determination of k value and used both the results in the estimation of landfill gas emission. This study helps in determining the range of LFG emission with the variation of k value. Again k value is not a constant parameter. It changes with time.

Table 26: k value for different cities in India based on precipitation

SL. No.	Name of the city	Average annual precipitation [a] (mm/year)	K [b] ($year^{-1}$)
1	Chennai	1370	0.05
2	Ahmedabad	737.5	0.03
3	Kolkata	1770	0.07
4	Mumbai	2225	0.08
5	Bengaluru	960	0.04
6	Dehradun	2175	0.08
7	Srinagar	712	0.03
8	Shimla	1387.5	0.05
9	Hyderabad	821.7	0.04

a)Source:www.weather-atlas.com, b) from equation 5

Table 27: k values of different cities in India based on simulation method

Sl. No.	Name of cities	$k_{lab, MSW}$	Annual average precipitation [a] (mm/day)	Average ambient temperature [a] (°C)	Field factor [b] (f)	$k_{field, MSW}$ [c]
1	Chennai	9.9299	3.75	28.6	0.0292	0.29
2	Ahmedabad	10.3315	2.02	27.4	0.0434	0.45
3	Kolkata	8.7969	4.85	26.1	0.0046	0.04
4	Mumbai	10.7213	6.10	26.5	0.0185	0.20
5	Bengaluru	11.7285	2.63	24.7	0.0147	0.17
6	Dehradun	9.2855	5.96	20.9	0.0590	0.55
7	Srinagar	10.1157	1.95	13.3	0.0625	0.63
8	Shimla	9.94	3.80	12.6	0.0928	0.92
9	Hyderabad	8.72	2.25	28.5	0.047	0.42

a)Source:www.weather-atlas.com, b) from equation 8, c) from equation 6.

Table 28: k value of different waste composition in Kolkata

Composition	Food waste	Branches /wood	Green waste (leaves + grass)	Textile	Paper	Other organics
% waste [a]	45.5	1.2	5	4	4	3.4
k_{lab} ($year^{-1}$) [b]	15.02	1.56	24.5	3.08	3.27	13.68
f vaule [c]	0.0046	0.0046	0.0046	0.0046	0.0046	0.0046
k_{field} ($year^{-1}$) [d]	0.07	0.007	0.11	0.014	0.015	0.06

a) source Assessment report, Dhapa, Kolkata, 2010, b) from Table 20, c) from Table 27, d) from Equation 7

4.3 Estimation of methane yield (L_0)

Methane yield is another important factor which control the total gas generation from MSW landfill sites. Accurate determination of L_0 value of MSW is necessary for proper estimation of gas generation. L_0 mainly depends on type of waste and fraction of waste present in MSW. Table 29 shows L_0 value of MSW in different city in India with change in fraction of different waste. L_0 value of MSW is calculated by using experimental method but using secondary data. It is seen that Kolkata has L_0 value of 46.51 m^3/Mg (Calculated in Table 29). It is seen that Ahmedabad has highest L_0 value (68.15 m^3/Mg) and Hyderabad has lowest L_0 value (40.49 m^3/Mg). The variation of L_0 value takes place due to the variation of waste composition.

Table 29: Percentage Composition and CH_4 yield of MSW in different city in India.

Sl. No.	Name of city	Waste composition (% wet basis)			L_0(m^3/Mg)
		Compostable matter	paper	textile	
1	Chennai	47.24	6.45	3.14	45.78
2	Ahmedabad	50.5	23	3	68.15
3	Kolkata	51.7	4	4	46.51
4	Mumbai	58.86	10	5	59.52
5	Bengaluru	62.95	8.76	4.6	61.25
6	Dehradun	45.86	3	4	40.66
7	Srinagar	58.38	7.5	2.2	55.81
8	Shimla	59.31	7.31	4.22	56.57
9	Hyderabad	40.00	7.0	1.7	40.49

Degradable organic carbon (DOC)

Degradable organic carbon (DOC) is the organic carbon in waste that is available for biological decomposition. DOC value is a characteristic of waste and depends on type of waste and fraction of different waste. The DOC in bulk waste is estimated based on the composition of waste and can be calculated from a weighted average of the degradable carbon content of various components of the waste stream. By using waste composition data of Kolkata and DOC value of individual waste of IPCC model, the DOC value of MSW of Kolkata is calculated. For Kolkata, DOC value of MSW is obtained as 0.12 kg C/kg of waste which is within the range of DOC value of MSW in India as 0.11-0.16 kg C/kg of waste obtained by Kumar et al. 2004.

4.4 Estimation of LFG emission from Dhapa MSW disposal site using LandGEM

LFG emissions from Dhapa MSW disposal site during period 2010-2030 are shown in Table 30. The emissions are calculated using k value as 0.04 y^{-1} and 0.07 y^{-1}. The total LFG, CH_4 and CO_2 emission during period 2010-2030 is 716.35 Mm^3, 393.99 Mm^3 and 322.331 Mm^3 respectively for k value of 0.04 y^{-1} and 956.94 Mm^3, 526.32 Mm^3 and 448.99 Mm^3 respectively for k value of 0.07 y^{-1}. Chattopadhyay et al., 2018 obtained CH_4 emission of 1325.5 Mm^3 for the period of 1987-2021 using k value of 0.1 $y^{-1}$and L_0 value of 70 m^3/t. Figure 25 and Figure 26 shows the LFG emission over the period of 1981-2100 from Dhapa open dump site. It is also shown that maximum emission takes place in the closure year i.e. in the year 2020. The total emission over 20 year increase by 33.6 %, if k value increased from 0.04 y^{-1} to 0.07 y^{-1}. Figure 27 shows change in LFG emission pattern with different k values. It is seen that peak rate of emission increase with increase in k value. Figure 28 shows change in LFG emission pattern with different L_0 values and it is seen that peak rate of emissions also increase with the increase in L_0 values.

Table 30: LFG emissions from Dhapa open dump site during period 2010-2030

Year	**Total LFG** (Mm^3/year)		**CH_4 emission** (Mm^3/year)		**CO_2 emission** (Mm^3/year)	
	k= 0.04 y^{-1}	**k=0.07** y^{-1}	**k=0.04** y^{-1}	**k=0.07** y^{-1}	**k=0.04** y^{-1}	**k=0.07** y^{-1}
2010	19.76	30.10	10.87	16.56	8.891	13.55
2011	23.31	35.55	12.82	19.55	10.49	16.00
2012	26.81	40.77	14.75	22.42	12.07	18.35
2013	29.23	43.99	16.07	24.19	13.15	19.80
2014	31.54	47.00	17.35	25.85	14.19	21.15
2015	33.77	49.80	18.57	27.39	15.20	22.41
2016	35.91	52.41	19.75	28.82	16.16	23.58
2017	37.96	54.84	20.88	30.16	17.08	24.68
2018	39.93	57.11	21.96	31.41	17.97	25.70
2019	41.83	59.23	23.01	32.58	18.82	26.65
2020	43.65	61.21	24.01	33.66	19.64	27.54
2021	41.94	57.07	23.07	31.39	18.87	25.68
2022	40.30	53.21	22.16	29.27	18.13	23.94
2023	38.72	49.61	21.29	27.29	17.42	22.33
2024	37.20	46.26	20.46	25.44	16.74	20.82
2025	35.74	43.13	19.66	23.72	16.08	19.41
2026	34.34	40.22	18.89	22.12	15.45	18.10
2027	32.99	37.50	18.15	20.62	14.85	16.87
2028	31.70	34.96	17.43	19.23	14.26	15.73
2029	30.46	32.60	16.75	17.93	13.70	14.67
2030	29.26	30.39	16.09	16.72	13.17	13.68
Total (Mm^3)	716.35	956.94	393.99	526.32	322.33	448.99

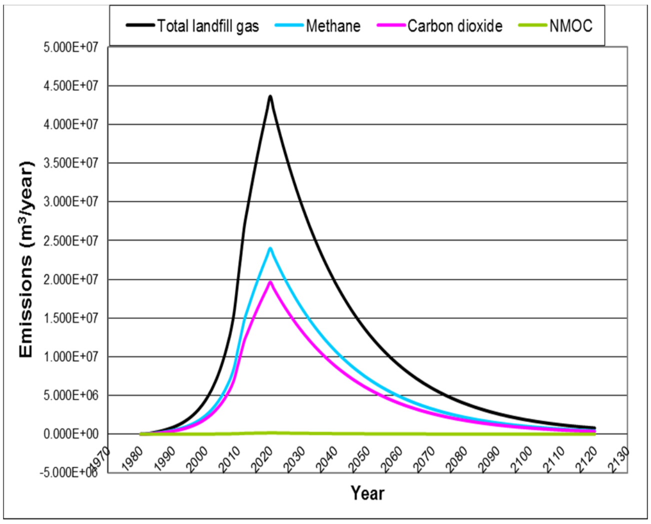


Fig. 25: LFG emission from Dhapa open dump site (k=0.04 y^{-1})

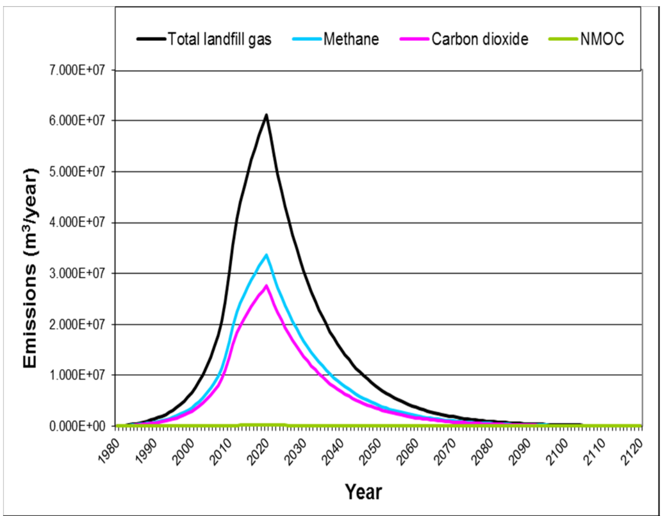


Fig. 26: LFG emission from Dhapa open dump site (k=0.07 y^{-1})

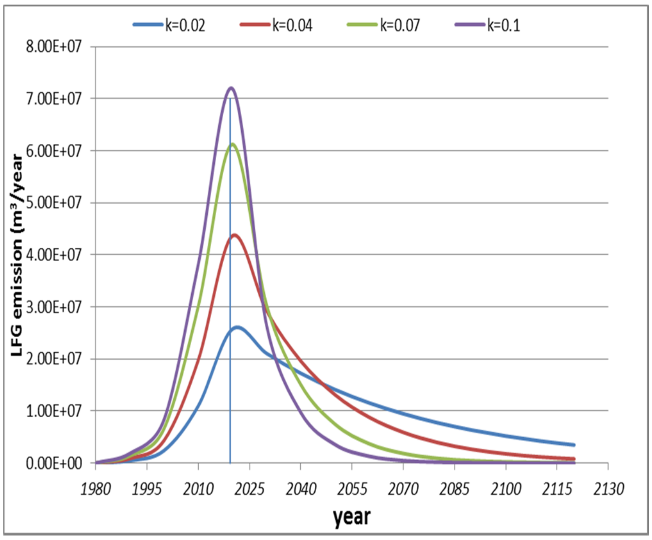


Fig. 27: Variation of LFG emissions with different value of k

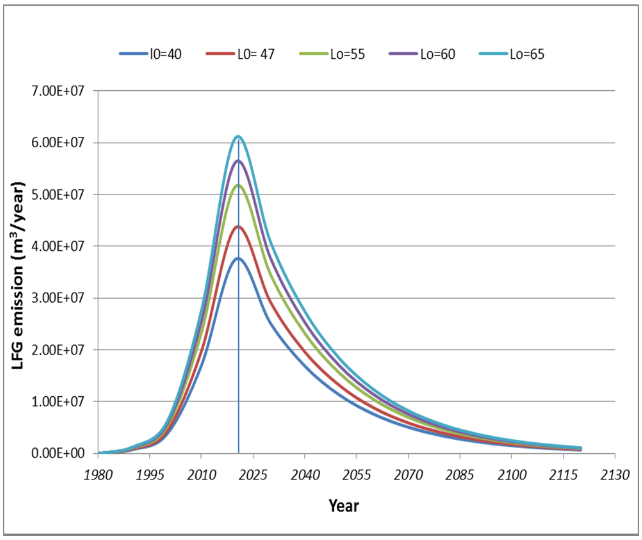


Fig 28: Variation of LFG emissions with different value of L_0

4.5 Estimation of LFG emission from Dhapa open dump site using IPCC (2006) FOD model

LFG emissions from Dhapa open dump site over 20 year time period (2010-2030) are shown in Table 31. The emissions are calculated using k value as 0.04 y^{-1} and 0.07 y^{-1}. The total LFG, CH_4 and CO_2 emission during period 2010-2030 is 652 Gg, 309.6 Gg and 253.3 Gg respectively for k value of 0.04 y^{-1} and 755 Gg, 415 Gg and 339 Gg respectively for k value of 0.07 y^{-1}. Chattopadhyay et al., 2018 obtained CH_4 emission of 656 Gg for the period of 1987-2021 using IPCC default parameter. Figure 29 and Figure 30 show LFG emission over the period of 1981-2060 from Dhapa open dump site. It is also shown that maximum emission takes place one year after the closure year i.e. in the year 2021. The total emission over 20 year increase by 34.6 %, if k value of MSW increased from 0.04 y^{-1} to 0.07 y^{-1}.

Table 31: LFG emissions from Dhapa open dump site over 20 year (2010-2030)

Year	**Total LFG** (t/year)		**CH_4 emission** (t/year)		**CO_2 emission** (t/year)	
	k= 0.04 y^{-1}	**k=0.07** y^{-1}	**k=0.04** y^{-1}	**k=0.07** y^{-1}	**k=0.04** y^{-1}	**k=0.07** y^{-1}
2010	14917.7	22696.3	8205	12,483	6713	10213.34
2011	17602.6	26799.7	9681	14,740	7921.2	12059.87
2012	20247.5	30738.2	11136	16,906	9111.4	13832.19
2013	22068.4	33168.6	12138	18,243	9930.8	14925.87
2014	23818	35434.7	13100	19,489	10718.1	15945.62
2015	25498.9	37547.6	14024	20,651	11474.5	16896.42
2016	27114	39517.7	14913	21,735	12201.3	17782.97
2017	28665.7	41354.6	15766	22,745	12899.6	18609.57
2018	30156.6	43067.3	16586	23,687	13570.5	19380.29
2019	31589	44664.2	17374	24,565	14215.1	20098.89
2020	32965.2	46153.1	18131	25,384	14834.3	20768.9
2021	34287.5	47541.4	18858	26,148	15429.4	21393.63
2022	32943.1	44327.3	18119	24,380	14824.4	19947.29
2023	31651.4	41330.5	17408	22,732	14243.1	18598.73
2024	30410.3	38536.3	16726	21,195	13684.6	17341.34
2025	29217.9	35931	16070	19,762	13148.1	16168.95

Year	Total LFG (t/year)		CH_4 emission (t/year)		CO_2 emission (t/year)	
	k= 0.04 y^{-1}	k=0.07 y^{-1}	k=0.04 y^{-1}	k=0.07 y^{-1}	k=0.04 y^{-1}	k=0.07 y^{-1}
2026	28072.3	33501.9	15440	18,426	12632.5	15075.86
2027	26971.5	31236.9	14834	17,180	12137.2	14056.61
2028	25914	29125.1	14253	16,019	11661.3	13106.3
2029	24897.9	27156.1	13694	14,936	11204.1	12220.25
2030	23921.6	25320.2	13157	13,926	10764.7	11394.09
Total (tone)	562931.2	755,149	309612	415,332	253,319	339,817

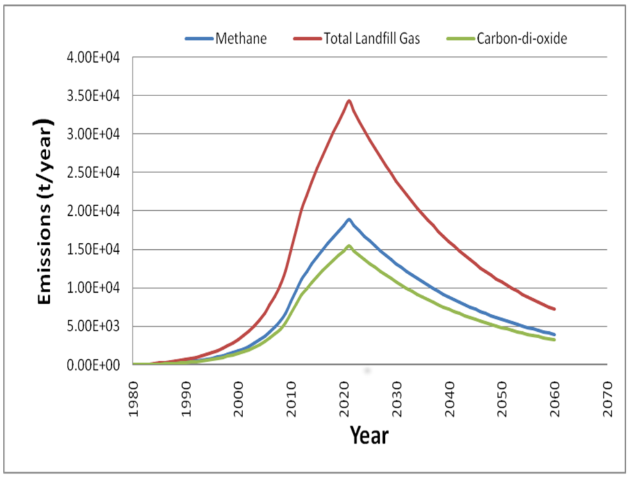


Figure 29: LFG emissions from Dhapa open dump site ($k=0.04\ y^{-1}$)

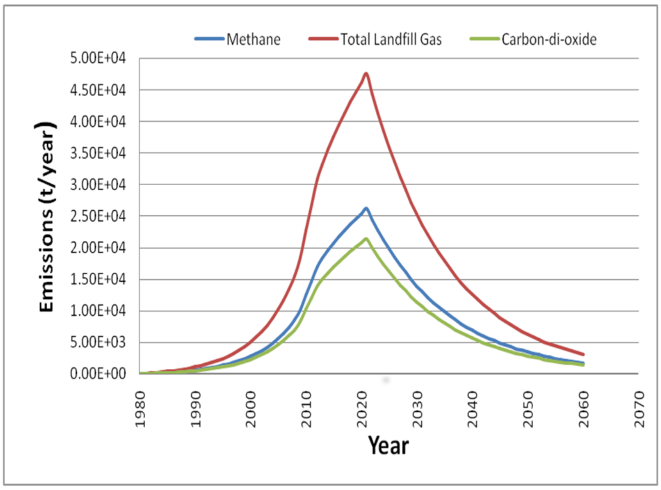


Figure 30: LFG emissions from Dhapa open dump site ($k=0.07\ y^{-1}$)

4.6 Estimation of LFG emission from Dhapa open dump site using modified triangular method (MTM)

LFG emissions from Dhapa open dump site during period 2010-2030 are shown in Table 31. The total LFG, CH_4 and CO_2 emission during period 2010-2030 is 1160.731 Mm^3, 638.402 Mm^3 and 522.329 Mm^3 respectively. Figure 31 shows the LFG emission over the period of 1981-2035 from Dhapa open dump site. It is also shown that maximum emission takes place two year after the closure year i.e. in the year 2022.

Table 32: LFG emissions from Dhapa open dump site over 20 year (2010-2030)

Year	Total LFG (m^3/year)	CH_4 emission (m^3/year)	CO_2 emission (m^3/year)
2010	51.57	28.36	23.20
2011	67.55	37.15	30.39
2012	79.68	43.82	35.85
2013	88.25	48.54	39.71
2014	85.74	47.15	38.58
2015	82.33	45.28	37.04
2016	80.07	44.04	36.03
2017	79.13	43.52	35.61

Year	Total LFG (m^3/year)	CH_4 emission (m^3/year)	CO_2 emission (m^3/year)
2018	79.65	43.80	35.84
2019	80.03	44.01	36.01
2020	80.28	44.15	36.12
2021	80.41	44.23	36.18
2022	80.45	44.24	36.20
2023	54.15	29.78	24.37
2024	33.83	18.61	15.22
2025	19.54	10.74	8.79
2026	11.33	6.23	5.10
2027	92.28	5.07	4.15
2028	73.83	4.06	3.32
2029	57.42	3.15	2.58
2030	43.06	2.36	1.93
Total (Mm^3)	1160.73	638.4	522.32

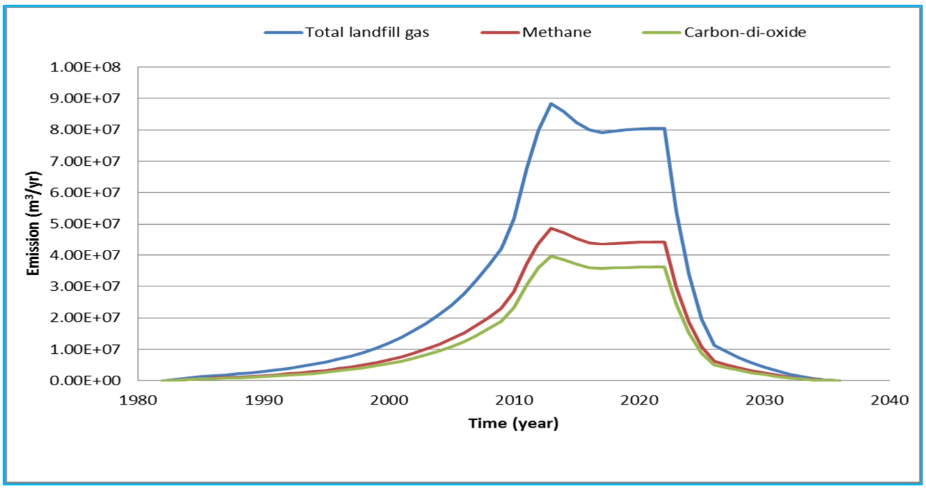


Figure 31: LFG emissions from Dhapa open dump site

LandGEM, IPCC (2006) and MTM models are applicable for estimation of LFG from engineered landfill sites. These models assume that all the degradable portion of MSW received by landfill goes on anaerobic decomposition and produce CH_4. Engineered landfill with proper cover, liner, collection facility and management facility may fulfil the assumption but there may also some aerobic decomposition of organic matter. In case of open dumping, there is no facility of cover system, liner system and collection system or very negligible covering system. So, in open dumping a considerable portion of MSW goes on aerobic decomposition. Hence methane generation predicted by models is higher than actual generation. In order to consider this phenomenon, IPCC introduce a factor called methane correction factor. The values of MCF are shown in Table 22. By applying correction factor (0.8 for uncontrolled deep site), the present study compare the methane generation from Dhapa open dump site and Dhapa landfill site (if Dhapa would be an engineered landfill site). Table 32 shows methane emission from open dump site and landfill site by applying IPCC correction factor.

Table 32: Methane emission from Dhapa open MSW dump site using various models applying field correction factor

Year	Methane emission (Gg/year)					
	LandGEM		IPCC FOD		MTM	
	Landfill Site	Open dump site	Landfill site	Open dump site	Landfill Site	Open dump site
2010	7.13	5.70	10.25	8.20	18.61	14.89
2011	8.40	6.73	12.10	9.68	24.37	19.5
2012	9.67	7.74	13.92	11.14	28.75	23
2013	10.54	8.43	15.17	12.14	31.84	25.47
2014	11.38	9.10	16.37	13.10	30.94	24.75
2015	12.18	9.74	17.52	14.02	29.70	23.76
2016	12.95	10.36	18.64	14.91	28.89	23.11
2017	13.70	10.96	19.71	15.77	28.55	22.84
2018	14.38	11.51	20.72	16.58	28.74	22.99
2019	15.11	12.08	21.71	17.37	28.87	23.10
2020	15.75	12.60	22.66	18.13	28.97	23.17
2021	15.13	12.11	23.57	18.86	29.02	23.21
2022	14.54	11.63	22.65	18.12	29.02	23.22
2023	13.97	11.17	21.76	17.41	19.54	15.63
2024	13.42	10.74	20.91	16.73	12.21	9.77
2025	11.11	8.89	20.08	16.07	7.05	5.64
2026	12.39	9.91	19.3	15.44	4.1	3.27
2027	11.90	9.53	18.54	14.83	3.33	2.66
2028	11.43	9.15	17.81	14.25	2.66	2.13
2029	10.99	8.80	17.11	13.69	2.07	1.65
2030	10.55	8.44	16.45	13.16	1.55	1.24
Total	256.62	205.32	387	309.6	418.8	335.1

Methane emission from Dhapa open dump site is 20 % less than the emission from engineered landfill site. Methane emission obtained using LandGEM is 33.68 % less than the methane emission using IPCC FOD model. Again, methane emission estimate by MTM is 8.2 % more than IPCC estimate. In MTM method, it is assumed that the total LFG emission occur from MSW, disposed in a year, within a base period of 16 year from the time of disposal. But actually the emission takes place beyond the period of 16 year. This may lead to give the higher result in MTM method. Again MTM method assume linear variation of LFG emission, but actually the variation of landfill gas emission follow exponential distribution due to first order biological reaction. This assumption also may lead to give higher result. Total methane emissions during period 2010-2030 vary from 205.62 Gg to 335.1 Gg for open dumping site. Total methane emissions during period 2010-2030 vary from 256.62 Gg to 418.8 Gg for engineered landfill site. Jash et al. 2016 obtained LFG emission of 7.5 Mm^3 by using LandGEM method and 111.7 Mm^3 by using FOD method for the year 2011 from Dhapa disposal site. Kumar et al. 2014 obtained methane emission of 406.12 Gg during the period of 2001-2020 from Kolkata using LandGEM model. Kumer et al. 2014 also concluded that Kolkata is the second largest methane emitter from waste sector among India. The total CH_4 emission value of three landfill sites in Delhi was calculated by Chakraborty et al.(2011), for the year 2009 using the DM, MTM and FOD method and obtained a result of 45.7 Gg, 41.4 Gg and FOD 31.1Gg respectively. In the observation of Chakraborty et al.(2011), MTM method give higher result than FOD model by 33.3 %. In present study using LandGEM, it is seen that CH_4 emission from Kolkata increase from 5.7 Gg/ year to 12.6 Gg/year during period 2010-2020 in open dumping condition. For the same duration and disposal condition IPCC and MTM method show that CH_4 emission increase from 8.2 Gg/ year to 18.13 Gg/year and 14.89 Gg/ year to 23.17 Gg/year respectively. These huge amounts of CH_4 generated from Dhapa disposal site may be due to high percentage of biodegradable portion in disposed waste. Again economic development, increase in population and increase in per capita income lead to generation of higher amount of MSW which leads to higher generation of LFG. From the LFG emission curves, it is shown that highest rate of gas emission occur between the period 2010 to 2030. So, present study shows the value of LFG emission between the periods of 2010-2030. But, gas emission also takes place beyond this time period. Moreover, the emission rate will be less. After the closure year LFG emission rate decrease faster than the LFG emission rate before the closure year. From the FLG emission graphs, it is also shown that considerable LFG emission takes place during the period of 10-15 years after the closure year.

Chapter – 5
Management of Landfill Gas

Presently, in India most of landfills are open dump site with no gas collection system. As a result Green House Gases (GHGs) generated in the disposal site directly emitted to the environment. This creates global warming, air pollution and explosive hazard. Climate change impact of LFG is estimated (5.94 kg CO_2 eq/KWh_e) globally. This chapter presents the possible environmental hazards due to uncontrolled emission of LFG from the study area and possible sustainable management options to minimise the impacts.

Global warming

The phenomenon of increasing average air Temperature near the surface of Earth is known as global warming. There are many reasons for global warming, but one of the main reasons is greenhouse effect. The greenhouse effect is the process by which radiation from the earth surface is absorbed by the greenhouse gases present in the atmosphere and warms near the surface of the earth. Global warming is one of the most burning issues of recent time and is caused by GHGs emitted to the atmosphere which ultimately lead to climate change. The greenhouse gases are CH_4, CO_2, N_2O, H_2O, O_3 etc. Landfill gases contain two major greenhouse gases i.e. CH_4 and CO_2 in large amount. CH_4 and CO_2 both constitute 70-80 % of the landfill gas. Methane has Global Warming Potential (GWP) of 21 with respect to CO_2 i.e. it has capacity to trap the thermal radiation 21 times more than CO_2.

Estimation of Global warming potential (GWP)

GWP is calculated as the ratio of radiative forcing of 1 kg GHG to that from 1 kg CO_2 over a period of time (100 year) (INCCA, 2010). GWP of a GHG may be defined as the potency of gas to trap heat in the atmosphere relative to CO_2. GWP of CO_2 is taken as 1. The cumulative GWP of all GHGs is expressed as the term CO_2 equivalent. The CO_2 eq is sum of CO_2 multiplied by its GWP i.e. 1, CH_4 multiplied by its GWP i.e. 21, N_2O multiplied by its GWP i.e. 310. In this study, the emission of CH_4 and CO_2 are estimated. Therefore, total CO_2 eq signifies the total GWP of CH_4 and CO_2 emitted to the atmosphere. LandGEM estimates that total GWP of GHG emitted through MSW dumping from Kolkata during period 2010-2030 is found to be 4950 Gg of CO_2 eq with 87.10 % contribution from CH_4 and balance is due to CO_2 by considering k value as 0.04 y^{-1} and that of 8139.46 Gg of CO_2 eq by considering k value as 0.07 y^{-1}. Similarly from IPCC FOD model, total GWP of GHG emitted through MSW dumping from Kolkata during period 2010-2030 is found to be 6755.2 Gg of CO_2 eq with 96.25 % contribution from CH_4 and balance is due to CO_2 by considering k value as 0.04 y^{-1} and that of 9061.8 Gg of CO_2 eq by considering k value as 0.07 y^{-1}. Similarly from MTM model, total GWP of GHG emitted through MSW dumping from Kolkata during period 2010-2030 is found to be 8071 Gg of CO_2 eq with 87.15% contribution from CH_4 and balance is due to CO_2.

Air pollution

Landfill gases contain different air pollutant such as carbon monoxide, benzene, Ni, As, Benzo-a-pyrene and different VOCs. These air pollutants have different adverse effect on public health and welfare. Collection and combustion of LFG in a flare or energy project equipment greatly reduces emissions of methane and Non-methane Organic Compounds (NMOC). But, the combustion process generates criteria pollutants including carbon monoxide (CO), nitrogen oxides (NO_X), sulphur dioxide (SO_2), and particulate matter (PM). NO_X formation is strongly tied to the combustion temperature in the equipment, while CO and PM emissions are primarily the result of incomplete combustion of the gases. SO_2 production depends upon the amount of sulphur in the LFG. With the increase in landfill gas emission to the atmosphere, increase these air pollutants in the atmosphere. Once the concentrations of these gases cross the threshold limit, it become toxic to the environment and different undesirable activities take place.

Explosive hazard

People may be exposed to landfill gases either at the landfill or in their communities. Landfill gases may migrate from the landfill either above or below ground. Gases can move through the landfill surface to the ambient air. Once in the air, the landfill gases can be carried to the community with the wind. Gases may also move through the soil underground and enter homes or utility corridors on or adjacent to the landfill. Landfill gas may form an explosive mixture when it combines with air in certain proportions. Methane is the constituent of landfill gas that has greatest explosion hazard. Methane is explosive between its lower explosive limit (LEL) (5% by volume) and its upper explosive limit (UEL) (15% by volume). As methane concentrations within the landfill are typically 50% (much higher than its UEL), methane is unlikely to explode within the landfill boundaries. As methane migrates and get mixed with air, the methane gas mixture may also be at explosive levels. Hence it create problem in the residential areas away from landfill. Methane is susceptible to fire hazard. Other landfill gas constituents such as ammonia, hydrogen sulphide, and NMOCs are flammable. However they rarely exceed the concentrations above their LELs. So they rarely pose explosion hazards as individual gases. Table 33: presents potential explosion hazards from common landfill gas components.

Table 33: Potential Explosion Hazards from common landfill gas components

Component	Potential to Pose an Explosion Hazard
Methane	Methane is highly explosive when mixed with air at a volume between its LEL of 5% and its UEL of 15%. At concentrations below 5% and above 15%, methane is not explosive. At some landfills, methane can be produced at sufficient quantities to collect in the landfill or nearby structures at explosive levels.
Carbon dioxide	Carbon dioxide is not flammable or explosive.
Nitrogen dioxide	Nitrogen dioxide is not flammable or explosive.
Oxygen	Oxygen is not flammable, but is necessary to support explosions.
Ammonia	Ammonia is flammable. Its LEL is 15% and its UEL is 28%. However, ammonia is unlikely to collect at a concentration high enough to pose an explosion hazard.
NMOCs	Potential explosion hazards vary by chemical. For example, the LEL of benzene is 1.2% and its UEL is 7.8%. However, benzene and other NMOCs alone are unlikely to collect at concentrations high enough to pose explosion hazards.
Hydrogen sulphide	Hydrogen sulphide is flammable. Its LEL is 4% and its UEL is 44%. However, in most landfills, hydrogen sulphide is unlikely to collect at a concentration high enough to pose an explosion hazard.

To avoid these major problems, landfill gases should collect and manage it with eco-friendly technology in order to protect the environment. Collection and flaring or oxidizing in bio filters and recover of energy from CH_4 may be possible management options of LFG.

5.1 Flaring of landfill gases

A common method of treatment for landfill gases is combustion in which the methane and any other trace gases (including VOCs) are combusted in the presence of oxygen and converted to CO_2, sulphur dioxide (SO_2), oxides of nitrogen, and other related gases. Combustion technologies such as flares, incinerators, boilers, gas turbines, and internal combustion engines thermally destroy the compounds in landfill gas. Methane is converted to carbon dioxide, resulting in a large greenhouse gas impact reduction. Combustion or flaring is most efficient when the landfill gas contains at least 20% methane by volume. At this methane concentration, the landfill gas will readily form a combustible mixture with ambient air, so that only an ignition source is needed for operation. Landfills gas with less than 20% methane by volume requires supplemental fuel to operate flares, greatly increasing operating costs. The thermal destruction of landfill gases is usually accomplished in a specially designed flaring facility. Because of concerns over air pollution, modern flaring facilities are designed to meet rigorous operating specifications to ensure effective destruction of VOCs and other similar compounds that may be present in the landfill gas.

This method of treatment of landfill gases is not an efficient and suitable method because of-

1. It release a number of air pollutant which cause air pollution.
2. A large amount of capital is invested to develop combustion facility system and also there is an operation cost but there is no profit from the system.

5.2 Landfill gas energy recovery system

LFG with high methane content can be used as a valuable energy source for generation of electricity or thermal energy. It can be used as vehicular fuel. By using LandGEM method, it is estimated that CH_4 emission varies from 10.87×10^6 m^3/year to 24.01×10^6 m^3/year and annual energy generation varies from 397.17 TJ to 877 TJ (1 TJ= 10^{12} J). Power generation varies from 12.6 MW to 27.8 MW which is about 1-2% of power demand of Kolkata city. By using IPCC method, it is estimated that CH_4 emission varies from 8.2 Gg/year to 18.8 Gg/year and annual energy generation varies from 456 TJ to 1047 TJ (1 TJ= 10^{12} J). Power generation varies from 14.5 MW to 33.2 MW which is about 1-2.3% of power demand of Kolkata city. By using MTM method , it is seen that CH_4 emission varies from 28.36×10^6 m^3/year to 44.3×10^6 m^3/year and annual energy generation varies from 1036.2 TJ to 1618 TJ (1 TJ= 10^{12} J). Power generation varies from 32.86 MW to 51.3 MW. Kolkata Municipal Corporation can earn revenue by utilising the energy and that revenue can be utilised to develop the open landfill to engineered one in phased manner or for operation and maintenance of LFG and leachate control system. This helps in reducing methane emission and protects the environment from different undesirable activities of global warming and air pollution. With increasing anthropogenic activities environmental sustainability gets affected and all nations should take necessary action to hold the environmental sustainability. In this situation, energy generation from landfill gas is an economic and environmentally sustainable project. For estimation of energy recovery potential, the present study use the methane emission estimates obtained by considering k value of 0.04 y^{-1} which is calculated by using laboratory simulation method. As laboratory simulation method is more realistic than precipitation method.

The feasibility of installing a landfill gas recovery system depends on many factors such as landfill gas generation rates, the availability of users and the potential environmental impacts. Many different landfill types with varying gas production rates and composition can support energy recovery projects. If feasible, energy recovery can be implemented by use of combustion or non-combustion based technologies. Combustion-based technologies that recover energy include boilers, process heaters, gas turbines and internal combustion (IC) engines. It may be combusted in an industrial process heater to provide heat for a chemical reaction. Turbines and IC engines can combust landfill gas to generate electricity. The electricity can be used to meet power needs at the landfill or a nearby facility or the electricity may be sold to the power grid. The use of landfill gas for energy recovery may not be practical in all situations because of low gas production rate from landfills because of uncertainty in distribution of biodegradable fraction in waste, unavailable moisture content, degree of compaction etc.; less gas collection rate because of faulty cover and closure system, presence of high impurities like H_2S in landfill gas causing corrosion in IC engine; high initial cost of the project; lack of skilled labour etc.

Chapter – 6
Conclusion

The rapid industrialisation, increased urbanization, uncontrolled population growth and changing life style have resulted in generation of large quantity of MSW in India. The solid waste management system in India has not been improved with time up to the desired limit. Presently developing countries like India use conventional solid waste management. In this conventional system, one of the stages is disposal of waste in low-lying areas located in and around the urban centre without any separation of biodegradable, combustible and recyclable waste. As a result, the organic matter present in the mixed waste undergoes anaerobic decomposition and produce greenhouse gases mainly CH_4 and CO_2. If these greenhouse gases enter into the atmosphere, they affect the environmental sustainability and cause global warming and air pollution. Due to global warming, the average temperature of earth increases. As a result melting of ice mass in polar region is started and which cause the rise in sea water level. This leads to occurrence of different natural disaster like Tsunami, flood tornado etc. Again different air pollutants emitted from solid waste dumping sites lead to development of different air pollution episodes. To protect the environment, proper management of LFG emission should be done. Again methane has high energy potential of 55.7 KJ/g. it can be used as a fuel in energy generation. To use LFG in energy generation project, it is required to know the amount of LFG generation. The present study estimates the amount of LFG generated from Dhapa MSW disposal site, Kolkata using LandGEM, IPCC and MTM model. The model parameters such as methane generation rate constant (k), methane generation capacity (L_0) and DOC value are determined by using MSW composition data, temperature and rainfall data of Kolkata to make the estimates more realistic. Some other researchers also estimate LFG emission from Dhapa MSW disposal site but they use model predefined default parameters. The waste composition data, waste disposal data are collected from the work of Chattopadhyay et al. 2009 and SCS engineers, 2010. The present study revealed that CH_4 emission from Dhapa open dump site of Kolkata varies from 5.7 Gg/year to 12.6 Gg/year estimated by using LandGEM, 8.2 Gg/year to 18.86 Gg/year estimated by using IPCC model, 14.89 Gg/year to 23.22 Gg/year estimated by using MTM method during the period of 2010-2030. Presently, there is no experimental data on LFG emission of Dhapa disposal site for comparison of the model obtained values. So, it is difficult to say that which model gives accurate value of LFG emission. Yet, the results obtained from LandGEM and IPCC model can be considered as realistic estimate as they are based on first order reaction kinetics and they use site specific value of different parameters. Presently this huge amount of GHGs is directly emitted to the atmosphere and cause greenhouse effect which leads to global warming and different undesirable activities in the environment. If Dhapa open dump site is upgraded to engineered landfill with liner system, cover system and gas collection system, CH_4 emission increased by 20% (according to IPCC guidelines). CH_4 recovery from disposal site also increases. The recovered biogas can be used for power production or as fuel. Using the value of methane generation of LandGEM model, it is estimated that power generation varies from 12.6 MW to 27.8 MW and that of for IPCC and MTM model are 14.5 MW to 33.2 MW and 32.86 MW to 51.3 MW. It can be used as a source of income. The revenue obtained from the energy project can be used for proper management of solid waste and it supports the environmental sustainability. This management process also support the economy of the country and give a renewable energy source. Environmental benefits can also be claimed through reducing GHGs emission. Therefore, engineered land filling is the best method of waste disposal and should be adopted.

Future scope

To improve the present study, some key areas are identified for future research.

- The present study has been done adopting waste disposal, composition and characteristics of waste obtained from secondary sources. Primary data should be collected to get accurate data.
- The present study determines k value of MSW landfill site by using k values of different type of waste determined in developed countries. There is no experimental data on k value of different types of waste in Kolkata, India condition. So experiments should be conducted to determine k value of different types of waste.
- The present study also determines k value of the disposal site based on precipitation on the disposal site only where k value of an MSW landfill site depend on various other factors like temperature, rainfall, waste composition, pH of waste, density of waste, distribution of waste and many other minor factors. So, field experiment should be conducted to determine k value of studied MSW landfill site.
- The present study also use L_0 and DOC values determined in other countries as no data is available for Indian condition. So research should be done to determine the L_0 and DOC for Kolkata, India.
- There is no experimental data on LFG emission for Dhapa open dump site. So experiment should be conducted to know the actual gas emission from the disposal site and to check the viability of different types of models.

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