ENVIRONMENTAL IMPACT OF BIO-MINING OF LEGACY WASTE USING LIFE CYCLE ASSESSMENT METHODOLOGY

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2022

DECLARATION

*The Thesis titled "***Environmental Impact of Bio-Mining of Legacy Waste Using Life Cycle Assessment Methodology***" is prepared and submitted for the award of the degree of* ***Master of Engineering in Civil Engineering*** *course of* ***Jadavpur University*** *for the session of 2020-2022. 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 awarded in the thesis, has been duly acknowledged.*

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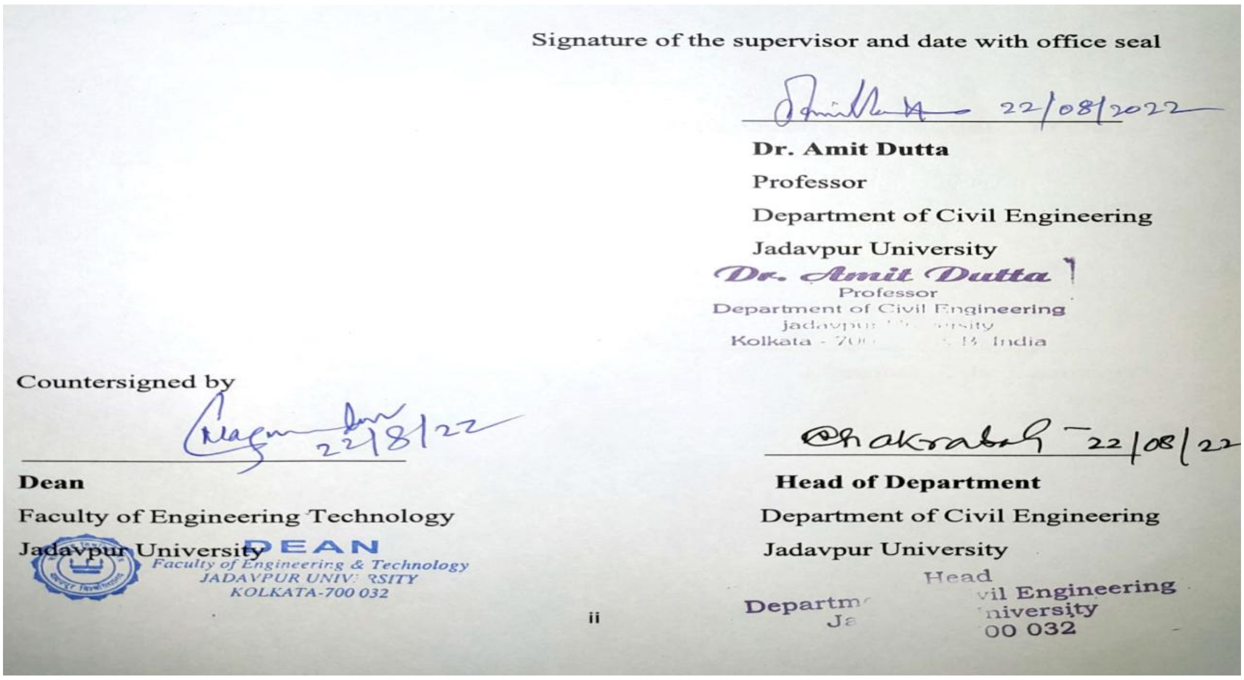

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ACKNOWLEDGEMENT

I am extremely thankful and indebted to Dr. Amit Dutta, Professor of Civil Engineering Department, Jadavpur University, for his valuable guidance, constant support and encouragement throughout my thesis work. This thesis would never been completed without his blessings, guidance, constant vigil, careful supervision and inspiration throughout the session.

I am sincerely thankful and obliged to other professors of Environmental Engineering Division Prof. S. Chakraborty, Prof. S.N. Mukherjee, Prof. T. Hazra, Prof. Anupam Deb Sarkar, Prof. A. Roy, Prof A. Majumdar for their constant and thorough guidance during my coursework of Master of Civil Engineering lead me the acquiring of clear concept of Environmental Engineering help me to understand the subject of thesis work as well full completion and submission within stipulated period.

I would likely to mention the contribution of my senior Samran Banerjee, Research Scholar of Environmental Engineering specialization, in successful completion of this thesis work. His continuous support and guidance help me to learn a lot of new things throughout the research work starting to end of thesis.

Last but not least, I express my sincere gratitude to all of my batchmates of Environmental Engineering Division for being with me.

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ABSTRACT

Urban India accounts for 62 million MT of MSW generation annually. Increased growing rate of waste generation has acquired huge land area by converting virtual mountains of old legacy waste. These old landfills are possessing real threat to the environment in terms of contaminating air, water and land. Emission of CH_4, CO_2, NH_3, H_2S and VOCs causing from landfill degradations, persistence of heavy metals to vegetations, groundwater and surface water due to leaching of toxic leachate, emission of carcinogenic compounds, HC, dioxins and furans from landfill fires are all such aspects not only deteriorating environmental standards but also inculcating human and ecological risk. In India around 10,000 hectares of urban land is locked in these open dumpsites. From 2014 onwards, the Swachh Bharat Mission has giving importance on reclamation of landfill sites and minimization of adverse environmental impact adhering to the Solid Waste Management (SWM) Rules, 2016. Recently, Hon National Green Tribunal (NGT) mandated for implementing bio-mining and bioremediation of legacy waste throughout the Indian landfills. Bio-mining involves the excavation, waste stabilization, screening and separation of materials from landfills into various components including soil i.e., good earth or bio earth, recyclable materials, combustibles and residuals with a sustainable approach to prolong the landfill life and to remediate contamination from unlined open dumps. A precise study on the potential environmental impact of bio-mining is of utmost importance in the Indian scenario. The Bio-mining project has already started in the major dumpsite of Kolkata city i.e., Dhapa landfill. This landfill site follows open dumping for more than 30 years. The condition of Dhapa has been exhausted with a huge pollution impact. The research methodology will rely on this case study. The impact analysis study is of utmost importance because of the following reasons i.e., conservation of landfill space, reduction in landfill area, elimination of a potential contamination source, mitigation of an existing contamination source, energy recovery from excavated legacy waste, reuse and recycling of recovered materials, reduction in waste management costs, GHG emission reduction and site re-development.

This study is done in two parts. In the first part, legacy waste characterization followed by its landfill degradation nature, material balancing of different bio-mining components, landfill gas and leachate generation have been studied. And in the second part, the quantitative environmental impact of bio-mining has been calculated using life cycle assessment tool.Firstly, from onsitemonthly data analysis of legacy waste, it is found that legacy waste consists of decomposable components such as Waste Soil (55.12%), Wood (0.42%), Coconut (1.01%), Animal Bone (0.66%), Textile Fabric (0.51%) and non-decomposable components such as Plastic (21.16%), Glass (1.21%), Thermocol (0.45%), Ceramic (1.55%), Gravels (9.22%), Kankar (6.61%), Mix (2.08%).During compositional analysis, the degradable matter such as food waste, wood, coconut shell, animal bone and textile fabric is assumed that the degradation pattern follows the IPCC model i.e., first-order kinetic decay rate model. Using these assumptions, the percentage transformed or degradation a portion of above-mentioned waste i.e., food waste, wood, coconut shell, animal bone and textile fabric from landfill comes 93±2%, 39±2%, 88±1%, 88±1%and 59±2% respectively consideringdecay rate constant according to the mean annual temperature (MAT) and mean annual precipitation (MAP) of the study area.The percentage transformed or average degradation of non-decomposable waste is done based on literature and from field data analysis.After taking all consideration, average physical material compositions have redistributed into six components i.e., Recyclable, Construction and Demolition waste (C & D waste), Refused-Derived-Fuel (RDF), Bio-Earth or Good Earth, Coarser Fraction and Process Rejects and material balance diagram have formed which can be used for quantity estimation of actual amount of legacy waste processing. The percentage of bio-earth obtained is around 22.484%, recyclable fraction as 3.32%, C&D waste as 18.14%, RDF as 19.747%, Coarser fraction as 19.947% and process reject is found to be 2.477%. The generated landfill gases can be reduced by around 41% in 25 years potential after implementation of bio-mining treatment. Total land area 23.5 ha can be reclaimed after bio-mining for which an estimated reduction of leachate by 68% is achievable over the bio-mining period.

In the present work, the estimation of PEI of bio-mining process is done based on LCIA approach considering three impact categories i.e., global, regional and local. Weightage of different categories and sub-categories are calculated based on analytical hierarchy process (AHP). After normalizing different sub-categories respective PEI have been calculated for different bio-mining scenario. During bio-mining condition, ATP is the highest PEI contributor (38.14%) among all sub-category due to its high weightage value and relatively higher equivalency factor. PEI contribution of HTPI and TTPL are 34.65% and 12.59%. Higher value of HTPI and TTPL are due to local impact of liquid pollutants is much more than gaseous pollutant. Percentage of PEI contribution of HTPE and TTPG are 8.53% and 2.07% respectively. In sub- category acidification potential (AP), PEI is very less due to

emission of PEI contributing pollutants in this sub-category is substantially lower in quantity. But, POCP has a significant impact potential (3.18%) majorly due to toluene. The impact sub-category ODP did not contribute any PEI value as no pollutant is generated to breakdown the ozone layer in this system. The PEI value of GWP is less (0.81%) in local perspective as the relative weightage value is less compared to other impact sub- category but it is very significant in global perspective. The resource is recovered in the form of land though the PEI value of RDP is not much but it has a significant positive impact in local perspective. The overall potential impact obtained from during bio-mining scenario is 0.3167 whereas PEI obtained before bio-mining as 0.39. So, the percentage reduction of impact is around 19% after one year of implementation of bio-mining operation. Though all the potential environmental impact will be minimized after completion of bio-mining operation.

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LIST OF ABBREVIATIONS

AHP- Analytical Hierarchy Process

AP- Acidification Potential

ATP- Aquatic Toxicity Potential

C&D- Construction and Demolition

CBA- Cost-Benefit Analysis

CFC- Chlorofluorocarbon

CPCB- Central Pollution Control Board

CPHEEO- Central Public Health and Environmental Engineering Organisation

CSE- Centre for Science and Environment

DCF-Discounted Cash Flow

EF- Equivalency Factor

EPA- Environmental Protection Agency

FOD- First Order Degradation

GHG- Greenhouse Gas

GWP- Global Warming Potential

HC- Hydrocarbon

HELP- Hydrologic Evaluation of Landfill Performance

HTPE- Human Toxicity Potential by Inhalation

HTPI- Human Toxicity Potential by Ingestion

IPCC- Intergovernmental Panel on Climate Change

IRR- Internal Rate of Return

ISO- International Organisation for Standardisation

KMC- Kolkata Municipal Corporation

LCA- Life Cycle Assessment

LCIA- Life Cycle Impact Assessment

LFG- Landfill gas

LFM-Landfill Mining

MAP- Mean Annual Temperature

MAT- Mean Annual Precipitation

MOEFCC- Ministry of Forest, Environment and Climate Change

MRF- Materials Recovery Facility

MT- Metric Ton

MWC- Municipal solid Waste Combustor
NGT- National Green Tribunal
NIOSH- National Institute for Occupational Safety and Health
NPV- Net Present Value
ODP- Ozone Depletion Potential
OSHA- Occupational Safety and Health Administration
PEI- Potential Environmental Impact
PIB- Press Information Bureau
POCP- Photochemical Ozone Conversion Potential
RDF- Refused Derived Fuel
RDP- Resource Depletion Potential
SLM- Soil Like Materials
SOP- Standard Operating Procedures
SWM- Solid Waste Management
TLV- Threshold Limit Value
TOC- Total Organic Carbon
TPBP- Toxicity, Persistence and Bioaccumulation Profile
TTPG- Terrestrial Toxicity Potential by Gases
TTPL- Terrestrial Toxicity Potential by Liquids
USEPA- United states Environmental Protection Agency
VOCs- Volatile Organic compounds
VOM- Volatile Organic Matter

Chapter 1

INTRODUCTION

Waste management is becoming challenging day by day due to the global awareness for environmental protection, sustainable development in material management and campaign of recycling and reusing materials as well as worldwide space and economic constraints.Though in the solid waste management hierarchy landfilling is least preferred option, it is still the most practiced approach of waste management around the world.In India also, the landfilling is the most favoured method for Municipal Solid Waste (MSW) disposal. Lack of appropriate technology and its improper implementation & management, the existing technology and its associated impact leads to accumulation of waste in a different shape in designated and non-designated places of each urban local bodies (Mandpe et al., 2019). At present according to PIB (Press Information Bureau) (CPCB, 2019) approx. 62 million tonnes of waste are generated in India mixed waste both recyclable and non-recyclable with a 4% average annual growth rate. The dumping of this huge amount of waste turns into a virtual mountain and becoming a point source of pollution. Dark foul liquid leachate, the evolution of foul gases e.g., Methane (CH_4), Hydrogen sulphide gas (H_2S), etc due to rotting of this waste in the airless or anaerobic condition which inevitably pollutes the groundwater and the ambient environment respectively (CPCB, 2019).To overcome this problem recently National Green Tribunal (NGT) has directed a committee to assess the amount of damage caused to the dump sites. The Hon’ble NGT additionally instructed that each city and town follow clause "J" of Schedule-I of the SWM Rules, 2016. Last but not least, the Hon'ble NGT directed CPCB to propose Standard Operating Procedures (SOP) for the implementation of bio-mining and bio-remediation of legacy waste.

1.1 PRESENT STATUS OF LEGACY WASTE

The term "legacy wastes" refers to wastes that have been collected and stored for many years on a landfill or other area of unused land (an area to dump solid waste).The management of solid waste in cities or towns is impeded by two main issues: (1) the handling of the daily constant flow of solid waste, and (2) dealing with the legacy of neglect that has led to the accumulation of waste piles at dump sites that were intended for waste processing and landfills. Uncontrolled dumping of mixed municipal waste, aided by flawed laws, has created around 3,159 dumpsites in the country (CSE, 2020). In the past, these dumps were frequently found on the periphery of urban growth, and as cities grew, the urban periphery expanded past the open dumps, bringing residential and commercial development into close proximity with the open waste.

In India, these dumpsites are estimated to contain more than 10,000 hectares of urban area (CPCB, 2019). These landfills have developed into ticking time bombs, with all the potential environmental effects that come along with them, such as air, water, and soil pollution. In the absence of exposure to the air, these landfills produce methane, a greenhouse gas, and other landfill gases which contributes to global warming. They also produce leachate, a waste-generated liquid that pollutes groundwater. Air pollution results from frequent fire outbreaks at the landfills. Even if these landfills are already filled with waste and cannot accommodate any more, the appearance of these dumps encourages more waste to be dumped there.

Legacy waste consumes huge space as well as becomes the favourite place for the microbe, flies, rank gases, and age of leachate which may prompt ground water or surface water contamination. They likewise add to the age of ozone-depleting substances and posture hazards to wild fire. The methane delivered at strong garbage removal destinations contributes around 3 to 4 percent to the yearly worldwide anthropogenic ozone harming substance discharge (IPCC, 2001).The simplest and quickest method to minimize our nation's emissions and protect neighbouring villages from polluted water sources, smoke, flies, and odour is to remove these mountains of decades-old waste or legacy waste.Also due to the inherent problem of old dumpsite waste or legacy waste, National Green Tribunal (NGT) has directed a committee to determine the extent of the damage caused in the dumpsite and also recommends the clearing of dumpsite by implementing Standard Operating Processing (SOP), known as Bio-mining and Bioremediation under the supervision of CPCB (Central Pollution Control Board) (CPCB, 2019).The NGT has directed that the remediation of these dumpsites be carried out in accordance with clause "J" of Schedule-I of the SWM Rules, 2016, i.e., the observation being made by the following: (1) where bio-mining and bioremediation is possible, such choices can be exercised, which are not only economical but also environmentally safe. There is a very rare situation when bioremediation is not possible. (2)The option of capping legacy wastes, which has severe negative effects on the environment and human health, is completely out of the question, with the exception of inert materials, which must once again be disposed of in a scientifically secured landfill.

1.2 PROCESS OF BIO-MINING

Biomining (also referred as landfill mining) refers to the process of digging out the previously dumped/disposed materials from a Landfill to recover metal, plastic, glass, combustibles, soil,C&D waste and other fine materials. It also refers to clearing the open dumpsites by segregating the prevailing waste into different constituents and converting the biodegradable portion into compost, methane gas or bio-diesel and the remaining non-recyclable plastic as refused derived fuels, which in turn can be used as an alternate fuel in industries. The compostable fraction of the waste is separated through screening and sold for use in landscaping or as a soil enhancer or fertiliser. The major factors which have contributed to the rising need of bio-mining concepts are: reducing the greenhouse gas emissions, avoiding the surface water and groundwater contamination due to open dumps since it is unlined, reducing the footprint area of landfill i.e., increasing land value and economic costs associated with it, rising energy demand, improved reuse and recycling concepts especially the variety of metals available which have a market value and reducing the post-closure operation and maintenance costs(Mohan & Joseph, 2020).

The overview of Bio-mining process is explained below:

Generally, Bio-mining is done in three phases:

Phase 1: Waste Stabilization

Initially, the dumping site is converted into equal-sized windrows and turned frequently, bio-culture is added onto it.This stage eliminates pathogens, lessens moisture and flies, and removes odour. The addition of bio-culture increases the rate of the decomposition of waste to carbon dioxide and water vapour and produces biological heat inside of it which helps to dry up the waste and reduce its volume by 35–40%. In this process (termed as bioremediation), the waste material is dried out enough for screening.The waste is regarded as stable when there is no longer any production of heat, landfill gas, or leachate.

Phase 2: Sorting and segregation

In this stage, stabilised excavated landfill waste is separated to obtain soil, stones, and combustibles and other type of waste fraction. The aggregates and other heavy construction debris are separated using a series of trommels and manpower.

Phase 3: Disposal of segregated waste

In this phase, the non-combustible fractions including soil and stones are disposed of for further processing into finer aggregates or used as earth fill; metals, glasses are sent for recycling facility. The combustible fractions, often termed as refuse-derived fuel (RDF), are generally delivered for co-processing in cement industries.

1.3 POTENTIAL BENEFITS AND LIMITATION OF BIO-MINING

Benefits

- Reduction in Green House Gas Emissions, ground water contamination and soil pollution
- Revenue generation from the sale of recyclable materials and reclaimed soil
- Energy production from the combustible reclaimed waste
- Reduction in landfill closure costs and reclamation of land for other various uses
- Increase in local real estate and rental values
- Upliftment of the environmental, aesthetic and social parameters of entire area

Limitations/ Challenges

- The challenges of bio-mining associated with proper management of hazardous waste that may be uncovered during reclamation operations
- Managing the releases of gases, odours, its associated risks to human health and controlling any fire, subsidence or collapse
- Due to the high density of was being handled, reclamation activities reduce the useful life of equipment, such as excavators and loaders.

1.4 REQUIREMENTS BEFORE IMPLEMENTATION OF BIO-MINING

It is suggested before starting of the operation of project, precursor studies including history of the site, waste compositional analysis should be done. A total station survey or drone mapping of any landfill site must be carried out prior to start of the project. Volume of waste to be determined through total station survey and site measurements. Drone mapping of heap volumes at different stages is fast and most cost-effective.

Before and after biomining operations, it is necessary to conduct baseline studies of heavy metals in surface and subsurface soils and water, as well as surface hydrology, topography, rainfall, soil type, and wind direction. Periodic study needs to be done even after completion of biomining to check for any adverse effects in the surrounding area.

Chapter 2

LITERATURE REVIEW

Landfill is the term used to describe a unit operation for final disposal of solid waste materials on large area of land.According to Krook et al., 2012, landfills have been serving as a final way or the destination of storing waste around the world at minimum cost. Most regions have accumulated a considerable number of old or still active landfills throughout the years, each storing vast amounts of obsolete materials and products, some of which are more valuable than others (Lifset et al., 2002).Due to current global conditions such as increased resource competition, rising raw material prices, limited natural reservoirs for valuable resources, and rising environmental issues, resource extraction from alternate sources is a realistic option (Kapur, 2006; Halada, 2009, Krook et al., 2012).Such possibilities bring into question the present understanding of landfills as waste disposal facilities and indicate the birth of a new Landfill Mining approach, focusing on valuable material extraction and energy resource recovery (Krook et al., 2012).The excavation of waste from disposal sites for the recovery of certain materials is far from being a novel and unprecedented concept which is known as landfill mining (LFM).According to Cossu et al., landfill mining (LFM) is the "excavation and treatment of waste from an inactive landfill for one or more of the purposes such as landfill area conservation, landfill area reduction, elimination of the potentially contaminated source of pollution, mitigation of an existing source of contamination, energy and resource recovery by excavating waste, reuse of recovered materials, reduction of waste management system costs, and site re-development."andKrook et al., 2012, defined LFM as “a process for extracting materials or other solid natural resources from waste materials that had previously been disposed of by burying them in the ground”.In India this process termed as Bio-mining which follows the circularity concept, involves recover, recycle, and reuse with the goal of creating a sustainable resource to protect the environment by eliminating waste, as well as enabling society to become more autonomous and pollution-free (Joshi and Nachiappan, 2007).In terms of efficient resource recovery and landfill reclamation, landfill mining or bio-mining has common aspects in both the Indian and global contexts.

2.1 GLOBAL SCENARIO OF LANDFILL MINING

According to Savage et al. (1993), the first known operation of an industrial excavation of a landfill, which included heavier machines such as excavators and sorting equipment, was carried out in Israel in 1953 to produce fertilisers for orchards. According to Krook et al. (2012), no cases were reported after that until the 1990s, when stricter landfill regulations made approvals for new landfills difficult to get, forcing a few dump owners to think outside the box. As a result, some landfill owners in the United States have begun to exhume landfills and utilise materials in order to extend the life of their landfills, obtain useful landfill space, and postpone the costly final cover (Spencer, 1990; Richard et al., 1996). Similar trends could be observed in Europe and Asia, though these regions' landfill mining was primarily motivated by the increase in demand for contaminated waste cleanup and the removal of landfills that were obstructing urban development (Cossu et al., 1996; Hogland et al., 1995).Landfillmining emerged in the 2000s, but this time it was fueled primarily by a resource perspective and many policymakers' concerns about long-term mineral supply. Around the same time, material flow researchers (e.g., Baccini& Brunner, 1991; Sörme et al., 2001; Graedel et al., 2004) began to look at the flow of materials in a different way, not to predict future sources of pollution, but to find out where resources accumulated in the built environment. Increased commodity prices increased landfill owners' interest in the discarded material, which was valuable. As a result, a number of recycling companies have expressed an interest in recovering materials from their dumps. Many small-scale LFM projects have been carried out around the world, such as in Denmark (Rosendahl, 2015), Belgium (Jones et al., 2013), Finland (Kaartinen et al., 2013), Germany (Franke et al., 2010), Italy (Zanetti &Goido, 2006), the United States (US EPA, 1997), India (Kurian et al., 2003), and Thailand (Prechthai et al., 2008). Different LFM activities around the world are described below-

2.1.1 Landfill mining operation in USA

In US during the 1990s environmental legislation, either directly or indirectly, was one of the most major factors for the revival of interest in landfill mining. Many landfills were forced to close as a result of these regulations, which also included stricter standards for final closure and post-management, such as long-term monitoring of pollutants (Spencer, 1990; Richard et al., 1996a; 1996b). This occurred at a period when landfilling was still the most popular waste disposal option in the country, and obtaining authorization to build new landfills was becoming increasingly difficult, due to strong public opposition. Excavation, handling, treatment, and recovery of landfilled materials then emerged as a promising approach for dealing with the growing shortage of landfill void capacity while also lowering or delaying costs related to final closure, retrofitting, and post-monitoring of the increasing number of old landfills approaching the end of their useful lives (Dickinson, 1995; Reeves and Murray, 1996; 1997).At the same time, other advantages like revenue from recovered materials and reclaimed land could be achieved. In the United States, the first projects were initiated in

Naples, Florida (1986-1992) and Edinburgh, New York (1988). Both projects were implemented to avoid and reduce landfill closure expenses as well as the environmental footprint of the landfills (US-EPA, 1997). Several pilot and full-scale studies were conducted in a various of states across the United States, including Florida, New York, Pennsylvania, Massachusetts, New Hampshire, and Delaware, as well as Ontario, Canada, with each project having a distinct goal (Guerriero, 1996). The following are some of the implemented and reported landfill mining projects in US

2.1.1.1 Naples Landfill, Collier County, Florida

The Collier County Solid Waste Management Department undertook landfill reclamation initiatives at the Naples Landfill in 1986, which was the first landfill reclamation projects in the United States. At that time, 33-acre unlined Naples landfill, contained MSW buried for up to 15 years. The objectives of landfill mining were to reduce the potential for groundwater contamination, recover and reuse cover material, decrease site closure costs, recover recyclables and reclaim landfill capacity (Stein, 1993). Total area of the Naples landfill was reclaimed by open face mining using a front-end loader as a demonstration project (Guerriero, 1996). Excavated material was fed through a vibrating screen plant (with a two- and half-inch screen) at a rate of 90-100 tons/ hour, with 85% of the material passing through the screen being recycled as cover material and the rest being considered residue, which included glass, plastics, metals, woods, and rocks (Spencer 1990). According to Collier Solid Waste Department (1991), 15% of ferrous metal from excavated waste was recovered during LFM operation in a Florida landfill, which met the quality requirements for recycling. Though the LFM project intended to reclaim the material for use as a supplementary fuel in a waste-to-energy plant, which was not implemented in reality, but the reuse of recovered soil as a landfill cover made the project feasible from an economic standpoint (Guerriero, 1996). Since the LFM activity was proved economically feasible in terms of reuse of soil material rather than a waste to energy facility by saving $4 million on cover dirt versus a $300,000 investment in landfill mining equipment, Collier County has terminated the contract for the proposed waste to energy facility (Spencer, 1990). Additional permits for mining in the Naples landfill were issued due to concerns about hazardous waste and asbestos exposure during excavation. The advantages of reclamation project according to county officials are as follows: lower operating costs due to the reuse of cover materials, a longer landfill life, reduced risk of ground-water contamination and possible avoidance of future remediation costs.

2.1.1.2 Thompson, Connecticut

30-year-old landfill in the town of Thompson, Connecticut initiated a landfill mining operation in 1986 with the objective of recapturing landfill volume and extending the life of the landfill temporarily while a permanent disposal alternative could be selected (Strange, 1998). A local excavation contractor conducted the project and excavated about 20 test pits in the landfill by using a bulldozer, a pay loader, a truck, and a screen. The dumpsite was set on fire periodically as a result the mined waste was a combination of residuals and bulky waste. At the time of the mining project, the cost of potential disposal options, including transportation, ranged from \$66 to \$88 per tonne and the cost of the mining project was \$117,000, including grading the base of the mined area to receive new MSW (Dhar, 2017). This mining operation helps the town to acquire around 18 months of disposal capacity and more time to plan its waste management program (Guerriero, 1996).

2.1.1.3 Edinburg and Hague Landfill, New York

Based on the success of the Naples Landfill reclamation project, the New York State Energy Research and Development Authority (NYSERDA) and the New York State Department of Environmental Conservation sponsored projects to assess the feasibility and cost effectiveness of undertaking landfill reclamation efforts to avoid closures and reduce the footprint of state landfills. Because of small size (5 acre) and lack of buried industrial waste in Edinburg Landfill, NYSERDA chose to conduct first demonstration project for the reclamation of one-acre land (Rosendal, 2009). NYSERDA's objectives in undertaking the Edinburg project are to determine equipment needs and develop optimal procedures for the excavation, appropriate uses for the reclaimed material, develop recommendations regarding health and safety requirements, conduct contingency planning for future landfill reclamation projects in New York (Strange, 1998). Reclaimed materials consisted of 75% soil fraction which was tested and approved for offsite use as construction fill in non-surface applications and rest 25% non-soil materials was sent for recycling. Although the evaluation indicated that 50% of the non-soil materials were taken to a Materials Recovery Facility (MRF) for recycling and the remaining materials were sent to a nearby landfill (Reclamation, 1997). The Edinburg Landfill Reclamation Project was effective in finding off-site uses for recovered soil as well as reducing the landfill footprint to lower closure costs (USEPA, 1997).

The Hague Landfill Reclamation Project, which began in 1994 after a feasibility assessment, was the first attempt in the United States to dig up and completely remove an old landfill in order to return the site to its natural form (Nelson, 1995). The goal of the project was to clear a 2.7-hectare dump from the middle of a 52-hectare area owned by the rural township so that it could be used for recreational purposes. Approximate 76,500 m^3 of waste was removed and separated for recovery of ferrous metal and for the beneficial use of soil fraction. At the Hague reclamation project, it was demonstrated that a full-scale composting process could be implemented. Composting and re-screening resulted in a 31% reduction in material that needed to be transported off-site (Steuteville, 1996).

2.1.1.4 Frey Farm Landfill, Lancaster County, Pennsylvania

In 1990, a municipal solid waste combustor (MWC) was constructed by the Lancaster County Solid Waste Management Authority to use in reducing the volume of waste deposited in the Frey Farm Landfill, a lined site containing MSW deposited for up to 5 years. Officials initiated landfill mining operation in 1991 and between 1991 and 1993, about 219,500 m^3 of MSW were excavated from the landfill (USEPA, 1997; Joseph 2004). The main goals of this operation were landfill space reclamation, increase in energy production at the Resource Recovery Facility, ferrous metal and soil cover recovery (Guerriero 1996). A 1-inch trammel screen was used to process the waste that was excavated from the landfill and approximately 56% of the landfill's excavated material was acceptable for intake at the MWC, with 41% of that being soil. Only 3% of the total excavated material was non-combustible or unsuitable for use as cover soil at the landfill, so it was returned back to the landfill for disposal (Clark et al., 2016). Benefits of the project involved reclamation of landfill space, production of supplementary energy from the recovered combustible materials, recovery of soil and ferrous metal (RenoSam 2009). Drawbacks of the project were higher ash generation due to the high soil content found in reclaimed waste, increased generation of ash caused by the high soil content found in reclaimed waste, increased odour and air pollutants, increased traffic on highways between the MWC and the landfill, and increased wear on both the landfill operation and MWC equipment (RenoSam 2009). To summarise, the resource recovery of this LFM operation was relatively low due to the long distance between the landfill site and the recovery unit for transportation of reclaimed waste and ash, as well as the avoidance of commercial hauling prices for using its trucks and employees for transportation of reclaimed waste and ash, and the lack of tipping fees due to operation by the same management authority (RenoSam, 2009).

2.1.1.5 Bethlehem Landfill, New Hampshire

MSW wastes was accumulated in Bethlehem landfill site from small towns and rural tourist areas between 1979 to 1987. The permission was given in 1989 by the New Hampshire Department of Environmental Services (NHDES) to mine the unlined landfill and transport around 160 tonnes of material from the old, unlined section to the newly lined section (Joseph et al. 2004). The permit restricted any mining or waste removal operations during the months of June, July, and August due to odour concerns, and mandated that odour-masking chemicals be used to the wastes being processed (Strange, 1998). The effects on air quality, storm water runoff quality, and quantities of oxygen, hydrogen sulphide, and volatile organics in the air were all assessed during the landfill mining process. Two excavators, one front-end loader, four dump trucks, two bulldozers, one trommel screen, and one odour control sprayer were among the mining equipment used (Joseph et al., 2004).

2.1.1.6 Barre and Newbury Landfill, Massachusetts

A proposal to mine a piece of the property that had been filled between the mid-1950s and 1970s was submitted as part of a permit application to expand a private sanitary landfill in Barre, Massachusetts (Joseph et al., 2004). Some of the cells were built to be almost completely impermeable to external water infiltration, according to tests pits excavated for material evaluation. The excavated contents were a very little degradation condition, and the recovered soil portion was employed as a cover material (Strange, 1998).

In Newbury, Massachusetts, a 3.6-hectare landfill serving a population of 6,400 people was reclaimed in 1993 to make way for a new 1.6-hectare lined landfill. Soil made about two-thirds of the mined material, which was stored for future use as cover material (Nelson, 1995).

2.1.1.7 Wyandot County Environmental Sanitary Landfill, Ohio

Wyandot County Environmental Sanitary Landfill located in Carey, Ohio is operated and owned by Central Disposal Systems (Ohio), Inc. The landfill has a total approved disposal area of 188 acres, with both unlined and lined cells. As groundwater contamination was detected near the site, the Ohio Environmental Protection Agency ordered the owners to relocate waste from unlined to lined cells. To minimize odour problem the waste relocation was started by a private contractor during winter season in 1992 and the process consisted of excavation and hauling of material to the on-site lined unit via off-road trucks. There was no impact of hazardous material but some odours were detected with minimal impact during the waste excavation process. Hard hats, steel-toe boots, long-sleeve shirts and gloves, as well as health and safety protocols for workers and the provision of respirators to workers, were all provided and maintained. After mining began, berms were built to manage storm water runoff, and runoff that came into contact with the waste was managed as leachate, resulting in an improvement in groundwater quality (IWCS 2009).

2.1.1.8 Shawano County Landfill, Wisconsin

Shawano Country landfill contained both lined and unlined cells and the leachate collected from the unlined cells were sent for off-site treatment. A waste relocation project was started to extract waste from unlined cells and dispose of it in the adjacent lined cell to lower the cost of leachate treatment. The project was started in 2001 winter for minimization of the odour problem and was completed in early 2002. Two excavators were used in the excavation, and the waste was carried to an on-site lined cell. Based on concentrations from samples collected from the stockpiled soil, bulk amounts of soil were stockpiled and classed as clean soil used for road construction, mildly contaminated soil for using with at least 2ft of clean soil and contaminated soil used for daily and intermediate cover. A private contractor completed the project, and all full-time site excavation workers received training in hazardous waste and emergency response operations. During the waste excavation process, a small amount of hazardous material (freon tanks, propane tanks, etc.) was discovered, and the hazardous materials were temporarily kept in a designated area. As the excavation was done at below grade, storm water run-off was collected and treated as leachate (IWCS 2009).

2.1.1.9 Central Disposal Systems Landfill, Iowa

This landfill consisted of 10-acre unlined and lined cell is located in Lake Mills, Iowa and operated by Central Disposal Systems, Inc. Landfill Mining operation in the unlined cell was initiated in 2000 with the objective to avoid future groundwater contamination. The waste relocation process involved extracting waste from unlined cells and disposing it into lined cell. One backhoe was used to excavate, and four trucks hauled the excavated waste to an on-site lined facility. Rather than significant waste processing in this operation, this project considered only well-decomposed mining waste as a daily cover. The waste excavation plan included a staging area for temporary storage of hazardous waste and provisions for asbestos management, but no hazardous material was encountered in the waste excavation process. To avoid odour problems, the waste relocation activity was mostly done in the winter. During the excavation, the air quality was checked at least once an hour. Storm water runoff and the runoff that came into touch with the waste was handled through the use of berms (IWCS 2009).

2.1.1.10 Pike Sanitation Landfill, Ohio

This landfill is located in Waverly, Ohio and started operation in the mid-1980s. It contained both lined and unlined cell, unlined cell (40-acre) as located in the middle of lined cell (125-acre). For the requirement of 1 foot "select waste" on the drainage layer the LFM operation was started from unlined cell to lined unit to protect the liner system. The project was started in 1996 by a private contractor and completed in 2000. Materials processing was not performed during the project. The existence of asbestos-containing material was indicated in the record of the waste so respirators were given to the stuff to use. Other than asbestos, no hazardous materials were discovered during waste excavation. Asbestos-containing materials were discarded in the lined cell. There were no odour issues, and no dusting issues were recorded. To avoid rainwater runoff to the exposed waste, waste was excavated from a lower elevation to a higher elevation (IWCS 2009).

2.1.1.11 La Crosse County, Wisconsin

The landfill consisted of both lined cell and unlined cell (about 25 acre) and operated from 1976 to 1990/1991. Despite the presence of vertical leachate and gas extraction wells in the unlined cell, groundwater contamination was found in the vicinity. The main reason behind the waste relocation project was expansion of the existing lined cell and reduction of potential future liability. The project was started in 2005 and to minimize odour issue the project was operated only in winter. With the proper health and safety plan, the project was executed by a private contractor. Soil (clay) was collected from the cap and other locations and used in future landfill operations and contaminated soil was heaped on the lined landfill. There was no requirement of trommel screen as only a small amount of residue was encountered. Limited amount of hazardous waste was discovered and it was properly managed during the project. To reduce odour from the working face, the gas-extraction system was actively operated and monitored. Residents in the area were educated about the project's relevance and potential odour issues, and no odour complaints were received throughout the project's initial phase. No dust issue was arrived during the project. The daily cover was not used. Storm water runoff was managed by the construction berms, and the runoff that came into contact with the waste was treated as leachate (IWCS 2009).

2.1.1.12 Winnebago County, Wisconsin

The landfill is located in Winnebago County, Wisconsin and consisted of both unlined and lined cells which were sealed in 1989-1990. The primary factors behind the landfill mining operation were to reduce monitoring near unlined cells and eliminate the procurement of soil for filling depressions on the tops of lined cells (2 feet of clay as final cover). To avoid odour problems, the project was started in winter season in 1990. The clay cover over the lined cell was scraped. Excavated waste from the unlined section was disposed of on top of the lined area with a dozer. Using an electromagnet, only ferrous metals were recovered from the mined materials, and the residual mined materials were disposed of on top of a lined cell. There were no other waste-processing methods used. Hazardous waste was stored in a designated area until it could be managed. Lead-acid batteries, which were later recycled, were the most dangerous materials encountered. A total of 3 to 4 acres were reclaimed (IWCS 2009).

2.1.1.13 Clovis Landfill Reclamation Project, California

A MSW landfill was located in the city of Clovis, California and it was operated by the city since 1957. LFM project was started in 1998 and was completed in 2008. The main reasons behind this landfill mining project were to minimize groundwater contamination, airspace recovery, and soil recovery. A private contractor and the city staff jointly executed the LFM operation. Excavator, 2-inch screen size trommel, conveyors, dozers were used during the landfill mining activity. Around 60% of the material excavated was comprised of soil. Hazardous materials found during mining were temporarily stored in an isolated area. Odour and dust emission were controlled from the working place. Storm water from the mining area was collected and sprayed back onto the facility's composite lined portion. In this project daily cover was not applied over the exposed waste (IWCS 2009).

2.1.1.14 Dean Forest Landfill, Georgia

Dean Forest Landfill is located in the City of Savannah, Georgia and is owned and operated by the city since 1984. The site consisted of three unlined cells and one partially lined cell. Since 1987, the city had been incinerating its waste, and the ash generated at the plant was disposed of at this location. Some MSW, construction and demolition (C&D) debris, and other waste items such as sludge were also discarded into the site. The necessity to expand and cap a 35-acre area of the landfill served as the primary motivation for the waste relocation project. The undertaking began in 1997 and was finished in 2006. Due to lack of space and time constrains the excavated waste material was not processed. The project was executed by a private contractor and detailed health and safety plan was implemented during the operation. No hazardous waste, no dust and odour issues were encountered during mining operations. Daily cover was applied and berms were constructed to handle storm water. Total 130-acre land was reclaimed (IWCS 2009).

2.1.1.15 Phoenix Rio Salado Project, Arizona

Due to deterioration of vegetation and wetland during the construction of a federal dam in the early 1900s, the Phoenix North Central Landfill, Del Rio Landfill, and various dumpsites along the low flow channels adjacent to it were partially mined under the motivation of environmental restoration under the authorization of The Water Resource Development Act of 1999. Total area covered under this project was more than 600 acres. Only in few sites waste processing was performed otherwise waste was hauled directly to a landfill. The project was started in mid-1990s and was last mentioned to be ongoing in 2012. As part of this restoration project, the City of Phoenix and the US Army Corps of Engineers performed multiple landfill mining projects all along Salt River. The excavated waste was dried before screening as the waste was primarily in wet condition. C&D waste made up the majority of the hauled material, which was recycled. Larger waste pieces were removed from the excavated material using a front-end loader and a trommel and Grizzly screen were utilised to screen around 100,000 tonnes of material, which was then re-used as clean soil. Overall, the project was reported to segregate 80% of the mined materials, while the rest was landfilled. There were very few hazardous waste and asbestos-containing waste products found.Toidentify contaminated soil, soil testing was carried out. During the project, no gas or odour issues were detected. As of 2005, more than 380,000 yd^3 of C&D debris, 20,250 yd^3 of municipal solid waste, and 600 tonnes of tyres were collected (IWCS 2009).

2.1.1.16 Perdido Landfill, Escambia County, Florida

In 2008, a pilot project was conducted in the Perdido Landfill in Escambia County, which involved the excavation of 2.5 acres of an unlined cell. The project's primary goal was to collect air space for disposal in the future.The processing of excavated waste was done by separating the waste with a shaker screen following shredding, utilizing a shaker screen without shredding and using a trommel screen for screening. From field testing, it was discovered that the trommel screen was the most effective at separating waste from cover soil. Approximately 70% of the excavated material was composed of soil which was stock piled at the site to be used at a later date for cover material. The residuals were returned back to the landfill for disposal. In terms of cost-benefit analysis, the project was found to be worthwhile. The value of the airspace acquired outweighed the mining expenditures (Clark et al., 2016).

2.1.1.17 McDougal, Ontario, Canada

The McDougal project was started in 1994. The objective of the project was removing the entire 3 ha landfill cell, lining the site, and then reintroducing the waste after screening using a power screen trommel to remove soil fractions. When contaminants were discovered in monitoring wells at the landfill, the project was encountered to address leachate issues. Furthermore, the initiative was to extend the landfill's life by 5-10 years. Soil made up around 50% of the reclaimed waste, and the majority of it was used as daily cover and landscaping (Nelson, 1995).

2.1.2 Landfill Mining in Europe

The first landfill mining experience in Europe was gained in Germany, at the Burghof landfill site in 1993 with the objective to check the technical and economic feasibility of LFM project(Rettenberger et al., 1995; Kruse, 2015). Total 53,700 tons of material was excavated from the landfill in 14 months and was screened to different fraction. About 70.5% (by weight) of the reclaimed waste was fine fraction which was reuse at the landfill and 17.5% of the reclaimed waste was light fraction which was used at waste to energy facility. The project helped to increase waste deposition volume, enhance the long-term behaviour of displaced waste, analyse the technical and economic feasibility of landfill mining, and establish more appropriate procedures for ensuring ideal environmental conditions for workers and the surrounding community (Cossu et al, 1996). Further research was carried out at the Schoneiche Landfill, one of Europe's largest site, where residential waste from Berlin's western suburbs and industrial & commercial waste from Eastern Germany had been placed for over 15 years (Obermeier and Saure, 1995). In 1994, the first landfill mining study in Italy was performed at an ancient landfill site in Sardinia, with the goal of acquiring all design criteria such as landfill characteristics and old waste quality (Cossu et al., 1995). A 10-year-old part of the Filborna landfill in Sweden was excavated as a pilot test in a research project in the summer of 1994 (Hogland et al, 1995). In 1996, Sweden hosted an international workshop on landfill mining to bring together researchers and practitioners from several nations (Hogland, 1996). The increased interest in landfill mining from domestic recycling industry and academia has led to the formation of a European consortium for landfill mining (EURELCO, to support innovation and diffusion of the subject) (Johansson, 2016). Policymakers have also started to participate in this emerging field. Some of the landfill mining activities in European countries are discussed as below

2.1.2.1 Måsalycke Landfill, Sweden

The Måsalycke landfill is located in the Southeastern part of Sweden and it was operated from beginning of the 1970s. A field study was conducted in this landfill to assess the feasibility, benefit of landfill mining. Representing samples were taken from different layers of excavated landfill and were sent to laboratory for the analysis of moisture content, % dry solids (DS), ash content, calorific value and the chemical composition. During landfill excavation, observations on the nature and composition of the waste were made and volume of pit, temperature, amount of methane in air, conductivity or resistivity of the leachate were measured. The unsegregated materials were weighted and then screened into different fraction e.g., coarser fraction, medium sized fraction, and fine fraction. The coarser fraction (>50 mm) contained large amounts of wood and paper, together constituting about 50% of the fraction. Stones and indefinable soil-like material were found in the medium-sized fraction (18-50 mm), whereas peat-like material and other small waste components e.g., partially decomposed particles of paper and garden waste, and some small particles of glass and metal were found in the fine fraction (<18 mm). The recovery system includes soil recovery for sol amendment, moistened organic fraction and re-landfilling in a bioreactor for energy generation, a unique prototype of shredder for plastic breaking up and plastic recovery for the production of polyplanks (a system of plastic planks and wood fibres). The focus is on making construction materials from waste plastic recovered from excavated landfills combined with industrially recovered waste plastic for new production (Carius et. al 1999, Hogland et al 2001).

From the laboratory analysis of the excavated samples, it was found that moisture content of the cover as well as the bottom layer in the pit was low. There was very little decomposition of the waste items discovered, and no methane production was detected. The heavy metal concentration was also determined and it was seen that in the upper layers, 0.5-2 m and 2-4 m, the concentration was low. No unexpected results were encountered. The amount of leachate generation was less and from the analysis of the leachate samples it was observed the landfill was in the methanogenic phase that means very low concentrations of volatile fatty acids, neutral/basic pH, low BOD, low BOD/COD ratio, high contents of NH_4 can be seen. The excavated material was moistened with landfill leachate before being returned to the pit. Cell 1 was filled with sorted material from the 18-50 mm fraction, whereas cell 2 was filled with unsorted material. The cells were created in a simple and cost-effective manner. Temperature, methane, and flow were all detected in the cells' pipes. The production of landfill gas in the excavated material began almost immediately after the test pits were refilled and the collection line was installed. After three months, gas production in cell 2 was very low, and methane content decreased in the landfill gas. Gas output is likely to have decreased because of the waste material dry up (Rosendal, 2009). Based on analysis of different quantitative parameters of the old landfill site, this study evaluates the stage of degradation of legacy waste and address the potential of excavated material for recycling and energy recovery. This study showed landfill mining is a feasible option for long term expansion and remediation of small and medium sized landfills.

2.1.2.2 Landfill Mining in Latvia: Status, Problem and Challenges(Dāce & Bendere, 2017)

This study is based on the assessing the state of non-remediated dumpsites in order to identify potential concerns and challenges in performing landfill mining initiatives in Latvia. In Latvia, more than 500 dumpsites have been closed, and 11 new sanitary landfills have opened. The majority of the dumpsites have been remediated, but the rest are still awaiting remediation projects. This study analysed the landfill mining project of “Kekava” dumpsite which is situated near Riga city. Covering total area of 7.35 ha, the Kekava dumpsite was formed on a foundation of sand and sandy loam with no protective layers. Mainly MSW were deposited in the site during operation time and was closed the dumpsite for further disposal in 2001. The LFM project was started in 2005-2006 with the primary aim to clean the site for development of a new residential area, material recovery was a secondary aim which was also important as substantial amount can be made from materials recycling specially from metals. The wastes were separated into three categories during the excavation process: fine fraction (mainly biodegraded organic waste residues), medium fraction (primarily plastic films), and bulky waste (tyres and metals). Tires and metals were recycled, but the medium fraction was too contaminated to recycle and was dumped in a sanitary landfill. The fine fraction was analysed to determine the proportion of organic and non-organic fraction, heavy metal concentration, quantity of oil product and concentration of sulfur, chlorine and ferrous.

From the analysis it was seen about 10-20% of the fine fraction was organic matter and the rest was non-organic compounds. The chemical analysis showed that the majority of the material was contaminated. Cu, Pb, and Zn concentrations were higher in samples taken from the top stratum of the dumpsite, with less pollution from oil products. Other heavy metals were found in higher concentrations in deeper layers, as well as significant pollution from oil products. The excavated soil didn't meet the requirement of the quality of soil that can be used as soil enhancer or greenery of road sides. So, it was deposited in a sanitary landfill.

In general, the mining operation at the 'Kekava' dumpsite cannot be considered as a complete success. Only 20% of the excavated wastes were utilised in total and the remaining 80% were contaminated by degradation of organic waste and were disposed of in a sanitary landfill. Because the soil beneath the waste had not been completely remedied and groundwater pollution had exceeded permissible levels, any dwelling house projects in the vicinity were disallowed. There were multiple reasons behind the failure of the project. Those were -lack of knowledge and experience in landfill mining, lack of supervision and monitoring during the project, financial and business interests were prioritized more than interest in environmental and legal aspects. Lack of proper legislation and database or unified information system on the status of dumpsites were the challenges faced during the execution of the project but in order to design and implement landfill mining projects successfully in the future it is recommended that the legislative changes should be made. From this landfill mining analysis, it is concluded that without proper legislation and management LFM can be economically impractical. But landfill mining is becoming more popular as a way to clean up dumpsites and landfills around the world.

2.1.2.3 Landfill Mining in Greece (Domigos et al., 2016)

This research is based on the findings of a study of the LFM pilot project in the Polugyros landfill in Chalkidiki, Greece. The major goal of this research is to determine the economic feasibility of the LFM project in Greece, as well as the techno-economic elements that influence the feasibility of scenarios of LFM activities under consideration, taking into account the project's costs and benefits. Uncertainty analysis was guided through risk assessment to detect uncertainty in the operating economic model. Sensitivity analysis and stochastic analysis (using Monte-Carlo simulation technique) were undertaken for the involvement of uncertainty in the parameters of the economic model analysis, both internal and external, during the analysis of the Cost-Benefit study of LFM operations. The financial analysis used in the cost-benefit analysis of LFM operation was carried out using a typical discounted cash flow (DCF) equity valuation approach, in real prices, using economic indicators such as Net present value (NPV) and Internal Rate of Return (IRR), as well as cash flow generated by LFM operation. During the CBA (Cost-Benefit Analysis) of LFM activities, the following factors were considered:

ⅰ) Capital costs include Pre-activity research and inventory costs, consultancy and design costs, site preparation, purchase of excavation and hauling equipment (if the equipment is purchased), screening and sorting equipment (if the equipment is purchased), and other installation costs (e.g., construction of materials handling facilities, incineration facilities for heat and energy recovery, etc)

ⅱ) Operating costs which included rental of excavation, hauling and sorting equipment, labour costs, administrative costs, fuel / energy costs, maintenance costs, water costs, other costs (e.g., training in safety issues, purchase of safety equipment, disposal cost of ash from onsite waste incineration, etc).

ⅲ) Revenues included revenues from recyclable materials e.g., ferrous metals, non-ferrous metals, glass, plastics, combustible waste, stones and construction waste, waste of electrical and electronic equipment, reclaimed soils used as landfill cover material. Excavating waste, processing, and managing excavated materials were the three stages of the LFM operation. The waste was mined utilising surface (open pit) mining principles and typical mining equipment such as excavators, backhoe loader shovels, and dump trucks for hauling dump materials.

Table 2.1: The composition of excavated material and recovery rates during LFM in Polygyros landfill

Landfill composition item	**Material Composition (%)**	**Recovery rate (%)**	**Final composition after excavation (%)**
Ferrous metal	*4*	*90*	*3.6*
Non-ferrous metal	*0.5*	*85*	*0.43*
Glass	*3.5*	*85*	*2.98*
Plastics	*4*	*85*	*3.4*
Gravel, Stones	*5*	*90*	*4.5*

Fines, Soil	*50*	*90*	*45*
Residuals			*40*

The results obtained from sensitivity analysis focussing the critical technical and economic; parameters related to uncertainty in the range of marketability of recovered materials e.g., ferrous metals, non-ferrous metals, and plastic, the sensitivity analysis of LFM operation was performed using three scenarios:

1. Subcontractor scenario or scenario A is based on the assumption that subcontractors will handle the excavation and processing.
2. Scenario analysis B assumes a low-productivity operation with low-cost equipment and personnel, i.e., "Own Resource scenario with low-productivity."
3. Scenario analysis C assumes high-productivity equipment and employees, i.e., "Own Resource scenario with high productivity," implying a larger automotive sorting system capable of higher processing rates.

The results of this scenario analysis revealed that the price of plastic and its content were the most influential factors in the LFM project, followed by non-metal and ferrous metal prices, and the NPV (Net Project Value)>0 and IRR (Internal Return Rate) >discount factor, indicating that the operation with scenario B was financially acceptable. Due to the lack of data about the true distribution of critical parameters, stochastic analysis was used to improve the estimation of probabilities by emphasising the most likely values and theoretically provide values for determining the economic feasibility of the LFM process using triangular distribution. As a result of this research, the following conclusions were obtained:

- LFM projects are financially feasible when they are located near densely populated regions; for example, reclaimed land is scarce and more expensive near urban areas, and landfill reclamation is more valuable.
- In the case of LFM operations, sophisticated material handling and sorting facilities are financially possible for big volumes of waste, while capital costs are substantially higher.
- The overall recovery rate is estimated to be between 85- 90% of all mined MSW.
- The number of fine fractions and soil-like material obtained from LFM is 45%.

This study does not include the benefits from energy recovery, reclamation of landfill area, and reduction in waste management costs which includes the cost of closure of landfill and aftermath.

2.1.2.4 Landfill mining in Austria (Hermann et al., 2014)

This was a basic technical and economic studies for landfill mining which was carried out in Austria on the basis of a pilot project. The collecting of basic data as the basis for an integrated ecological and economic assessment of landfill mining projects' feasibility was an important goal of the research. For this reason, the study identified and investigated economic, ecological, technical, organisational, political, and legal influencing factors. In addition to the influencing factors, the spatial and temporal system boundaries was defined in order to conduct additional research. A material flow analysis was utilised as the basis for an integrated economic and ecological assessment of landfill mining operations in sub-areas. Based on a fundamental objective on economic and ecological assessment, the definition and accounting of landfill mining systems or landfill systems used for comparison was carried out which includes the definition or identification of subsystems that may be present within the system boundaries, as well as the spatial and temporal system boundaries, individual processes in the system, material and goods flows. (Beckmann et al., 2012; Gohlke, 2006). The spatial system boundary was defined based on the studies insofar as all necessary process steps, such as landfill mining, preparation, and sorting, as well as the landfill operator's provision of a marketable material/product, are taken into account. Because the various time-related influencing factors need an individual project-specific determination and modification to the facts of the on-site landfill mining project, there was no universally agreed definition for the temporal system boundary.

For an integrated assessment of landfill mining projects influencing factors were discussed in the study which includes economic influencing factors, ecological influencing factors, technical influencing factors, organizational influencing factors, political and legal influencing factors, and mutually influencing factors. Economic influencing factors were often cost and revenue items that correspond directly with other influencing parameters and allowed for an evaluation of landfill mining project economics (Gosten, 2009). As per German Association for Water, Wastewater and Waste, cost item involves cost for mining action planning and approval, including all opinions and evidence, surface seal mining and gas collecting system mining, as well as intermediate storage of reusable resources, measures to ensure that hazardous waste is properly recovered, protected, and disposed of, waste removal and loading, including rough sorting (excavator sorting) for waste and soil separation, as well as coarse contaminants and hazardous waste separation, transportation of dump material that can be recycled for further processing (sorting, treatment, etc.), all treatment products are sampled, analysed, and reviewed in accordance with the assignment values, basic or intermediate cover, refilling of non-recyclable waste bins, for example, construction of a new surface seal for the landfill (if non-recyclable residues were redeposited at the site), monitoring of emissions, Compensating measures for residents and neighbours. Revenue item involved revenue from the recovery of secondary raw materials and fuels (scrap iron, non-ferrous metals, high calorific fraction, and so on) based on their qualities and raw material market prices, recovery of landfill space and surface, recoveries from already-paid levy imposed on the landfilling of waste etc. Ecological factors that have a detrimental influence on landfill mining that can be emissions into the air, soil, and water caused by excavating the landfill, preparing the waste material, and necessary transportation methods. The removal of pollutants from the landfill, the renaturation of landfill space, the removal of a source of risk (e.g., hazardous landfill waste), and the clean-up of a polluted site are examples of ecological factors having good consequences (Schulte, 2012). The capacity to deconstruct a landfill site was mostly determined by technical influencing factors, which principally affect excavation, sorting (pulping, conditioning/packaging, and sorting), and landfill material preparation (Pretz and Garth, 2012; Rettenberger, 2012a). Operators, owners, and neighbouring structures of landfill sites were defined as organisational influencing factors on landfill mining projects, which are taken into account in order to account for the influence of individuals, groups, or institutions on such projects (Milosevic and Naunovic, 2013). At the European and national levels, the political and legal environment, particularly for landfill mining that takes into account the recovery of recyclable products from landfills, is now loaded with uncertainty. There was an extensive legal network in Austria that controls the licencing, operation, closure, and aftercare of landfills, but no substantial legislation exists for landfill mining.

At the time of this research, individual economic criteria, such as cost and revenue items, as well as technical specifications or needs, was available for an integrated and verifiable ecological/economic assessment of landfill mining projects, but there were no standardised assessment techniques. Land recycling, re-use possibilities, price variations on secondary raw material markets, operating structures or synergies, and expenses saved in aftercare were not taken into account, or were not taken into account sufficiently. However, the essential foundations, influencing elements, and system limits must be analysed and established in advance in order to construct these evaluation tools. The selection of the assessment instrument as well as the outcome of the subsequent evaluation are heavily influenced by the definition of the spatial and temporal system boundaries. Based on the results given in this study, a number of distinct research projects in a variety of directions were required. Quantification of the various affecting factors outlined in this article was desperately needed. The multidimensionality of the five categories of influencing elements, as well as the aggregation of individual factors within groupings (e.g., economic), creates several research problems that need to be answered. The evaluation, selection, adaption, or development of relevant integrated economic/ecological assessment methodologies for landfill mining projects should be a future emphasis. Overall, this study was a qualitative assessment for ecological and economics of landfill mining projects in Austria but this study didn't give proper validation of the obtained results as real data was not used.

2.1.3 Landfill mining in Asian Region

Landfill mining has been reported as a method of waste management planned or implemented in many developing countries in Asia. The first landfill mining was conducted in Asia is reported in Sin Lin, China (Kurain et al., 2004). The landfill mining activity was started in Nanjido landfill, Seoul, Korea to reduce the environmental problems and create a recreative area (Twyford, Keith 2008). The following are some examples of landfill mining in Asian countries:

2.1.3.1 Landfill mining in China

In China, landfill mining and greenhouse growing systems are two ways to combine existing Chinese landfills and horticultural activities (Sino - Australian Mission on Integrated Solid Waste Management, 1997). The first landfill mining activity in China was reported in Sin Lin with the objective to reuse the soil fraction as fertility, residual inorganic fraction to be used as a source of energy, space for disposal for new waste and reclamation of landfill. The excavated waste in-situ at Sin Lin was screened to produce three fractions i.e., biodegraded organics, combustible inorganics, and non-combustible residuals. Excavated cells were prepared for refilling with new waste, allowing for artificial lining of existing cells, reduced bund wall dimensions, and upgrades to leachate and gas collecting systems. The residuals that were non-combustible were returned to the prepared cell. As a final cover and the basis for the horticulture programme, biodegraded organics from old cells were blended with freshly excavated silts and bund wall trimmings to create a rich and healthy growing medium. To accomplish faster and more complete biodegradation of cell organics and larger gas outputs, the completed cells were maintained as in-situ bioreactors with enhanced leachate drainage and collection, as well as leachate recycling. Horticulture activities were carried out in greenhouses built on completed cells. A waste to energy plant on the site was used to combust the recovered combustible organic portion and methane from bioreactor cell.

A cost-benefit analysis of landfill mining and material recycling in China (Zhou et al., 2015).

This study was based on a cost-benefit analysis model to determine whether a landfill mining operation would be economically feasible. The Yingchun municipal solid waste landfill, which is situated in Jingmen, Hubei Province, central China, was the region of study selected for this research project.Covering 11.3 ha area, the landfill was constructed in 1989 and closed in 2004. LFM project was started in 2013. The total amount of disposed municipal solid waste was 1470 thousand ton and at the time of this research the stored waste in the landfill had been estimated to be approximately 501,000 ton (551,000 m^3). Before starting the study, necessary data like topographical, historical data were collected. The CBA model of landfill mining was used, and the economic viability was evaluated, based on field study and local investigation. Economic variables related to landfill mining and material-energy recovery were selected for evaluating the economic benefits of landfill mining based on earlier research by Vander Zee et al. (2004) and the USEPA,(1997).

For the preparation of framework of cost-benefit model, eight indicators of costs and nine indicators of benefits of the landfill mining activity were taken into account. Two types of cost were considered i.e., Capital cost and Operational cost. Capital cost includes site preparation, rental or purchase of excavation and hauling equipment, rental or purchase of screening and sorting equipment, construction or expansion of materials handling facilities. Operation cost includes pre-activity research cost, waste processing cost (excavation, screening, and sorting), cost of material transportation, waste final disposal cost. Benefit indicator were land and space reclamation for urban development and recovery of air space, Recovery of recyclable materials which include soil-like material for use of organic fertilizer and substrate, recycling of stone and construction material, glass, and metal. Recovery of energy e.g., production of RDF from waste plastics, generation of heat or electricity through incineration of combustible waste, and avoidance of post-closure care e.g., evasion of leachate collection and treatment, and emission of landfill gas.

Four landfill mining scenarios were developed and then analysed in accordance with the various methods of land reclamation and energy recovery to comprehend the cost-benefit ratio of landfill mining projects.Scenario 1 was occupied land of the old landfill reclaimed for urban and industrial development and generation of electricity through incineration of high calorific material and the total benefit was supposed to be obtained from this scenario. Scenario 2 was used for purpose of benefit due to the recovery of air space from the old landfill for use as a new landfill cell after mining and generation of electricity through incineration of high calorific material. Scenario 3 for benefits of reclamation of old landfill for urban and industrial development and the preparation of RDF from high calorific materials. Scenario 4 for benefits of the recovery of air space after mining and acquisition of RDF from high calorific materials and the total minimum benefit was supposed to obtain in this scenario. The indicator of net present value (NPV) was adopted for the determination of economic feasibility and the market potential of landfill mining.

As a conclusion, after evaluating of NPV it was seen that NPV of all four scenarios was higher than 0 which indicates the landfill mining project will result in a higher benefit than expected. The quantitative evaluation of cost-benefit showed that the cost of renting excavation and hauling equipment was the highest, followed by the cost of waste processing and the cost of material transportation; however, the benefit of generating electricity by incinerating combustibles came first, followed by the benefit of land reclamation, and finally the benefit of recycling soil-like materials. The NPV was sensitive to the technique used for reclaiming land, the method used for recovering energy, and the likelihood of reaping the benefits of eliminating post-closure care.This study was an entirely quantitative analysis to assess economic feasibility and market potential of landfill mining which is important for making decision on landfill mining projects.

2.2 LANDFILL MINING PROJECTS IN INDIA

In India more than 3000 unscientific constructed landfills need to be closed permanently or reclaimed as these landfills create serious damage to the environment in terms of generating leachates, emitting greenhouse gases, polluting groundwater etc (https://www.downtoearth.org.in). To remediate this problem, CPCB has published a guidelinein 2019 for implementation of Bio-mining and Bioremediation all over India for treatment of raised in all over India as the best approach for landfill reclamation. Though, in 1989 first pilot scale basis mining project was done at Deonar dumpsite near Mumbai with the objective to enable the recovery of decomposed waste as compost (Kurian et al., 2003). The first bio-mining experiment was adopted in 2002-03at Panchvati, Nasik city in Maharashtra, where a 28-acre site with an average 4-7 m depth of garbage was engulfed by the expanding the existing facility.Bio-culture was employed at a rate of 250 g/m3 to improve the windrow composting process of old waste and the waste was removed in 120 days at a total cost of 6.4 million rupees(Mohan & Joseph, 2020). Currently in India various state adopted bio-mining operation, some of which successfully completed bio-mining operation and some of are in ongoing stage. From various literature, several bio-mining activitiesthathave been done and are being conducted in India are discussed as follows:

2.2.1 Landfill Mining at Kumbakonam, Tamil Nadu

The 40-year-old Karikulam dumping yard inKumbakonum was accumulated with total volume of 1.1 lakhs cubic meter of unsegregated waste. There was no space left for future MSW dumping and the average height of the dump yard was 7 meters from the ground level. Around7.5 acres of land was dumped indiscriminately with MSW out of total 10.5 acres, with the remaining areas being used for green cover and other facilities. The Kumbakonam Municipality considered a number of possibilities for a permanent solution to prevent pollution from the dumping ground. The first proposal was to do bio-cappingbut in this case lot of disadvantage arises like land area would not be reclaimed permanently, leachate would continue to pollute groundwater, Odour would not be reduced. This made them go for biomining in 2015.

The municipality decided to provide the contract to Zigma Global Environ Solutions Pvt. Ltd after considering two points: the quantity of the prevailing waste and time required to clear the entire dump yard.Zigma conducted a contour mapping survey before the presentation to assess the quantity of waste dumped and then assessed the time required to clear the entire dump yard.The plant started operations in the month of August 2015 and with the help of different machineries including trommels, vibro separators, air density separators, conveyors and magnetic separators, it managed to segregate around 14 different aggregates enabling efficient and responsible disposal of all of them. The plant has achieved 0% rejects, which implies it disposes off all its aggregates in a completely responsible manner to the tune of 100%(MOUD, 2016).

After segregation of waste material, different ways it has been used as resource are 17% for cement companies and power plants, 15% pyrolysis plants, 6% recyclers, 2% reclaimers, 3% recycling companies, 0.5% steel plants, 5% pipe making companies, 6% soil enricher to sugarcane farmers and 6.5% consisting of wood cloth and other organic items are shredded and sold as refuse-derived fuel to cement companies and power plants(Mohan & Joseph, 2020). As of now the entire quantity of legacy waste is processed and the ULB has built an RCC Compost Plant and a 70 MT per day MSW Processing plant in the 2 acres land reclaimed.

2.2.2 Bioremediation / Bio-miming at Indore, Madhya Pradesh

The 100 acres dumping ground in Devguradia was accumulated with 15 lakh metric tonnes of legacy waste over 50 years. This huge amount of waste led to frequent fires at the dumping ground due to hidden methane pockets that affected air quality. The dumping ground also posed soil pollution, ground water contamination and serious health hazards for those living nearby(Cities, n.d.). In 2016, Indore Municipal Corporation (IMC) took initiative to bioremediate the land and handed over the project to E-Tech Projects Private Limited. The objective of the project was to clear legacy waste dumps as well as existing operational dumpsite and to Reclaim 100 Acre land of worth Rs.300 Cr. With the help of 10 Trommels, 15 Horizontal Screens, more than 50 excavators, back hoe loaders with 200 plus workers, Indore treated 15 lakh metric ton of legacy waste in 3 year(Management, n.d.). The project work was completed in December 2018 with the 100% remediation of legacy waste.

After segregation of waste component from the bio-mining process, the recyclable material like plastic, glass, metal, rugs cloths were bundled and sold. The coarser fraction like stone, brick, ceramics were sent for land filling or for filling up the low-lying area. The soil recovered from the process was used for refilling the ground on the same site where a greenery is developed. The recovered construction and demolition (C&D) waste wassent to C&D processing facility to produce building materials and the left-over waste was sent to secured landfill(Highlights & Objectives, 2017). 100 acres of land had been reclaimed and the area has been made as a green park with thousands of plants.

2.2.3 Bio-mining Project at Tirupati, Andhra Pradesh

With a 4.5 lakhs city population and more than 1 lakh floating population, the city Tirupati generated about 240 metric ton of municipal solid waste every day. For the last few years, the waste generated in the city was disposed at Ramapuram Dumpsite which was 12 km away from the city. Frequent fire at the dumpsite had led to create panic among people in these areas and calls for yards to be closed(https://timesofindia.indiatimes.com). The Tirupati Smart City Corporation Limited (TSCCL) decided to implement Bio-mining project at Ramapuram Dumpsite under Implementation of the Smart City Mission in Tirupati. Tirupati Municipal Corporation (TMC) handed over the project to Zigma Global Environ Solutions Private Limited. The work of bio-mining has started in Jan 2019 and operation and maintenance work is expected to complete in Jul 2022.

Total 106750 Tonnes of legacy waste was processed by the end of January2020 and the quantity of extracted reusable materials were dispatched to third party trader for proper use of the materials. Different component recovered from bio-mining process were as follows: Bio-Earth 44630.735 ton, RDF 4826.07 ton, Stones/ C&D 5090.795 ton, Wood Scrap 5.8 ton, Rubber Scrap 18 ton, Ferrous Scrap 2.74 ton, Glass Scrap 63.76 ton, Plastic (Non-RDF) 0.32 ton (USEPA, 1997).The advantage of conducting bio-mining operation at Ramapuram comes out to be: dumping yard land will completely remediated and reclaimed, water, soil &air pollution will be reduced, overall health of the people in the surrounding area will be improved and fauna & flora in the surrounding area will be improved.

2.2.4 Bio-mining at Vijayawada, Andhra Pradesh

45 acres dumpsite yard in Ajit Singh Nagar at Vijayawada had been reclaimed by Vijayawada Municipal Corporation (VMC). The residents who live next to the dumping yard are now free from foul smells, mosquitoes, and flies after many years of struggle and suffering. Thousands of tonnes of waste that had been piled up in the dumping yard for more than 20 years has finally been segregated and removed by the process Bio-mining. The VMC handed over the project to Zigma Global Environ Solutions Pvt Ltd and the operation started in 2018 (Management, n.d.).

45 acres of valuable land had been reclaimed by installing bio-mining plant in the dumping ground which segregates plastic, earth and other materials. Total 3,05,897 tonnes of waste have been processed, out of that total 47,212 tonnes of Refuse Derived Plastics were sent to cement companies. Out of 45 acres reclaimed land, five acres were converted into a construction and demolition waste facility, two acres into a plastic waste management

facility, two acres into a waste to compost processing facility, five acres into a farmer produce market, and five acres into a children's park (https://www.thehansindia.com).

2.2.5 Bio-mining in Ambikapur, Chhattisgarh

Ambikapur, cleanest city in the state Chhattisgarh is a landfill free town in India and also an example in effective and efficient decentralized waste management. But before decentralized waste management system the waste was dumped across 14000 sq. m in mixed form (Management, n.d.). The local body decided to clear the area by the process of bio-mining. As the bio-mining is an expensive process, Ambikapur Municipal Corporation (AMC) started studying about the process and executed the process themselves and reduced the cost of managing the landfill. With the help of women from 20 self-help groups (SHGs) AMC carried out the whole process of reclamation and converted landfill into a green park. From this study, it can be concluded that bio-mining is not only an optimal solution for huge landfill project but it can be experimented in small scale project also and better result can be experienced.

2.2.6 Bioremediation of Legacy Waste in Nawanshahr, Punjab

Legacy waste site of measuring about 2-acre areas near the town Nawanshahr, was accumulated mix type of waste comprises of 50% bio-degradable, 25% dry recyclable and 25% non-recyclable dry and inert. The dumpsite was a great threat to the environment and the people residing nearby. So, the municipal corporation was looking for a solution that would eliminate the need to relocate the disposal site. A low-cost possible solution was found to remediate the dumpsite i.e., screening of waste materials with mechanical separator machine. Bio-remediation process was started in January 2019 with the help of a mechanical separator machine, one supervisor, one JCB operator and one helper. Segregated legacy waste categorized into different waste component i.e., degraded or composted wet waste, non-biodegradable plastic or rag waste, and C&D waste. Composted waste was tested in the laboratory and found it containing all the quality parameter of the city compost, was sold it to the farmers. Dry waste extracted from legacy waste was sold to the local junk dealer. Combustible waste was sent to nearest cement industry for co-processing and C&D waste was used as raw materials for construction works. After remediation of legacy waste, a composting plant and material recovery facility were build and a small park also created on the cleared space (USEPA, 1997).

2.2.7 Pirana Dumpsite Biomining Project, Ahmedabad, Gujrat

Pirana has been a dumping site since 1980. More than 80 lakhs metric ton of legacy waste has been accumulated over 84 acres area of land. There are three heaps of waste i.e.,Ajmeri Dump, High Dump and Excel Dump with the height ranging from 25 to 55 meter with steep slope. The Ministry of Environment and Forests (MoEF) has directed the Ahmedabad Municipal Corporation (AMC) to look for alternatives to capping at the Pirana dump site. In order to overcome and resolve the legacy waste problem effectively and efficiently, AMC has started bio-mining project from 2019 by its own. Current status of project work is ongoing and it is expected to complete within 3 year from starting of the project (USEPA, 1997).

For this bio-mining operation total 69 trommel machines with 60 machines of 300 metric tonne and 79 automatic trommel machine with 1000 metric tonne capacity are used. On a daily basis, the shale processes approximately 12000 metric tonnes of legacy waste. More than 55 lakh metric tonnes of waste have been handled till now and a 35-acre disposal site in Aajmeri has been reclaimed (https://www.gujaratheadline.com). At the moment, processing work of High dump is being carried out. After segregation of Legacy waste, components are divided into four categories mainly which are: a) Refuse Derived Fuel (RDF) b) Construction & Demolition Waste c) Semi-Compost d) Inert. AMC is giving the RDF to the companies where it is used as a fuel in their bio-mass gasification. The C & D waste has been transported to their own C & D plant to reuse and produce paver blocks, precast walls, manhole covers and many more products. The semi-compost has been transferred to existing MSW compost plants, for further treatment and sale to farmers. The inert has been transferred to a Gyaspur Landfill Site, which is 3.0 kilometres away from the Dump Site (USEPA, 1997). From this bio-mining process of Pirana dumpsite it would lead to reduction of global methane gas emission and prevent the ground water contamination occurring due to seepage of leachate into the ground water table. It would generate revenue from the mined waste and create job opportunity due to various activities which shall take place around the dumpsite.

2.2.8 Perungudi and Kodungaiyur Dumping Grounds, Chennai, India

Chennai Corporation has two major dumping sites; Perungudi and Kodungaiyur located south and north of Chennai, both sites operated since 1985. The Perungudi dumping ground (PDG) is low-lying and poorly drained, with large swaths of marshy land that are always wet and seasonally immersed. This site covers over 250 hectares, with approximately 22 hectares dedicated to dumping. (ERM, 1996). The Kodungaiyur Dumping Ground (KDG) is a 160-hectare marshy area adjacent to the Kodungaiyur Sewage Treatment Plant on the southern borders of the Korattalaiyar River's flood-prone alluvial lowlands.Surface water percolates through these open dumpsites and waste release harmful chemical and heavy metal which lead to environmental pollution. When people consume contaminated groundwater, it has a significant impact on their health. Thus, bore wells and tube wells near the dumpsite endanger the lives of those who reside nearby(Mohan & Joseph, 2020).

Aresearchwas conducted on the reclamation and upgradation of the dumpsites at Kodungaiyur and Perungudi, through Landfill Mining with the objective to evaluate the degradation status of the solid waste and the feasibility of recovering the soil fraction as compost or landfill cover material.The solid waste samples were collected from 6 locations in Perungudi and 18 locations in Kodungaiyur at intervals of one meter depth from the top of the waste dumpsite and was analysed them to determine density, temperature, moisture content, particle size, organic and inorganic fractions, macro nutrients (N, P, K) and heavy metals (arsenic, cadmium, chromium, copper, lead, mercury, nickel and zinc) (Kurian Joseph, et al, 2008).

From the sample analysis, soil fraction obtained in Kodungaiyurand Perungudilandfill site wasreported 65-68% and 40%.respectively.The combustible fractions obtained from Kodungaiyur was reported 4% whereas in Perungudi it was 40%.The non-combustible portion reported in this study was in Kodungaiyur as 28% and in Perungudi it was 20%(Kurian et al., 2003). Large variation between these values may be due to the age of MSW at the sampling locations. The soil fraction from both landfill sites was tested in the laboratory for determination of chemical characteristics e.g., VOM at 550°C and ash content, TOC (Total Organic Carbon), Heavy Metal Concentrationetc(Kurian et al., 2003). The heavy metal concentration of the soil fraction is compared with the Indian and international standards to check whether the soil fraction can be used as a compost. When comparing heavy metal concentration to Indian compost standards, report showed Cr, Cu, Hg, Ni, and Pb are beyond the limitations. When compared to USEPA regulations, all of the compost samples are within acceptable ranges. Hence, after establishing the geotechnical suitability, this fine fraction can be used as compost for non-edible crops or as a cover material.For landfill leachates collected from Perungudi andKodungaiyur, pH varied from 7 - 8.5; in some cases, the TDS was as high as 15000 mg/L; for most cases the BOD values were less than 100 mg/L while the COD varied from 100 – 8000 mg/L; heavy metal contents in leachates are in microgram levels(Kurian Joseph, et al, 2008).This study mainly focused upon qualitative analysis like determination of heavy metal concentration, compost standard, soil to waste ratio and its comparison among different landfill site etc. Altogether, except for focusing on the qualitative analysis of the characterization of finer fractions, this study did not include other aspects of landfill mining e.g., ways of reuse of other mined materials,combustible and non-combustible materials, minimization of gas emissions, economical aspects, social impacts on neighbourhood areas and environments.

2.2.9 Bhandewadi dumpsite in Nagpur, Maharashtra(Mandpe et al., 2019)

A study was conducted by the authors on the Bhandewadi old dumpsite situated in Nagpur in the state of Maharashtra to identify the most economical and technically feasible option for landfill reclamation. Two scenarios were considered as feasible removal techniques Ⅰ) mining for recovery, and Ⅱ) transferring MSW from the dump to a new sanitary landfill. This study revealed that from above two scenario which one is more economical and sustainable as compared to other one, cost-benefit analysis was used as a comparative tool. An open dumpsite Bhandewadiowns by Nagpur Municipal Corporation (NMC) since 1966. It is distributed over a total area of 21.57 hectares, with the usable and operational portions taking up 22 and 32 acres of land, respectively. The landfill site is bordered by habitation on three sides (east, north, and west).A sewage treatment facility is to the southeast of the landfill site, while a composting and RDF factory is to the south. With no operational MSW treatment facility, waste collected from different part of the city are dumped into the Bhandewadi dumpsite. The dumpsite possesses serious threat to theneighbouring inhabitantslike frequent fires, contamination of groundwater through leachate percolation and the GHG emissions.

The solid waste samples were collected by the quartering and coning method at varying depths of the dumpsite. Samples were analysed on wet weight basis and segregated into respective components including paper, cardboard, plastic, textile, biodegradables, wood, metal & glass and inerts comprising gravels, stones and sand. These components were weighted so as to determine percentage composition and also moisture content was analysed in the laboratory. Then chemical analysis was carried out for determination of total solids (TS), volatile solids (VS), pH, electrical Conductivity, total carbon content, C/N ratio, chemical oxygen demand etc. Physical composition analysis result showedaround 40% organics, followed by plastic (18%) and paper (11%).The result obtained from the chemical analysis are as follows: the average COD of the waste was 24%, the average density of waste was 440 kg/m3, and the C:N ratio of waste was around 24. The average moisture content, TS, VS, ash content, and the calorific value were 56.1%, 43.9%, 69.5%, 30.5%, and 1089 kcal/kg, respectively. Two dumpsite management scenarios werediscussed based on the result obtained.

For comparative analysis of two scenarios,a cost benefit assessment was carried out.For the cost-benefit analysis, the initial capital, operating, and maintenance costs in both scenarios were considered, and the total cost of the entire process was computed over 50 years.The first scenario that is transfer of MSW to new sanitary landfill involves the cost of setting up a new dumpsite which is calculated according to Central Public Health and Environmental Engineering Organisation (CPHEEO). The cost value and others are provided in CPHEEO manual as per year 1998 and the values for 2016 were calculated by multiplying with factor 2.52 accounting to the annual increase in the cost of materials and labour.The cost involved over 50 years in second scenario that is dumpsite mining for resource recoverywas calculated.The revenue generated from resource recovery from the mined waste is ignored and the cost of space is also not included in the calculation. It was seen that the cost involved in scenario 1 is more as compared to scenario 2, hence scenario 2 is more economically feasible.This study highlighted the relevance of dumpsite mining and economic usage in India as there is a lack of space for construction of new landfill in almost all cities and towns. Cost analysis showed that for the rehabilitation of the existing dumpsites, landfill mining is one of the most sustainable, economical and technically feasible options in Indian cities as compared to transferring the MSW in new dumpsites due to involvement of high cost.

2.2.10 A case study on Landfill Mining at Okhla landfill, New Delhi; Jawaharagr landfill, Hyderabad; and Ukkayyapalli landfill, Kadapa; India (Somani et al., 2018).

This study discussed about the possibility of landfill mining operationswith a focus on recovering soil-like material from three selected open dump site in India i.e., Okhla landfill, New Delhi; Jawaharagr landfill, Hyderabad; and Ukkayyapali landfill, Kadapa, Andhra Pradesh.The general information about the three landfill sitesis provided in table 2.2. Municipal solid waste was collected from three dumpsites, and preliminary tests like grain size distribution, compositional analysis, organic content, total dissolved solids, elemental analysis, heavy metal analysis and colour of the leached water from finer fraction were performed on the soil-like material of the municipal solid waste.

Table 2.2: Description of three landfills in India(Somani et al., 2018).

Landfill	Operation started	Total Area (acre)	Height (m)	Amount of Waste (MT)	Status
Okhla	*1994*	*40*	*65-70*	*6 million*	*Open dumping*
Jawaharnagar	*1999*	*350*	*N.A.*	*N.A.*	*Engineered landfill*
Ukkayyapali	*1965*	*10*	*10–12*	*0.2 million*	*Closed*

In Okhla and Jawaharnagar landfill sites, samples were taken between December 2016 and February 2017 from a depth of 4-5m, whereas at Kadapa landfill sites, samples were collected from waste stockpiles in preparation for this dump's closure.The composition of mined waste was determined through Grain Size Distribution analysis, which revealed that the finer fraction in Delhi landfill was 8% w.r.t dry basis and 43% w.r.t wet basis, while in Hyderabad landfill it was 2% w.r.t dry basis and 25% w.r.t wet basis, and in Ukkayyapali landfill it was 12% w.r.t dry basis and 35% w.r.t wet basis.From the compositional analysis, maximum soil-like material was found from the three above-mentioned old aged landfill sites named Ukkayyapali at Kadapa. In the Hyderabad dumpsite, the concentration of inert waste (particularly construction and demolition waste) was found to be almost negligible. Due to the consideration of old aged waste, the percentage of paper detected in all landfills was almost insignificant. From different test result, the study concluded thatthe majority of the soil-like material from old municipal solid waste dumps can be used as cover material for landfills at the site.However, to re-use the soil fraction in other geotechnical application, some treatment like washing, thermal treatment, blending with local soil, biological treatment, etc., is required.

2.3 INFERENCE FROM LITERATURE REVIEW

From the above literature survey, it is concluded that the landfill mining activity was performed in many states of USA, inmany European countries such as Germany, Italy, Austria, Latvia, Belgium, Greece, Lithuania, Estonia, Sweden and many other countries, in Asian countries like China and also in India. Previously, there was very few literatures of bio-mining in India but after the instruction of Hon’ble NGT and with the CPCB guidelines, various state currently adopted bio-mining operation for ultimate solution of legacy waste dumpsites.

The main objective of the most of the landfill mining reported in literature is the recovery of material like plastic, glass, ferrous and non-ferrous metal, wood, paper, combustible and non-combustible material and their characterization using different size of screening equipment, finding of soil to waste ratio, chemical characteristics of fine like fraction. Very few literatures described the probable reuse of recovered material and the marketability of ferrous and non-ferrous material, energy production from mined waste. Some of the research work was based on the technical and economic feasibility of landfill mining, potential concern and challenges during mining and cost benefit analysis. Various states in India adopted landfill mining operation in recent days but there is still limited number of literatures,field study present in Indian scenario.In India the research work on landfill mining was done for characterization of recovered material. But none of the literature work was based on the future impact of landfill mining or bio-miming on the environment in terms of landfill gas and leachate minimization. There is no research work based on evaluation of quantitative environmental impact using proper simulation tool such as LCA (Life Cycle Assessment).So, considering the above limitations of existing research works the landfill mining or bio-mining is taken a topic of research work.

Chapter 3

OBJECTIVE AND SCOPE OF WORK

OBJECTIVE

The main objective of this study is characterization and component analysis of legacy waste, gas andleachate generation from a MSW landfill and to evaluate the environmental impact of bio-mining using Life Cycle Assessment (LCA) model and to compare the impact with different bio-mining scenarios. Non-engineered landfill Dhapa at Kolkata is considered asthe study area of this work.

SCOPE OF WORK

- Onsite data and secondary data collection.
- Estimation of average composition of excavated legacy waste i.e., inventory of recovered materials and preparation of material balance flow chart
- Inventory analysis of data of the studied system.
- Potential environmental impact calculation of Bio-mining.
- Interpretation i.e., to provide basic for conclusions after summarizing and discussing the results.

Chapter 4

LEGACY WASTE CHARACTERIZATION AND PROCESSED COMPONENT ANALYSIS

4.1 STUDY AREA

In this present work,Dhapa landfill situated at Kolkata, India is taken as a study area sinceit receives a huge amount of waste and operating since 1987 and bio-mining operation has been started as per the direction of NGT (National Green Tribunal) from 2021-22The capital of the state of West Bengal, Kolkata is one of India's four major cities, and it is located at latitude 22° 34′ North and longitude 88° 24′ East.Elevation ranges from 1.5 to 9.0 m above sea level. The river Hooghly is the principal waterway and forms the western boundary of Kolkata, and the region contains numerous low-lying areas, marshes, wetlands, and shallow lakes or jheels.The Dhapa dumping area is owned and operated by Kolkata Municipal Corporation (KMC) and lies within Ward Nos. 57 and 58 of the KMC administrative boundaries, the eastern part of Kolkata.Nearly the entire area is a part of the East Kolkata Wetland, a large protected wetland area that is one of the Ramsar Site.The entire raw sewage from the city flows through drainage channels into the wetlands and is eventually discharged into the river Vidyadhari. The current “dumping area” is spread over about 36.34 hectares. It consists of two unlined dumpsites, spaced ~ 500m apart – one closed dump of area ~ 12.14 ha and one active dump of area ~ 24.2 ha. Later on, the KMC has used a new portion of land of ~14 ha at the south western fringe of the 24.2 ha (legacy waste area) for landfilling of fresh waste as no new landfill area is available for disposing the fresh waste. The closed dump site (referred to as the ‘closed dumpsite’) commenced operations in 1987 and was closed in 2009, which has been capped and not yet handed over to KMC. The concerned dumpsite area (24.2 ha) also commenced operations in 1987 is now going under bio-mining operation and this specific area is considered as a study area of present thesis work. The required field data such as various composition data of legacy waste, leachate characteristics etc. are taken from the sample analysis of legacy waste of this concerned area.

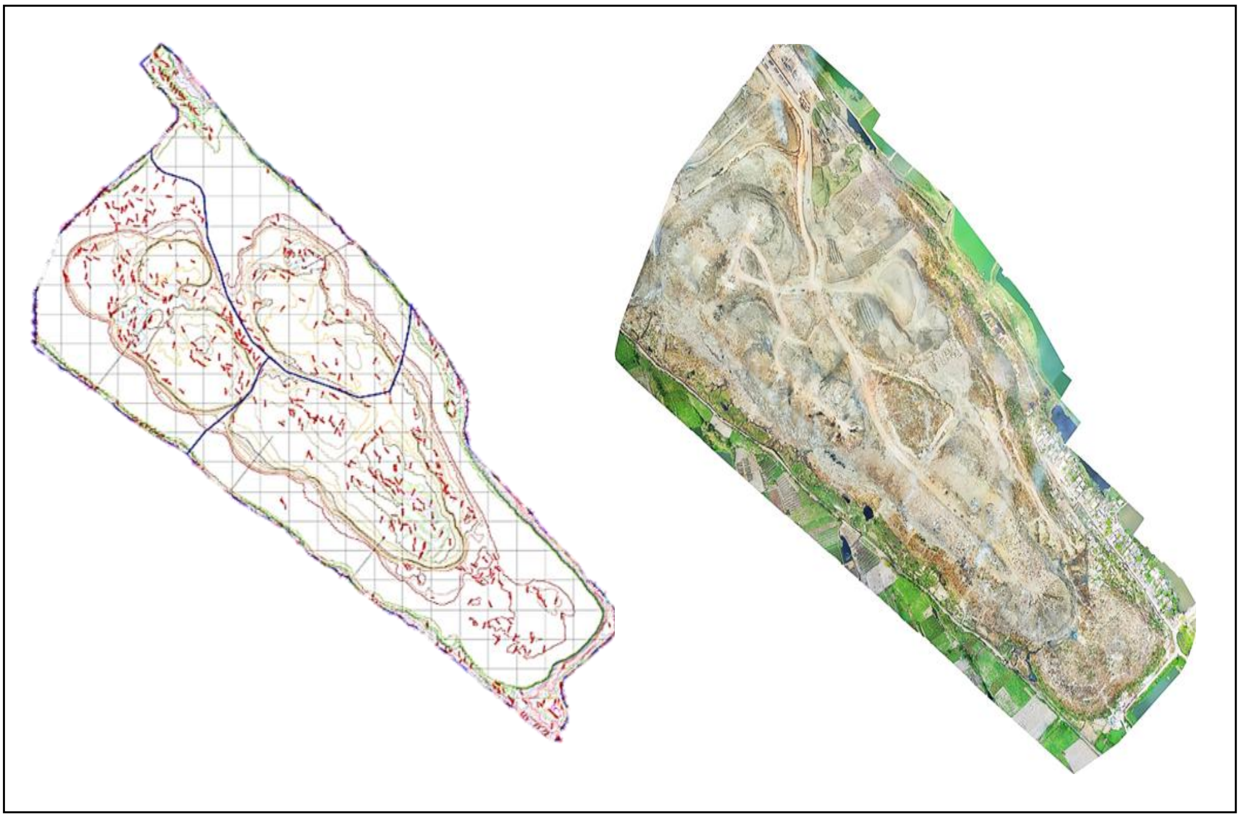

Fig 4.1: Contour map and aerial view of Dhapa dumpsite

4.3 MUNICIPAL SOLID WASTE GENERATIONIN KOLKATA

Kolkata is one the largest metropolitan city in India located on latitude 22° 34’ N and longitude 88° 24’E. With an area of 206.1 sq. km and a population of about 14.9 million, it generates around 4000-4500 t/day of municipal solid waste (MSW) at a rate of 500–650 g per capita per day.Due to an increase in population, rapid urbanization, industrialization the total waste generation/disposal has increased over the years.The huge amount of solid waste is disposed of in Dhapa landfill (approx. area 35 ha) and Garden Reach (approx. area 3.52 ha).Kolkata Municipal Corporation (KMC) owns and operates the Dhapa dumping area, which is located in Wards 57 and 58 of the KMC administrative borders in the eastern portion of Kolkata. Table 4.1 shows the average composition of waste in Kolkata accumulated in the landfill. For the years, the generation of solid waste is continuously increasing. There is also a lack of availability of infrastructure to handle the disposal of huge amount of solid waste. About 10% of disposed waste is recycled by rag pickers who perform their activities at vat points and landfill sites in an unorganized, unhygienic way, without any government support.

Table 4.1. Average composition of existing solid waste accumulated in Dhapa landfill (NEERI,1995; NEERI, 2005; KMC data).

Component	1995	2005	2009	2019	Total	Avg.
Biodegradables	44.29	50.56	41	64.84	200.69	50.17
Paper	4.64	6.07	3.18	5.25	19.14	4.79
Plastics	3.22	4.88	0.65	7.25	16	4
Metals	0.43	0.19	0.66	0.18	1.46	0.365
Glass	1.72	0.34	0.58	1.06	3.7	0.925
Coconut Shell	8.51	4.5	4.95	3.13	21.09	5.27
Inert	29.92	29.6	45.98	8.96	114.46	28.615
Wood	0.99	0.53	0.41	1.27	3.2	0.8
Textile	2.77	1.47	1.14	3.55	8.93	2.23
Others	3.51	1.86	1.45	4.52	11.34	2.835

It can be deduced from the preceding Table 4.1 that there has been a significant increase in the generation of organic waste. Over time, the organic component of waste degrades in anaerobic conditions, resulting in the creation of landfill gas, which contains CH_4, CO_2, H_2S, NH_3, and other contaminants that can pollute the surrounding air.Due to presence of high inert content and biodegradable fraction, the waste has low calorific value and moisture content is high. These wastes are not suitable for incineration plant.

4.3 ONSITE LEGACY WASTE CHARACTERIZATION

Site specific data are collected in Dhapa Landfill at different locations at different times. Some samples are taken from the top of the landfill some are taken from 5 feet or 10 feet bottom of the landfill. 11 no of samples are collected from July 2021 to December 2021 and these are characterized. After characterization different components are categorised into 2 groups i.e., Decomposable or biodegradable and non-decomposable. It is found that legacy waste consists of decomposable components such as Waste Soil (44.8% - 64.8%), Wood (0.36% – 0.56%), Coconut (0.38% - 2.8%), Animal Bone (0.32% - 0.86%), Textile Fabric (0.24%- 1%) and non-decomposable components such as Plastic (14.8% - 32.65%), Glass (0.2 – 3.84%), Thermocol (0.3% - 0.58%), Ceramic (0.58% - 2.8%), Gravels (5.4% -12.6%), Kankar (2.6% - 11.6%), Mix (0.44% - 7.8%). Onsite average physical composition of legacy waste is presented in table 4.2.

Table 4.2 Onsite Average Physical Composition of Legacy Waste.

Decomposable		Non-decomposable	
Waste Soil	*55.12%*	*Plastic*	*21.16%*
Wood	*0.42%*	*Glass*	*1.21%*
Coconut	*1.01%*	*Thermocol*	*0.45%*
Animal Bone	*0.66%*	*Ceramic*	*1.55%*
Textile Fabric	*0.51%*	*Gravels*	*9.22%*
		Kankar	*6.61%*
		Mix	*2.08%*

4.4 DEGRADATION OF DECOMPOSABLE OR BIODEGRADABLE WASTE

From the above table 4.1, it is easily recognized that more than 50% waste component is organic by nature. Waste starts degrades after few years of dumping because of its high organic matter and high moisture contentand so starts generating methane also. In our case waste has been accumulated in the landfill for several years and has a cumulative effect of methane generation. Thus, the analysis of degradation of biodegradable waste is important. The transformation of legacy waste rich in an organic fraction in the landfill follows first-order kinetic decay rate of differential equation yield the exponential decay equation which can be expressed as follows (Pippatti et al., IPCC guideline, 2006).

$SWt_{Di\ remaining} = SW_{Di} \cdot e^{(-kt)}$.Where,

$SWt_{Di\ remaining}$= Amount of dry matter of solid waste fraction i remaining after t time in tons;

SW_{Di} = Initial amount of dry matter of solid waste fractions i tons;

k = the first-degree decay rate constant for waste fraction i; (Table 4.3)

Table 4.3: The decay rate constant for tropical country is given in the following table (Pipati et al., 2016)

Type of Waste		**Climate Zone (Tropical MAT > 20°C)**			
		Dry (MAP < 1000mm)		**Moist and Wet (MAP ≥ 1000mm)**	
		Default	***Range***	***Default***	***Range***
Slowly Degrading	*Paper/textile waste*	*0.045*	*0.04-0.06*	*0.07*	*0.06-0.085*

Waste	*Wood/ straw waste*	*0.025*	*0.02-0.04*	*0.035*	*0.03-0.05*
Moderately Degrading Waste	*Other (non-food) organic putrescible/garden park waste*	*0.065*	*0.05-0.08*	*0.17*	*0.15-0.2*
Rapidly Degrading Waste	*Food waste/sewage sludge*	*0.085*	*0.07-0.1*	*0.4*	*0.17-0.7*
Bulk waste		*0.065*	*0.05-0.08*	*0.17*	*0.15-0.2*

(MAP= Mean Annual Precipitation, MAT= Mean Annual Temperature. Since the MAP in Kolkata is more than 1000 mm (1850 mm)that is why the k value applicable for MAP>1000 mm)

Degradation model helps to find out the degradation pattern of biodegradable waste, how much degradable portion will be remaining after certain period of time. Here waste samples are taken from different depth of the landfill (some samples are taken from top some are taken from 5 feet or 15 feet bottom). The samples which are taken from the higher depth we assume the wastes are 30 years old and the samples which are taken from lower depth we assume the waste is 15 years old. To compatible the range of analysis we take the 15 years and 30 years degradation analysis. Kolkata which is situated in a tropical country that's why the average decay rate constant for the tropical country is considered from the above table 4.3. Using this decay rate constant, the decomposable or biodegradable waste is categorized into slowly biodegradable, moderately degradable, and rapidly degradable and the remained portion in the landfill due to decay of 15 years and 30 years is calculated which is shown in the following table (Table 4.4 to Table4.13) for various kinds of biodegradable waste.

Degradation of Food Waste

Organic material, which includes carbon, hydrogen, oxygen, and nitrogen with trace amounts of other elements, makes up the majority of food waste.Food decomposition is mostly carried out by a varied microbial community in both aerobic and anaerobic conditions. The rate of degradation of food waste depends upon several factors such as temperature, moisture content, available source of carbon and nitrogen (Khalid et al., 2011). Because food waste is primarily carbon, firstly in aerobic conditions, carbon is reduced and easily converted to CO_2, resulting in rapid food waste breakdown. The estimation of average remained percentage over 30 years and 15 years using IPCC model is shown in table 4.4 and table 4.5 respectively.

Table 4.4: Food Waste (k =0.4) (Rapidly Biodegradable moist waste)(30 yr.)

Time (years)	Remaining amount (e(-kt))	% Remaining	% Transformed
1	*0.67033*	*67.033*	*32.967*
2	*0.44933*	*44.933*	*55.067*
3	*0.3012*	*30.12*	*69.88*
4	*0.2019*	*20.19*	*79.81*
5	*0.13534*	*13.534*	*86.466*
6	*0.09072*	*9.072*	*90.928*
7	*0.06082*	*6.082*	*93.918*
8	*0.04077*	*4.077*	*95.923*
9	*0.02733*	*2.733*	*97.267*
10	*0.01832*	*1.832*	*98.168*
11	*0.01228*	*1.228*	*98.772*
12	*0.00823*	*0.823*	*99.177*
13	*0.00552*	*0.552*	*99.448*
14	*0.0037*	*0.37*	*99.63*
15	*0.00248*	*0.248*	*99.752*
16	*0.00167*	*0.167*	*99.833*
17	*0.00112*	*0.112*	*99.888*
18	*0.00075*	*0.075*	*99.925*
19	*0.00051*	*0.051*	*99.949*
20	*0.00034*	*0.034*	*99.966*
21	*0.00023*	*0.023*	*99.977*
22	*0.00016*	*0.016*	*99.984*
23	*0.00011*	*0.011*	*99.989*
24	*0.00007*	*0.007*	*99.993*

25	*0.00005*	*0.005*	*99.995*
26	*0.00004*	*0.004*	*99.996*
27	*0.00003*	*0.003*	*99.997*
28	*0.00002*	*0.002*	*99.998*
29	*0.00001*	*0.001*	*99.999*
30	*0.00001*	*0.001*	*99.999*
		Avg. % Remaining 6.78%	***Avg. %Transformed 93.22%***

Table 4.5: Food Waste (k= 0.4) (Rapidly Biodegradable moist waste)(15 yr.)

Time (years)	Remaining amount (e(-kt))	% Remaining	% Transformed
1	*0.67033*	*67.033*	*32.967*
2	*0.44933*	*44.933*	*55.067*
3	*0.3012*	*30.12*	*69.88*
4	*0.2019*	*20.19*	*79.81*
5	*0.13534*	*13.534*	*86.466*
6	*0.09072*	*9.072*	*90.928*
7	*0.06082*	*6.082*	*93.918*
8	*0.04077*	*4.077*	*95.923*
9	*0.02733*	*2.733*	*97.267*
10	*0.01832*	*1.832*	*98.168*
11	*0.01228*	*1.228*	*98.772*
12	*0.00823*	*0.823*	*99.177*
13	*0.00552*	*0.552*	*99.448*
14	*0.0037*	*0.37*	*99.63*
15	*0.00248*	*0.248*	*99.752*
		Avg. % Remaining 13.52%	***Avg. % Transformed 86.48%***

Typical calculation showing the remaining portion of food waste as follows using IPPC, 2006 model,

For t-10 years,

$SWt_{Di\ remaining} = SW_{Di}\ .\ e^{(-kt)}$.

SWDi = 55.12 ton. (Table 4.2)

k= 0.4 (Rapidly Biodegradable moist waste) (Table 4.3)

Using these value, percentage $SWt_{Di\ remaining} = (55.12 * e^{(-0.4*10)}/55.12) *100= 1.832$ %

And Percentage Transformed = 98.168%

The typical graphical representation for food waste degradation is shown in the following figure 4.2.

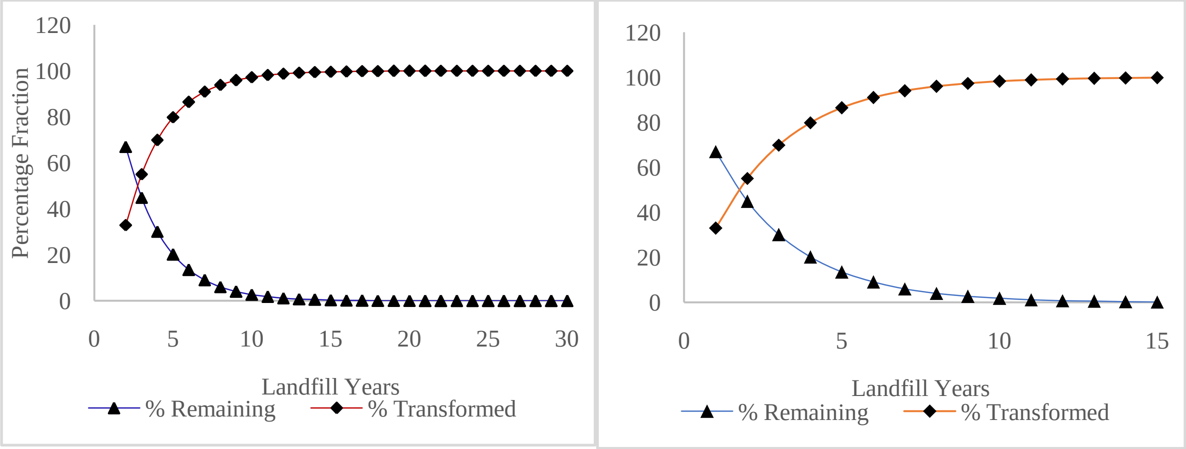

Fig 4.2: Degradation Pattern of food waste over 30 years and 15 years.

Degradation of Wood

Wood is decayed by organic microorganisms, including growths, microbes, and bugs. Growths colonize wood and corrupt cell divider parts to shape earthy coloured, or white decay. A lignin structure is left behind by earthy-coloured decay growths that breakdown the polysaccharide sections of wood. All cell divider segments may be degraded by white-decay growths. Different varieties of white-decay organisms have different rates and degrees of lignin, cellulose, and hemicellulose evacuation. Fungal decay of wood and wood products occurs even in the presence of oxygen (Blanchette et al., 1990). Thus, any biodegradation of the wood in anaerobic landfills is more likely to be caused by bacterial activity than by fungal interaction. Bacteria are known to degrade wood quite slowly than fungi (Blanchette et al., 1990). That is why degradation of wood is considered as slow degradation and for that decay rate constant is taken 0.035 (Table 4.3). The calculation of decay of wood over 30 years and 15 years are shown in the following table 4.6 and table 4.7 respectively.

Table 4.6: Wooden matter (k=0.035) (slowly degradable moist waste)(30 yr.)

Time (years)	Remaining amount (e(-kt))	% Remaining	% Transformed
1	*0.96561*	*96.561*	*3.439*
2	*0.9324*	*93.24*	*6.76*
3	*0.90033*	*90.033*	*9.967*
4	*0.86936*	*86.936*	*13.064*
5	*0.83946*	*83.946*	*16.054*
6	*0.81059*	*81.059*	*18.941*
7	*0.78271*	*78.271*	*21.729*
8	*0.75579*	*75.579*	*24.421*
9	*0.72979*	*72.979*	*27.021*
10	*0.70469*	*70.469*	*29.531*
11	*0.68046*	*68.046*	*31.954*
12	*0.65705*	*65.705*	*34.295*
13	*0.63445*	*63.445*	*36.555*
14	*0.61263*	*61.263*	*38.737*
15	*0.59156*	*59.156*	*40.844*
16	*0.57121*	*57.121*	*42.879*
17	*0.55157*	*55.157*	*44.843*
18	*0.5326*	*53.26*	*46.74*
19	*0.51428*	*51.428*	*48.572*
20	*0.49659*	*49.659*	*50.341*
21	*0.47951*	*47.951*	*52.049*
22	*0.46302*	*46.302*	*53.698*
23	*0.44709*	*44.709*	*55.291*

24	*0.43172*	*43.172*	*56.828*
25	*0.41687*	*41.687*	*58.313*
26	*0.40253*	*40.253*	*59.747*
27	*0.38868*	*38.868*	*61.132*
28	*0.37532*	*37.532*	*62.468*
29	*0.36241*	*36.241*	*63.759*
30	*0.34994*	*34.994*	*65.006*
		Avg. % Remaining 60.83%	***Avg. % Transformed 39.17%***

Table 4.7: Wooden matter (k=0.035) (slowly degradable moist waste)(15 yr.)

Time (years)	Remaining amount (e(-kt))	% Remaining	% Transformed
1	*0.96561*	*96.561*	*3.439*
2	*0.9324*	*93.24*	*6.76*
3	*0.90033*	*90.033*	*9.967*
4	*0.86936*	*86.936*	*13.064*
5	*0.83946*	*83.946*	*16.054*
6	*0.81059*	*81.059*	*18.941*
7	*0.78271*	*78.271*	*21.729*
8	*0.75579*	*75.579*	*24.421*
9	*0.72979*	*72.979*	*27.021*
10	*0.70469*	*70.469*	*29.531*
11	*0.68046*	*68.046*	*31.954*
12	*0.65705*	*65.705*	*34.295*
13	*0.63445*	*63.445*	*36.555*
14	*0.61263*	*61.263*	*38.737*
15	*0.59156*	*59.156*	*40.844*
		Avg. % Remaining 76.45%	***Avg. % Transformed 23.55%***

For t-10 years,

$SWt_{Di\ remaining} = SW_{Di} \cdot e^{(-kt)}$.

$SW_{Di} = 0.42$ ton. (Table4.2)

k= 0.035 (Slowly Biodegradable moist waste) (Table 4.3)

using these value percentage $SWt_{Di\ remaining} = (0.42 * e^{(-0.035*10)}/0.42) *100= 70.469\%$ and Percentage Transformed =29.531%

The typical graphical representation for the degradation of wooden matter is shown in the following Figure 4.3.

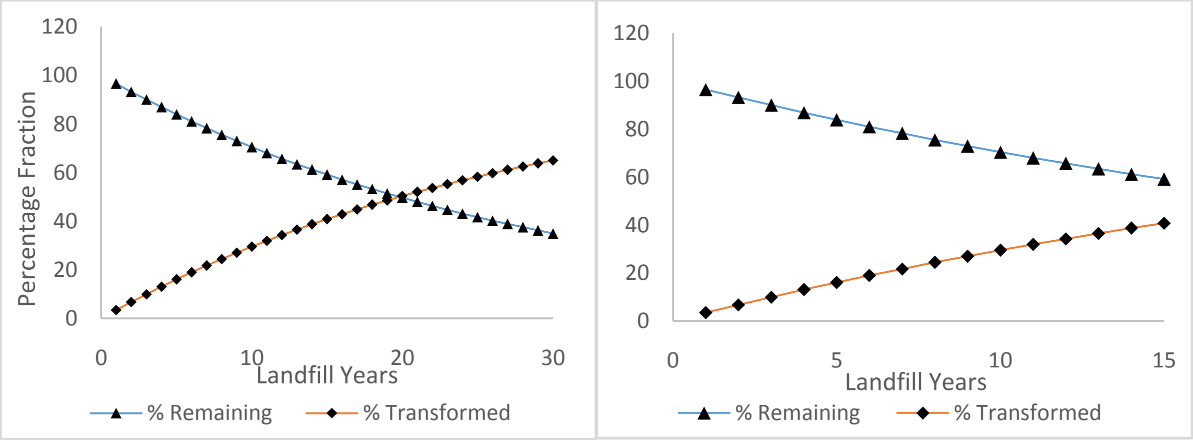

Fig 4.3: Degradation Pattern of wooden waste over 30 years and 15 years.

Degradation of Coconut shell

Through pyrolysis or incineration, coconut shell waste can be used as a fuel replacement.Coconut shell has high lignin, cellulose, and hemicellulose content which may degrade in aerobic and acetogenic phases which turns it into moderately degradable waste. The residual portion of the coconut shell can be used as an efficient source of bio-fuel (Said et al., 2015). Since coconut shell has a significant amount of lignin, it takes longer for it to degrade under aerobic conditions than food waste. That is why degradation of coconut shell can be considered as moderate degradation.The result of degradation of coconut shell for 30 years and 15 years are shown in the following table 4.8 and table 4.9 respectively and the figure4.4 depicts the decay trend.

Table 4.8: Coconut Shell (k=0.17) (Moderately degradable moist waste) (30 yr.)

Time (years)	**Remaining amount (e(-kt))**	**% Remaining**	**% Transformed**
1	*0.84367*	*84.367*	*15.633*
2	*0.71178*	*71.178*	*28.822*
3	*0.6005*	*60.05*	*39.95*
4	*0.50662*	*50.662*	*49.338*
5	*0.42742*	*42.742*	*57.258*
6	*0.3606*	*36.06*	*63.94*
7	*0.30423*	*30.423*	*69.577*
8	*0.25667*	*25.667*	*74.333*
9	*0.21654*	*21.654*	*78.346*
10	*0.18269*	*18.269*	*81.731*
11	*0.15413*	*15.413*	*84.587*
12	*0.13003*	*13.003*	*86.997*
13	*0.10971*	*10.971*	*89.029*
14	*0.09256*	*9.256*	*90.744*
15	*0.07809*	*7.809*	*92.191*
16	*0.06588*	*6.588*	*93.412*
17	*0.05558*	*5.558*	*94.442*
18	*0.04689*	*4.689*	*95.311*
19	*0.03956*	*3.956*	*96.044*
20	*0.03338*	*3.338*	*96.662*
21	*0.02816*	*2.816*	*97.184*
22	*0.02376*	*2.376*	*97.624*
23	*0.02005*	*2.005*	*97.995*
24	*0.01691*	*1.691*	*98.309*
25	*0.01427*	*1.427*	*98.573*
26	*0.01204*	*1.204*	*98.796*
27	*0.01016*	*1.016*	*98.984*

28	*0.00857*	*0.857*	*99.143*
29	*0.00723*	*0.723*	*99.277*
30	*0.0061*	*0.61*	*99.39*
		Avg. % Remaining 17.88%	***Avg. % Transformed 88.12%***

Table 4.9: Coconut Shell (k=0.17) (Moderately degradable moist waste)(15 yr.)

Time (years)	**Remaining amount (e(-kt))**	**% Remaining**	**% Transformed**
1	*0.84367*	*84.367*	*15.633*
2	*0.71178*	*71.178*	*28.822*
3	*0.6005*	*60.05*	*39.95*
4	*0.50662*	*50.662*	*49.338*
5	*0.42742*	*42.742*	*57.258*
6	*0.3606*	*36.06*	*63.94*
7	*0.30423*	*30.423*	*69.577*
8	*0.25667*	*25.667*	*74.333*
9	*0.21654*	*21.654*	*78.346*
10	*0.18269*	*18.269*	*81.731*
11	*0.15413*	*15.413*	*84.587*
12	*0.13003*	*13.003*	*86.997*
13	*0.10971*	*10.971*	*89.029*
14	*0.09256*	*9.256*	*90.744*
15	*0.07809*	*7.809*	*92.191*
		Avg. % Remaining 33.17%	***Avg. % Transformed 66.83%***

Typical calculation:

For t-10 years,

$SWt_{Di\ remaining} = SW_{Di} \cdot e^{(-kt)}$.

SW_{Di} = 1.01 ton. (Table 4.2)

k= 0.17 (Moderately Biodegradable moist waste) (Table 4.3)

Using these value percentage $SWt_{Di\ remaining}$ = (1.01 * e $^{(-0.17*10)}$/1.01) *100= 18.269 %. And percentage transformed= 81.731%.

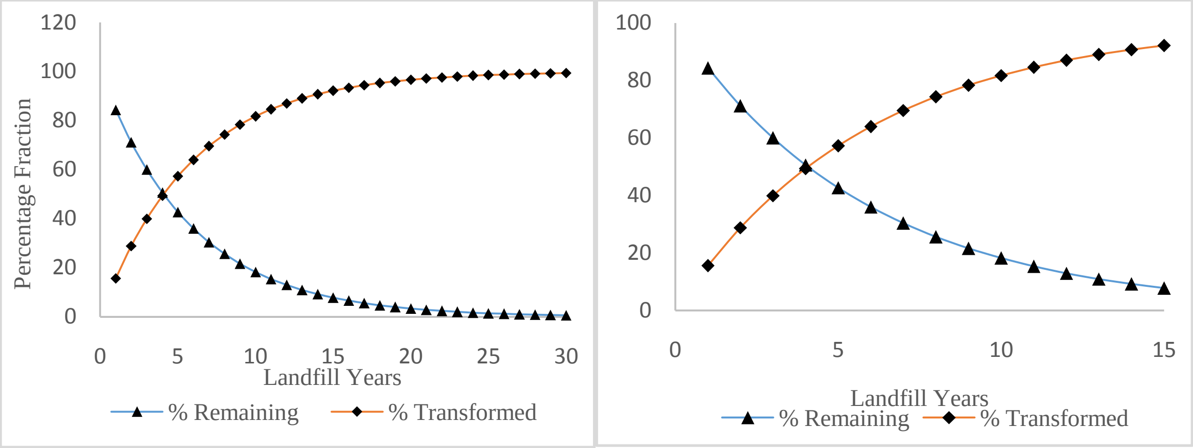

Fig 4.4: Degradation Pattern of coconut shell over 30 years and 15 years.

Degradation of Animal Bone

Bones are made of two components cells that make up approximately 5% of the bone's volume and the extracellular matrix, which accounts for the rest. This extracellular matrix is composed of organic matter and is primarily a matrix of the protein Collagen and minerals, chiefly Calcium which account for 50 to 70 % of the bone. The decay rate of bone is slower than other organic materials because of the presence of two components in bones- collagen and calcium. There isn't a standard estimate for how long bone decompose will take. Different bones, depending on their calcium content and structure, will decompose at different rates.In warm, moist conditions, bacteria and fungi attack the collagen protein, causing the skeleton to disintegrate over a period of years.As the degradation of animal bone takes comparatively more time than food waste it can be considered as moderately degrading waste.The result of degradation of coconut shell for 30 years and 15 years are shown in the following table 4.10 and table 4.11 respectively and the figure 4.5 depicts the decay trend.

Table4.10: Animal Bone (k= 0.17) (Moderately degradable moist waste) (30 yr.)

Time (years)	Remaining amount (e(-kt))	% Remaining	% Transformed
1	*0.84367*	*84.367*	*15.633*

2	0.71178	71.178	28.822
3	0.6005	60.05	39.95
4	0.50662	50.662	49.338
5	0.42742	42.742	57.258
6	0.3606	36.06	63.94
7	0.30423	30.423	69.577
8	0.25667	25.667	74.333
9	0.21654	21.654	78.346
10	0.18269	18.269	81.731
11	0.15413	15.413	84.587
12	0.13003	13.003	86.997
13	0.10971	10.971	89.029
14	0.09256	9.256	90.744
15	0.07809	7.809	92.191
16	0.06588	6.588	93.412
17	0.05558	5.558	94.442
18	0.04689	4.689	95.311
19	0.03956	3.956	96.044
20	0.03338	3.338	96.662
21	0.02816	2.816	97.184
22	0.02376	2.376	97.624
23	0.02005	2.005	97.995
24	0.01691	1.691	98.309
25	0.01427	1.427	98.573
26	0.01204	1.204	98.796
27	0.01016	1.016	98.984
28	0.00857	0.857	99.143
29	0.00723	0.723	99.277

30	*0.0061*	*0.61*	*99.39*
		Avg. % Remaining 17.88%	***Avg. % Transformed 88.12%***

Table 4.11: Animal Bone (k= 0.17) (Moderately degradable moist waste)(15 yr.)

Time (years)	Remaining amount (e(-kt))	% Remaining	% Transformed
1	*0.84367*	*84.367*	*15.633*
2	*0.71178*	*71.178*	*28.822*
3	*0.6005*	*60.05*	*39.95*
4	*0.50662*	*50.662*	*49.338*
5	*0.42742*	*42.742*	*57.258*
6	*0.3606*	*36.06*	*63.94*
7	*0.30423*	*30.423*	*69.577*
8	*0.25667*	*25.667*	*74.333*
9	*0.21654*	*21.654*	*78.346*
10	*0.18269*	*18.269*	*81.731*
11	*0.15413*	*15.413*	*84.587*
12	*0.13003*	*13.003*	*86.997*
13	*0.10971*	*10.971*	*89.029*
14	*0.09256*	*9.256*	*90.744*
15	*0.07809*	*7.809*	*92.191*
		Avg. % Remaining 33.17%	***Avg. % Transformed 66.83%***

Typical calculation:

For t-10 years,

$SWt_{Di\ remaining} = SW_{Di} \,.\, e^{(-kt)}$.

SW_{Di} = 0.66 ton. (Table 4.2)

k= 0.17 (Moderately Biodegradable moist waste) (Table 4.3)

Using these value percentage $SWt_{Di\ remaining}$ = (0.66 * e $^{(-0.17*10)}$/0.66) *100= 18.269 %. And percentage transformed= 81.731%.

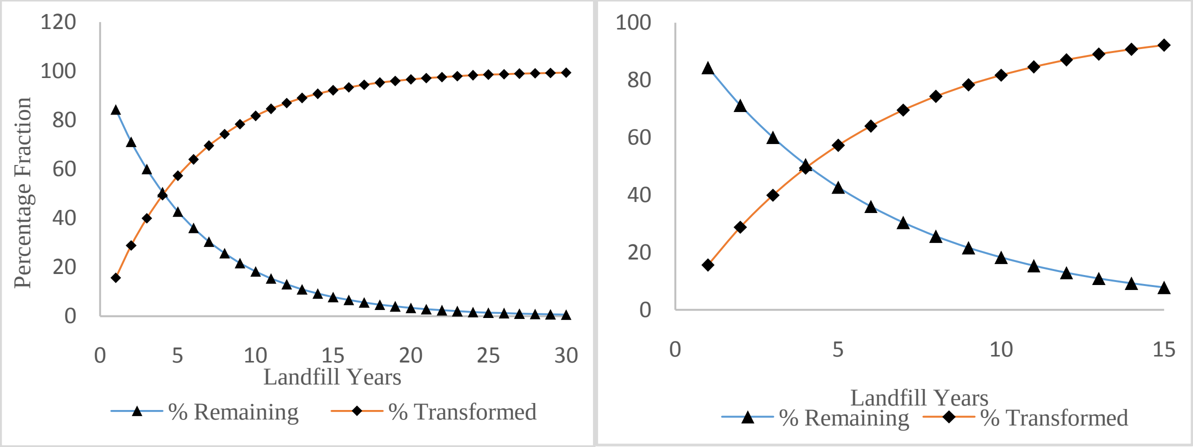

Fig 4.5: Degradation Pattern of Animal Bone over 30 years and 15 years.

Degradation of Textile Fabric

Textile waste is a type of waste which contains high amount of cellulose. The degradation rate of cellulose and cellulosic material as substrates relies upon its utilization by microorganisms. The two main groups of microorganisms responsible for the enzymatic breakdown of cellulose are microscopic organisms and growths. In the presence of growths of microorganism, after the restoration of the fingernail skin, the creatures infiltrate through the optional divider into a lumen where they develop and grow (Desai and Pandey, 1971). For Textile, jute is the main component that degrades very slowly undergone through chemical reactions that led to the deterioration of chemical structure which takes a very long time. That’s why rags are considered as slowly degrading waste and decay rate constant is used for slowly degrading waste. The calculation of decay of Textile Fabric of 30 years and 15 years are shown in the following table 4.12 and table 4.13 respectively and the figure 4.6 depicts the decay trend.

Table 4.12: Textile Fabric (k=0.07) (Slowly degradable moist waste) (30 yr.)

Time (years)	Remaining amount (e(-kt))	% Remaining	% Transformed
1	0.9324	93.24	6.76
2	0.86936	86.936	13.064

3	0.81059	81.059	18.941
4	0.75579	75.579	24.421
5	0.70469	70.469	29.531
6	0.65705	65.705	34.295
7	0.61263	61.263	38.737
8	0.57121	57.121	42.879
9	0.5326	53.26	46.74
10	0.49659	49.659	50.341
11	0.46302	46.302	53.698
12	0.43172	43.172	56.828
13	0.40253	40.253	59.747
14	0.37532	37.532	62.468
15	0.34994	34.994	65.006
16	0.32628	32.628	67.372
17	0.30423	30.423	69.577
18	0.28366	28.366	71.634
19	0.26448	26.448	73.552
20	0.2466	24.66	75.34
21	0.22993	22.993	77.007
22	0.21439	21.439	78.561
23	0.19989	19.989	80.011
24	0.18638	18.638	81.362
25	0.17378	17.378	82.622
26	0.16203	16.203	83.797
27	0.15108	15.108	84.892
28	0.14086	14.086	85.914
29	0.13134	13.134	86.866
30	0.12246	12.246	87.754

		Avg. % Remaining 40.34%	***Avg. % Transformed 59.66%***

Table 4.13: Textile Fabric (k=0.07) (Slowly degradable moist waste)(15 yr.)

Time (years)	Remaining amount (e(-kt))	% Remaining	% Transformed
1	0.9324	93.24	6.76
2	0.86936	86.936	13.064
3	0.81059	81.059	18.941
4	0.75579	75.579	24.421
5	0.70469	70.469	29.531
6	0.65705	65.705	34.295
7	0.61263	61.263	38.737
8	0.57121	57.121	42.879
9	0.5326	53.26	46.74
10	0.49659	49.659	50.341
11	0.46302	46.302	53.698
12	0.43172	43.172	56.828
13	0.40253	40.253	59.747
14	0.37532	37.532	62.468
15	0.34994	34.994	65.006
		Avg. % Remaining 59.77%	***Avg. % Transformed 40.23%***

Typical Calculation:

For t-10 years,

$SWt_{Di\ remaining} = SW_{Di} . e^{(-kt)}$.

SW_{Di} = 0.51 ton. (Table 4.2)

k= 0.07 (Slowly Biodegradable moist waste) (Table4.3)

Using these value percentage $SWt_{Di\ remaining} = (0.51 * e^{(-0.07*10)}/0.51) *100 = 49.659\%$. And percentage Transformed= 50.341%.

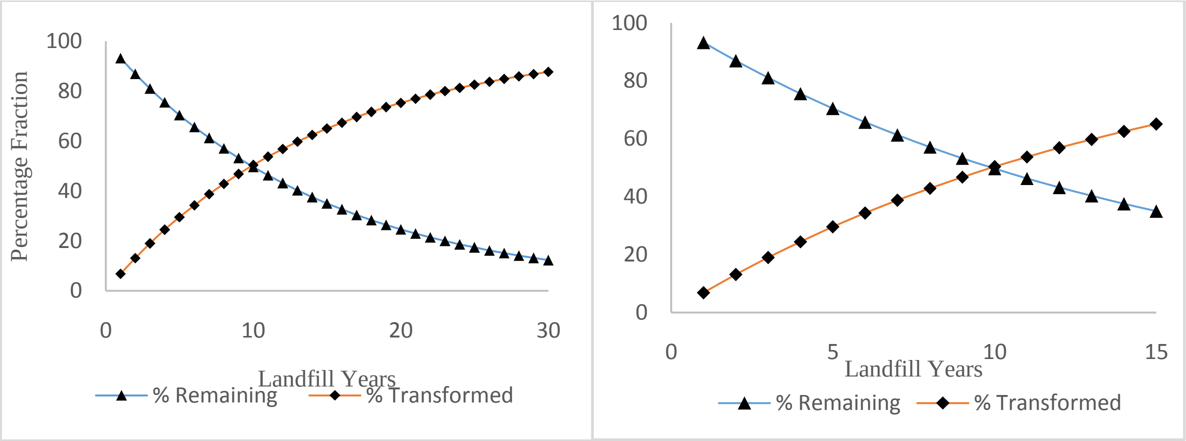

Fig 4.6: Degradation Pattern of Textile waste over 30 years and 15 years.

4.5 NON-DECOMPOSABLE WASTE

The non-decomposable materials such as Plastic, Glass, Ceramic,Thermocol and Inert may not be easily degraded as biodegradable wastes. However, it is likely that in old dump yard non-biodegradable waste deteriorates owing to weathering.Some amount of glass gets broken during disposal. Thermocol,Ceramic and plastic can also be weathered, resulting in finer fractions and turns into earthy material.During bio-mining after bio-remediation excavation and screening has to be done with proper screen size for recovery of unweather fraction for resource recovery. In landfill mining operation in Chennai, India in 2003 case study (Kurian et al., 2003) reported that screen size having<20mm is efficient for the separation of the finer fraction of the recyclable materials.

Plastic waste in landfills addresses one of the significant waste divisions that can be reused.Polyethylene (PE) and Polypropylene (PP) are the thermoplastics the most widely recognized components in the municipal solid waste. Photo degradation and thermo-oxidative deteriorations are the most basic reasons for degradation for PE and PP in an oxygen-consuming and anaerobic climate (Webb et al., 2013; Andrady, 2011; Gijsman et al., 1999).In the case of old dump waste plastic may not be easily degraded or take a long time for complete degradation. From the onsite data, approx. 10% of the total plastic is High-density polyethylene (HDPE) which can be recycled and rest is Low-density polyethylene (LDPE) which can be used as Refused-Derived-Fuel in the co-processing for the cement kiln and waste to energy facility.

Glass is one of our most easily recycled materials. When Glass is disposed some amount of it gets broken. Based on various literature surveys it is assumed that almost 75% of glass material can be recovered from old landfills. For 30 years waste sample, it is considered that 75% of glass material can be recycled and rest is in the form of coarser fraction. And in 15-year waste sample, the recyclable glass percentage would be slightly higher than 30-year waste sample.

Inert material mainly consists of construction and demolition waste, gravel, kankar etc. The degradation of inert material is a very slow process and the main cause of degradation is mechanical weathering due to sunlight, wind, rainfall, etc. but the rate of degradation is very small which causes the recovery rate of waste from landfill to be almost 90-95% and around 5-10% degradation turns into soil-like material (World Resource Foundation, 1998).

4.6 MATERIAL BALANCE FLOW CHART OF DIFFERENT COMPONENTS OF BIO-MINING

The main aim of bio-mining is to recover recyclable material and to increase the recovery efficiency through the minimization of soil-like material. The success of bio-mining relies upon the efficient resource recovery and composition of the mined waste (Cossu et al., 1996; Joseph et al., 2004). The mining of waste is applicable for 15 years old waste where the age of waste in Dhapa landfill is more than 30 years old so bio-mining can be applied efficiently for this landfill. The following factors play an important role in the consideration of processing of bio-mining (IWCS, 2009)

- The objective of the operation for determination of futuristic operation e.g., recycle, processing, co-processing of materials.
- Condition and properties of mined waste. The market value of recyclable materials including processing cost as per the certain quality requirements of recovered waste.

Site specific data were collected in Dhapa Landfill at different locations at different times and the average physical composition of legacy waste is presented in table 4.2. As the samples were collected from different depth of the landfill, the analysis is carried out for 15 years and 30 years till now. As the Dhapa landfill area is huge and the age of waste is more than 30 year it can be considered that the degradation of waste is almost completed. This is why, further analysis has been done considering the waste to be 30-year-old. The ultimate aim of this estimation is to prepare a material balance flow chart through which there will be a clear idea about the further reuse of different components obtained from bio-mining. Average physical material compositions are categorized into six components i.e., Ⅰ) Recyclable, Ⅱ) Construction and Demolition waste (C & D waste), Ⅲ) Refused-Derived-Fuel (RDF), Ⅳ) Bio-Earth or Good Earth, Ⅴ) Coarser Fraction, Ⅵ) Process Reject. Before this estimation certain assumptions have been made, which are as follows:

- Glass recycling is being done on 75% basis and 25% became coarser fraction.
- Only 10% plastic can be recycled and 90% is used as RDF.
- For inert material such as Gravel and Kankar, 5-10% partial degradation may be assumed. 90-95% of it will be treated as C&D waste and 5-10% as coarser fraction.
- As per IPCC model, 58-63% wood is recyclable and 37-42% can be used as RDF; 80-85% of coconut shell can be used as RDF and rest are process reject; 80-85% of bones degrades and form soil like material and 15-20% remains in form of coarser fraction; 40-45% textile can be recycled and 55-60% can be used as RDF.
- Due to heavy loading, dozing action, ceramics are supposed to be destructed either into small size material or maybe not of any use like materials. Hence major fraction of ceramics (80-85%) are found to be mixed up with coarser fraction and 15-20% is considered as process rejects.
- As, thermocol is a combustible material it is assumed 100% thermocol can be used as RDF.
- Mix waste consists of inert, e-waste and others which is considered as rejects.
- From site specific observation waste soil consists of coarser fraction and finer fraction i.e., bio-earth. However, bio-earth (<4 mm particle size) do not contained any C&D fraction. But coarser faction (20 mm to 4 mm particle size) contains smaller fraction of gravels, kankar, small fraction of brick which is exclusively around 10% of C&D materials. Thereby, 50% bio-earth, 40% coarser organic fraction and 10% C&D material is considered as Waste Soil as a whole.

Table 4.14: Percentage of Recyclable Material after bio-mining

Component	Percentage Fraction	Physical Composition (%)	Amount (%)
Wood	*60.5*	*0.42*	*0.254*
Glass	*75*	*1.21*	*0.908*

Plastic (HDPE)	*10*	*21.16*	*2.116*
Textile Fabric	*42.5*	*0.51*	*0.217*
Total			***3.495***

Table 4.15: Percentage of C & D Waste after bio-miming

Component	Percentage Fraction	Physical Composition (%)	Amount (%)
Gravel	*92.5*	*9.22*	*8.529*
Kankar	*92.5*	*6.61*	*6.114*
Waste Soil	*10*	*55.12*	*5.512*
Total			***20.155***

Table 4.16: Percentage of Refused-Derived-Fuel (RDF) after bio-mining

Component	Percentage Fraction	Physical Composition (%)	Amount (%)
Wood	*39.5*	*0.42*	*0.166*
Coconut	*82.5*	*1.01*	*0.833*
Plastic (LDPE)	*90*	*21.16*	*19.044*
Textile Fabric	*57.5*	*0.51*	*0.293*
Thermocol	*100*	*0.45*	*0.45*
Total			***20.786***

Table 4.17: Percentage of Bio-earth after bio-mining

Component	Percentage Fraction	Physical Composition (%)	Amount (%)
Waste Soil	*50*	*55.12*	*27.56*
Bone	*82.5*	*0.66*	*0.545*
Total			***28.105***

Table 4.18: Percentage of Coarser Fraction after bio-mining

Component	Percentage Fraction	Physical Composition (%)	Amount (%)
Glass	*25*	*1.21*	*0.303*
Ceramic	*82.5*	*1.55*	*1.279*
Bone	*17.5*	*0.66*	*0.116*

Gravel	*7.5*	*9.22*	*0.692*
Kankar	*7.5*	*6.61*	*0.496*
Waste Soil	*40*	*55.12*	*22.048*
Total			***24.934***

Table 4.19: Percentage of Process Reject after bio-mining

Component	Percentage Fraction	Physical Composition (%)	Amount (%)
Coconut	*17.5*	*1.01*	*0.177*
Ceramic	*17.5*	*1.55*	*0.271*
Mix Waste	*100*	*2.08*	*2.08*
Total			***2.528***

- **Moisture loss during legacy waste stabilization:**

Fresh legacy waste, stabilised waste soil, fresh legacy waste-soil have been analysed. Moisture loss in 7-8 days for coarser fraction and good earth is 17-19% from our sample analysis. Due to mixture of RDF, Recyclables with the soil in these sample, moisture loss was comparatively less rather than those only soil like material samples. Moisture loss regarding this case was 10-12% only. So, for recyclable and RDF, we are taking 5% moisture loss in comparison to 20% loss of moisture for the bio-earth and coarser fraction. Whereas for C&D, 10% loss have been presumed due to water absorption characteristics of bricks and aggregates. 1-2% moisture loss can be considered for process rejects.

Moisture loss from all six components have been calculated and percentage of all components after bio-mining process is shown in form of material balance diagram in figure 4.7.

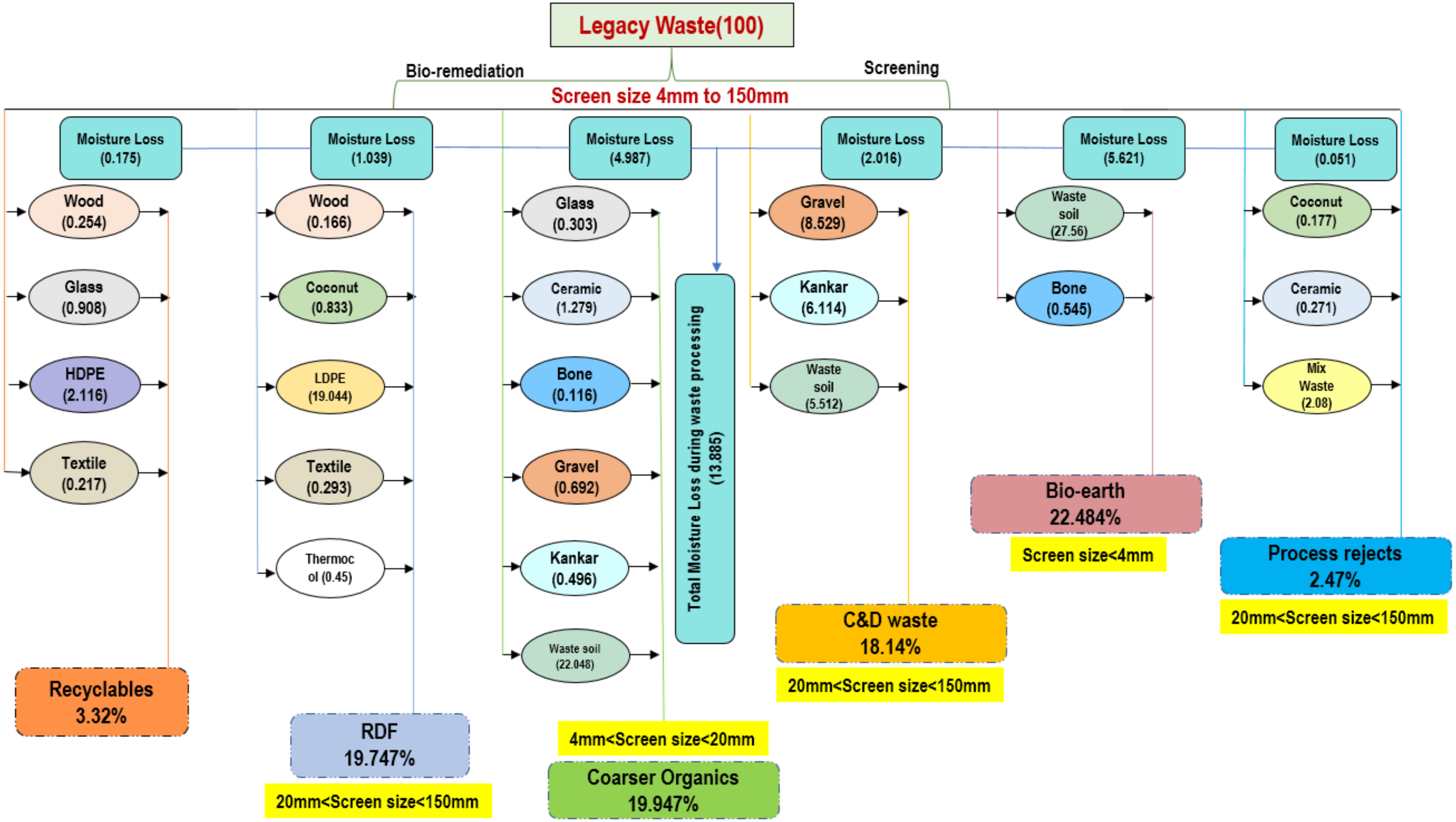

Fig 4.7: Material balance flow chart after bio-mining

Material balance flow chart of different components of bio-mining is shown in the figure 4.7. 100 ton of legacy waste are taken for analysis. Firstly, from excavated legacy waste, windrows are formed so as the moisture and leachate can be dried out through solar exposure and all the entrapped methane is removed from the heap. Bio-culture is added for speeding up the decomposition process and creates biological heat within the waste that helps to dry it. The waste is kept 7-10 days for stabilization. Then stabilized waste have been analysed and following results are obtained. Total moisture loss from the legacy waste is around 13.89%. The finest fraction which can pass through 4-6mm screen size is called bio-earth or good earth. The percentage of bio-earth obtained is around 22.484%. The recyclable fraction is found to be 3.32% which can be sent to material recycling facility.C&D waste obtained is around 18.14% which can be send to C&D recovery plant, using in infrastructural work. 19.747% RDF can be used as an alternate fuel in cement industries and 19.947% Coarser fraction can be used as a filling material.The residual obtained as process reject from the analysis is found to be 2.477% which meet the CPCB norms (CPCB, 2019).

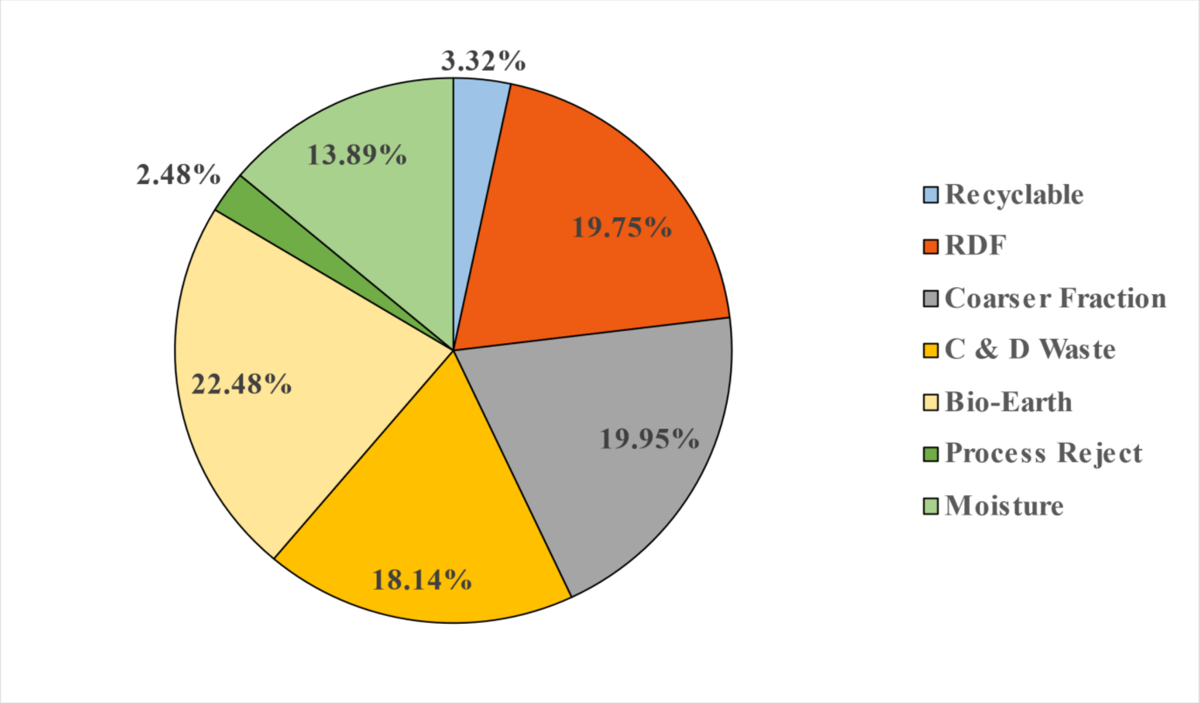

Fig 4.8: Pie chart showing fractional analysis of different bio-mining components

4.7 QUANTITY ESTIMATION OF DIFFERENT BIO-MINING COMPONENTS

From the flow chart (Figure 4.7), the quantity of different bio-mining components has been estimated. The total amount of legacy waste is 40 lakhs MT. Out of these 9 lakhs, 13 lakhs and 18 lakhs MT legacy waste will be processed in first,second and third bio-mining year respectively. Before mining or excavation, legacy waste has to be stabilized through addition of bio culture as stated in CPCB guideline (CPCB, 2019) which is called bio-remediation. After bioremediation, the waste has to be loosened, excavated, and screened through bio-mining equipment. Before that bulky waste e.g., coconut shell, piece of rag, clothes or other textile waste, broken glass, or other un-weathered portion of inert material mainly must be removed manually. Quantity estimation of different bio-mining components in different bio-mining year are shown in following tables. A Graphical representation of different bio-mining components along with moisture present in it is shown in fig 4.9.

Table 4.20: Quantity estimation of different bio-mining components in 1st bio-mining year

Total Amount of Legacy Waste (Lakhs MT)	***Components***	***Percentage Fraction***	***Amount (MT)***
9	*Recyclable*	*3.32*	*29,880*
	RDF	*19.747*	*1,77,723*
	Coarser Fraction	*19.947*	*1,79,523*
	C&D Waste	*18.14*	*1,63,260*
	Bio-Earth	*22.484*	*2,02,356*
	Process Reject	*2.477*	*22,293*

Table 4.21: Quantity estimation of different bio-mining components in 2nd bio-mining year

Total Amount of Legacy Waste (Lakhs MT)	**Components**	**Percentage Fraction**	**Amount (MT)**
13	*Recyclable*	*3.32*	*43,160*
	RDF	*19.747*	*2,56,711*
	Coarser Fraction	*19.947*	*2,59,311*
	C&D Waste	*18.14*	*2,35,820*
	Bio-Earth	*22.484*	*2,92,292*
	Process Reject	*2.477*	*32,201*

Table 4.22: Quantity estimation of different bio-mining components in 3rd bio-mining year

Total Amount of Legacy Waste (Lakhs MT)	**Components**	**Percentage Fraction**	**Amount (MT)**
18	*Recyclable*	*3.32*	*59,760*
	RDF	*19.747*	*3,55,446*

	Coarser Fraction	*19.947*	*3,59,046*
	C&D Waste	*18.14*	*3,26,520*
	Bio-Earth	*22.484*	*4,04,712*
	Process Reject	*2.477*	*44,586*

Table 4.23: Overall quantity estimation of different bio-mining components.

Total Amount of Legacy Waste (Lakhs MT)	Components	Percentage Fraction	Amount (MT)
40	Recyclable	3.32	1,32,800
	RDF	19.747	7,89,880
	Coarser Fraction	19.947	7,97,880
	C&D Waste	18.14	7,25,600
	Bio-Earth	22.484	8,99,360
	Process Reject	2.477	99,080

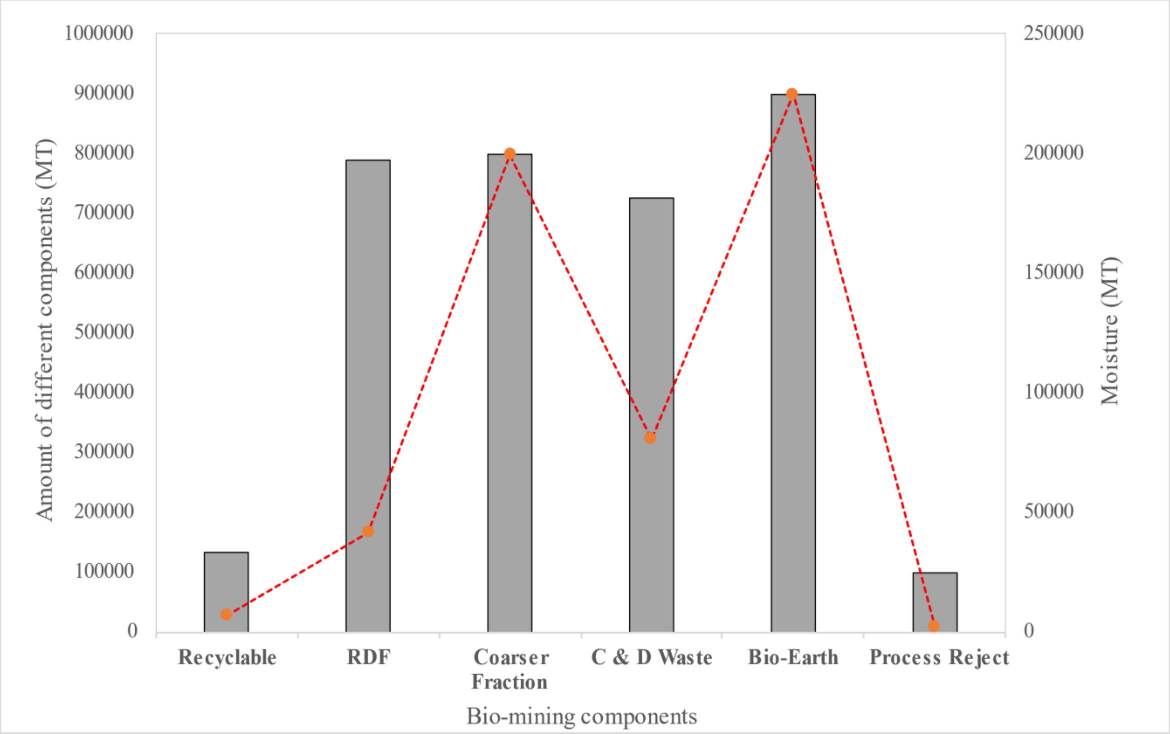

Fig 4.9: Graphical Representation of different bio-mining components after bio-mining.

4.8EQUIPMENT REQUIRED FOR BIO-MINING OPERATION

The major equipment that can be utilized to handle legacy waste, according to CPCB 2019, come under the following categories of operations: excavation, shredding, screening, air classification, and ferrous separation. Choices should be made appropriately based on the process' suitability and requirements, site condition and the economy.

Ⅰ. Handling Equipment

- **Excavator**

An excavator consistof a standard work unit on top of the undercarriage is used to uncover the waste materials and transport it to elevator conveyor belts.As usual, the functional arm is made up of a boom and a bucket. According to usage and demand, the front attachment can be modified.

- **Loader**

A loader is a piece of heavy equipment used in bio-mining operations to transfer or load materials like legacy waste, soil, rock, sand, C&D waste, etc. into or onto other pieces of equipment like a dump truck, conveyor belt, feed-hopper, or train car. There are various types of loaders named as bucket loader, front loader, front-end loader, pay-loader, high lift, scoop, shovel, skip loader, wheel loader, etc. depending on their design and intended use.

- **Dumper**

Dumper are mainly used in bio-miming process for carrying bulk material such as legacy waste and its fractional components. They are normally diesel powered**.**

- **Conveyors**

Conveyors system is extremely versatile and it is utilized for effectively transporting materials up steep inclines.

Ⅱ. Screening equipment

- **Ballistic Separators**

Ballistic separators arethe waste-sorting equipment. A ballistic separator is, as its name suggests, a high load segregating device that sorts different types of waste.Waste products with similar shapes and sizes are separated out from the rest in two or three fractions, for example, the stones, C&D waste, glass, and metal substances are easily separated from the reusable paper, plastic, cardboard, and other recyclable products.

- **Trommel**

In Trommel different size sieves separate the soil material, Combustibles and inert etc. The rotating cylindrical screens are inclined at a downward angle with the horizontal. At the high end of the trommel, material is fed, and as it moves down the drum, separation takes place. Materials that may be connected to one another can be successfully separated using the trommel's tumbling movement.Length, angle and diameter of the drum, depth of the material and the speed of rotation are important specifications in configuring the trommel to accomplish the desired goals. Screen sizes commonly used are one or more of the following: 150 mm. 80 to 100 mm, 24 to 50mm, 12-16 mm and 4-6. However, the machine requires some manpower for smooth operation, it is easy to use and operation safe.

- **Air Density Separators/Classifiers**

Air classification is utilized to separate light materials like papers, plastics etc. from heavier materials such as stones, bricks etc. through the use of an air stream of sufficient velocity to carry away the lighter materials. A cyclone separator may be used in conjunction with the air classifier to remove the lighter separated fraction from the air stream after it exits the classifier throat. The cyclone separator uses a centrifugal action that results from the airflow through the cyclone to move the materials to the walls of the separator. At present no Air Density Separators/Classifiers are being used in this Bio-mining project of Dhapa. In future planning it may be used to separate a coarser fraction from RDF materials which is coming out from the ballistic separators.

- **Ferrous Separation**

After shredding or screening, the ferrous materialwhich primarily comprises of iron and steel products is separated using magnetic separators.At present as the amount of recyclable ferrous metal is less so no magnetic separator is being used in the Dhapa Bio-mining project. It may be introduced later depending upon the change of characteristics of recyclable matter.

Chapter 5

LANDFILL GAS AND LEACHATE GENERATION FROM MSW LANDFILL

5.1 LANDFILL GAS GENERATION

Landfill gas is a mix of several gases produced by the action of micro-organisms within a landfill as they decompose organic matter. The major components of landfill gas are mainly $CO_2$and methane. The typical constituents of LFG and the usual concentrations at which they are observed are- Methane (CH_4) 40 to 60%, Carbon Dioxide (CO_2) 35 to 45%, Oxygen (O_2) < 1 to 5%, Nitrogen (N_2) < 1 to 3%, Water Vapor (H_2O) 1to 5%, Trace Hydrocarbon Constituents < 1 to 3%.When MSW is originally placed in a landfill, it goes through an aerobic (presence of oxygen) decomposition stage, where very little methane is generated. After that, anaerobic conditions are developed in less than a year, and methane-producing bacteria begin to decompose the waste and generate methane.

The changes in typical LFG composition after waste placement is shown in figure 5.1. Landfill waste is decomposed by bacteria in four phases. The composition of the gas changes with each phase, and waste in a landfill may be in multiple stages of decomposition at the same time. During the first phase of decomposition,aerobic bacteria utilise oxygen while breaking down the long molecular chains of complex carbohydrates, proteins, and lipids that make up organic waste. Carbon dioxide is the principal by-product of this procedure. The nitrogen level of the landfill is high at the start of this phase, but it gradually decreases as the landfill progresses through the four phases. Phase I will continue until all available oxygen has been used up.Phase II decomposition begins after depletion of oxygen in the landfill. Using an anaerobic process, bacteria transform chemicals produced by aerobic bacteria into acetic, lactic, and formic acids, as well as alcohols like methanol and ethanol, hence the landfill becomes acidic. When the acids react with the moisture in the waste, certain nutrients dissolve, making nitrogen and phosphorus available to the landfill's growing number of bacteriaspecies. Carbon dioxide and hydrogen are gaseous by-products of these reactions.Phase III decomposition begins when anaerobic bacteria digest the organic acids produced in Phase II and produce acetate.As a result of this process, the landfill becomes more neutral, allowing methane-producing bacteria to establish themselves.In phase IV, as the substrate gets depleted gas production becomes almost stable. Phase IV landfill gas typically contains 45- 60% methane(V/V), 40-60% carbon dioxide(V/V), and 2-9% other gases. In Phase IV, gas is produced at a constant rate for around 20 years; however, gas will continue to be released for another 50 years or more after the waste is disposed (Crawford and Smith 1985).

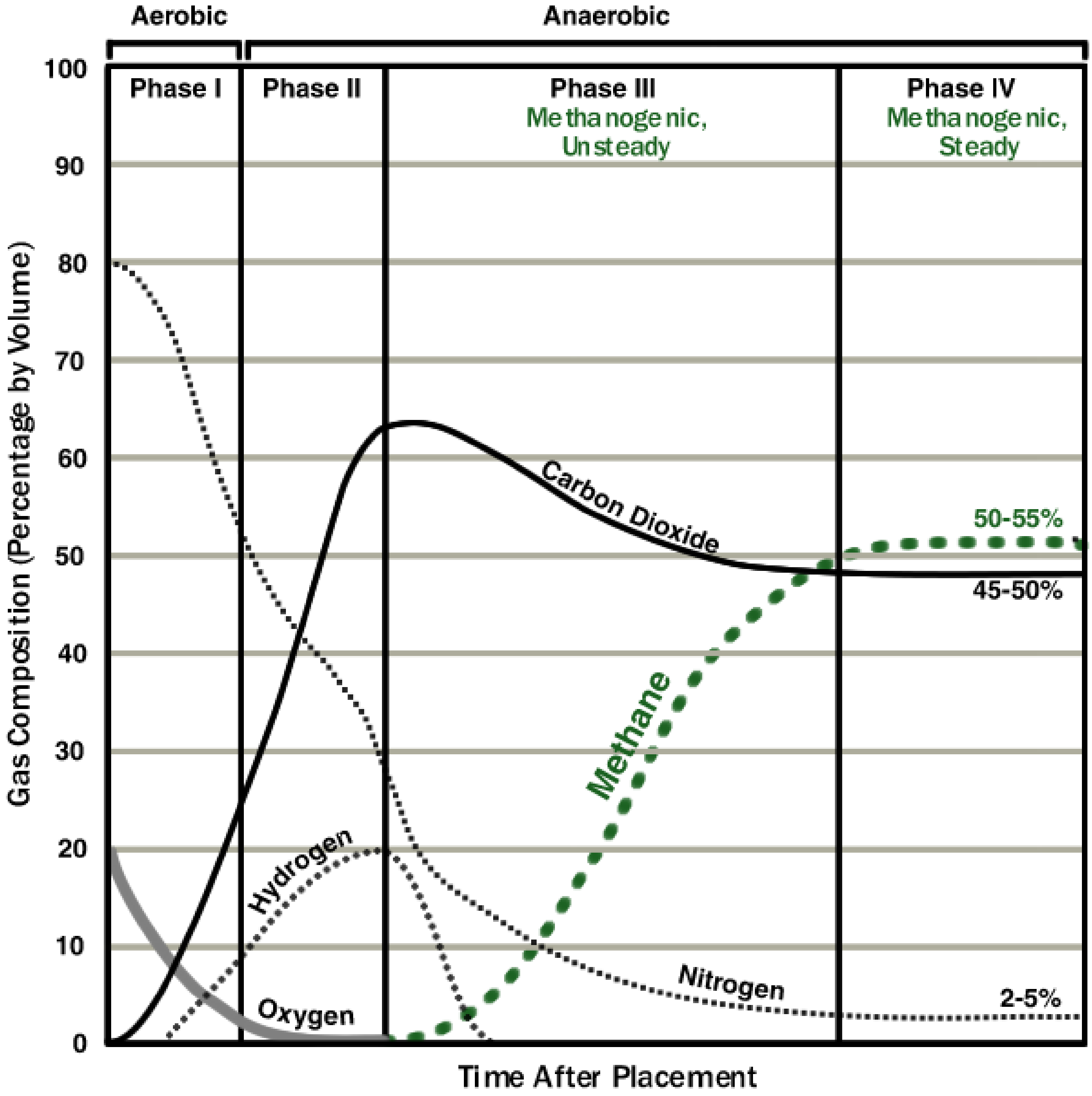

Fig 5.1: Production Phases of Typical Landfill Gas (Source: EPA 1997)

The rate at which LFG is produced is primarily a function of the categories of waste involved, e.g., rapidly decomposing food waste versus longer-lasting paper, cardboard, or other organic waste. Other variables, such as moisture content, temperature, refuse particle size, site configuration, compaction, and pH, can also have an impact on the overall rate of decomposition for all waste components in a specific region of a landfill.Basically, the better the conditions within a landfill are for the anaerobic bacteria, the faster the decomposition will occur, leading to a faster overall LFG generation rate build-up.

The composition of landfill gases and their percentage distribution is shown in table no 5.1. The pollution contributing gases presents in landfill are Methane, Carbon di-oxide, Hydrogen Sulfide, Ammonia, Carbon Monoxide and other gases like Nitrogen, Oxygen, Hydrogen and some trace components (Khan and Ashan, 2003). Among trace components, the major gases are taken based on their concentration and TLV value thoseare Acetone, Benzene, Chloroform, Dichloromethane, Ethyl benzene, Toluene, Tetrachloroethylene, Vinyl chloride, Styrene, Vinyl acetate.

Table5.1: Composition of Landfill Gases

Gases	**% by volume**	**% by weight**
Methane (CH_4)	*47.7*	*25.51*
Carbon di-oxide (CO_2)	*46*	*67.67*
Hydrogen Sulfide (H_2S)	*0.01*	*0.01*
Ammonia (NH_3)	*1*	*0.57*
Carbon Monoxide (CO)	*0.1*	*0.09*
Nitrogen (N_2)	*3.7*	*3.46*
Oxygen (O_2)	*0.8*	*0.86*
Hydrogen (H_2)	*0.1*	*0.01*
Acetone	*0.044*	*0.09*
Benzene	*0.014*	*0.04*
Chloroform	*0.002*	*0.01*
Dichloromethane	*0.164*	*0.47*
Ethyl benzene	*0.047*	*0.17*
Toluene	*0.222*	*0.68*
Tetrachloroethylene	*0.034*	*0.19*
Vinyl chloride	*0.023*	*0.05*
Styrene	*0.01*	*0.03*
Vinyl acetate	*0.036*	*0.1*

In many landfills due to lack a gas collection system, allowing methane to freely flow from the landfill envelope to the surface. A large portion of the LFG goes upward; however, only a small portion of the migrating gas gets oxidised in the cover, with the rest being released into the atmosphere. By trapping heat in the atmosphere, these releasing gases enhance the global warming potential. According to Stern and Kaufmann (1996), the decomposition of waste within landfills accounts for about 12% of global methane emissions. Because of its propensity to retain infrared radiation, methane is a powerful greenhouse gas 28 to 36 times more effective than CO_2 at trapping heat in the atmosphere over a 100-year period (USEPA, 2015). Due to its greater effectiveness as a greenhouse gas, methane has become a focus for emission reduction (Samir, 2014). The composition of organic components (cellulose, proteinsand lipids) affects thedegradation of waste and as a result affects the gas generation process. Presence of easily degradable organic carbon sources generates higher CH_4. Cellulose-to-ligninratio (CLR) has an effect on CH_4 production and it has also a negative relation with age of solid waste samples which indicate that the older samples are methanogenically active (Gurijala et al.,1997). Waste contains a high amount of moisture which helps in higher rate of CH_4 production.The estimation of methane generation using different model are computed below-

5.1.1 Estimation of methane generation by FOD Model

The amount of methane generated at the landfill is estimated, using first order degradation (FOD) model in spreadsheet, presented in the IPCC guideline (IPCC, 2006). The estimation of the formula of FOD model is described below. The FOD model calculates the amount of methane generated with the assumption that the rate of generation is proportional to the amount of reactant remaining, in this case the mass of degradable organic carbon decomposable under anaerobic conditions. In the FOD model, at the end of the year T at the landfill, the mass of organic carbon remaining and the mass of degradable organic carbon is worked out. In addition, the amount of accumulation and decomposition of decomposable degradable organic carbon each year is calculated. Based on these, the decomposable degradable organic carbon (DDOC) entering the solid waste disposal site is calculated in accordance with each category of waste (e.g., food waste, paper/cardboard, park and garden waste and wood). The amount of methane generated from the decomposable degradable organic carbon is calculated by the following equation:

$$\mathbf{Q_{T,\,x} = k * R_x * Lo * e^{-k(T-x)}}$$

Methane generation in year T from all solid waste landfilled in one specific year x can be calculated from this equation. Here,kis methane generation rate constant (l/year). The value of k describes the rate of degradation and is dependent on waste composition and site conditions. In the IPCC Guidelines, k is given a wide range of values between 0.005 and 0.4.

x: the year of waste input.

R_x: the amount of waste disposed in year x (Mg).

T: current year.

L_o: methane generation potential (m^3 /Mg of refuse). The IPCC Guidelines give a range of less than 100 m^3/Mg SW and more than 200 m^3/Mg SW. There is no justification for this range, no default values, and no explanation of the conditions that determine the factor. However, this factor is dependent on the DOC and DOC_F (these are discussed below in the IPCC default method section), as well as the conditions at the SWDS.

$Q_{T,x}$: the amount of methane generated in year T by the waste R_x (Mg).

In this model it is considered that methane emission from a particular year is cumulative sum of all the emissions of previous years. For example, the waste which is disposed in the first year has an effect in second year also. Likewise, even after 30 years there will be certain effect on methane emission due to the waste disposed in the first year. The following equation can be used to calculate all emissions from waste disposed of in prior years in the year T.Where,Q_T: total emissions in year T from waste disposed of in previous years (including year T).

$$\mathbf{Q_T = \sum Q_{T,\,x}}$$

Input data

- Waste has been continuously disposed in Dhapa landfill from 1987 and it is considered that 2015 is the final waste disposal year. But methane will continue to be emitted until bio-mining work starts. Bio-mining work is expected to be completed in 2024.But if bio-mining work was not implemented the LFG will continue to emit from dumpsite even after 50 years. So, methane generation from 1987 to 2050 has been calculated by using FOD modelto check the percentage gas reduction after implementation of bio-mining.

- In the IPCC Guidelines, k is given a wide range of values between 0.005 and 0.4. Here, k value is taken as 0.05 y^{-1} for developing countries (USEPA, 1998) based on half life of about 14-15 years for methane.
- L_o is methane generation potential (m^3/Mg of refuse). Here $L_o$is not considered in the model due to required unit of methane generation was in MT/Yr.
- Solid waste generation rate in Kolkata city in 2006 was around 3000 MT/day (Chattopadhyay et. al., 2007a). The rate of average increase of solid waste generation in Kolkata is about 3% annually. So, taking 3% annual growth rate, waste generation has been extrapolated and presented in table 5.2 considering 100% generated waste are disposed in Dhapa landfill.

Table 5.2: Year wise amount solid waste disposed (R_x) in Dhapa landfill.

Year	Waste Disposed (MT/Day)	Waste Disposed (MT/Year)
1987	*1711*	*624500*
1988	*1762*	*643232*
1989	*1815*	*662526*
1990	*1870*	*682400*
1991	*1926*	*702870*
1992	*1983*	*723952*
1993	*2043*	*745669*
1994	*2104*	*768037*
1995	*2167*	*791075*
1996	*2232*	*814804*
1997	*2299*	*839245*
1998	*2368*	*864419*
1999	*2439*	*890348*
2000	*2512*	*917055*
2001	*2588*	*944565*
2002	*2665*	*972900*
2003	*2745*	*1002086*
2004	*2828*	*1032147*
2005	*2913*	*1063110*
2006	*3000*	*1095000*
2007	*3090*	*1127850*
2008	*3183*	*1161686*
2009	*3278*	*1196539*
2010	*3377*	*1232437*
2011	*3478*	*1269412*
2012	*3582*	*1307496*
2013	*3690*	*1346722*
2014	*3800*	*1387124*
2015	*3914*	*1428741*

Sample calculation 1: Methane generation in year 1987 from all waste landfilled in year 1987 k=0.05

T=1987

x=1987

R_x =624500 MT/Yr. (table 24)

So, $Q_{87,\,87} = 0.05*624500*e^{-0.05(87-87)}$ =31225 MT/Yr.

Sample calculation 2: Methane generation in year 1988

i) Methane generation in year 1988 from all solid waste landfilled in year 1987

k= 0.05

T= 1988

x= 1987

R_x= 624500 MT/Yr. (table 24)

So, $Q_{88,\,87} = 0.05*624500*e^{-0.05(88-87)}$ = 29702 MT/Yr.

ii) Methane generation in year 1988 from all solid waste landfilled in year 1988

k= 0.05

T= 1988

x= 1988

R_x= 643232 MT/Yr. (table 24)

So, $Q_{88,\,88} = 0.05*643232*e^{-0.05(88-88)}$ = 32162 MT/Yr.

Total methane generation in the year 1988 =29702+32162 = 61864 MT/Yr.

Same way the total methane generation for different year has been calculated and presented in table 5.3.

Table 5.3: Total methane generation of individual year by FOD model

Year	**Total CH4 Generation (MT/Yr)**	**Year**	**Total CH4 Generation (MT/Yr)**
1987	*31225*	*2019*	*688657*
1988	*61864*	*2020*	*655071*
1989	*91973*	*2021*	*623123*
1990	*121607*	*2022*	*592733*
1991	*150820*	*2023*	*563825*
1992	*179662*	*2024*	*536327*

1993	*208183*
1994	*236432*
1995	*264455*
1996	*292297*
1997	*320004*
1998	*347618*
1999	*375182*
2000	*402737*
2001	*430324*
2002	*457981*
2003	*485750*
2004	*513667*
2005	*541770*
2006	*570098*
2007	*598686*
2008	*627572*
2009	*656792*
2010	*686382*
2011	*716377*
2012	*746814*
2013	*777728*
2014	*809154*
2015	*841128*
2016	*800106*
2017	*761084*
2018	*723965*
2025	*510170*
2026	*485289*
2027	*461621*
2028	*439107*
2029	*417692*
2030	*397321*
2031	*377943*
2032	*359511*
2033	*341977*
2034	*325299*
2035	*309434*
2036	*294342*
2037	*279987*
2038	*266332*
2039	*253343*
2040	*240987*
2041	*229234*
2042	*218054*
2043	*207420*
2044	*197304*
2045	*187681*
2046	*178528*
2047	*169821*
2048	*161539*
2049	*153660*
2050	*146166*

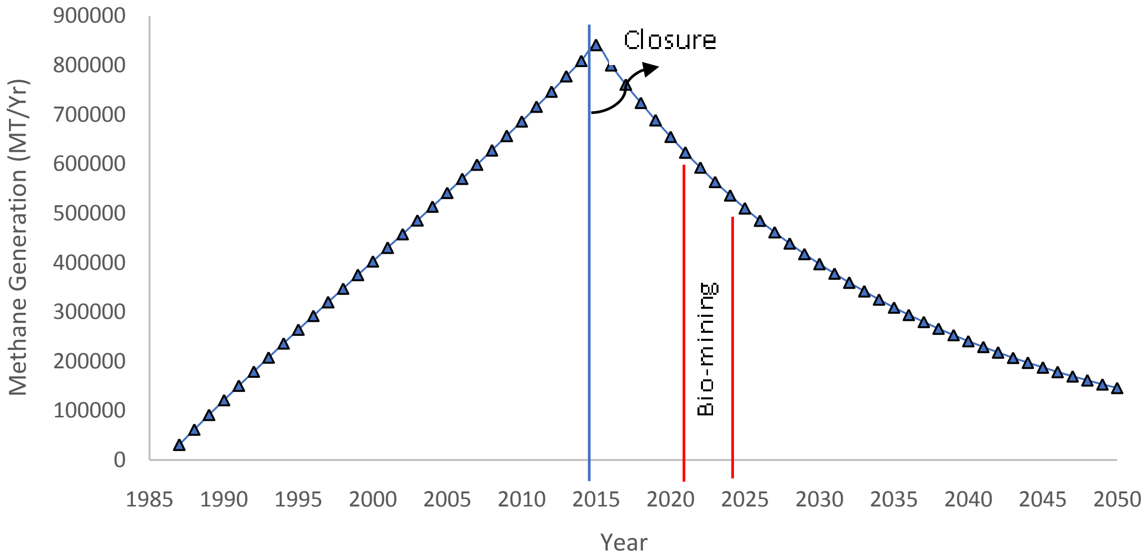

Fig 5.2: Year wise methane generation (FOD curve)

From the curve of FOD model total methane generation up to 2050 will be 2,60,98,935 MT which is equivalent to 73,07,70,180 MT of CO_2-eq (Global warming potential of CH_4 is 28 times of CO_2). But bio-mining has started in 2021 and it is expected to complete within 2024. So, upto 2024 total methane emission will be 1,84,89,173 MT. So, methane generation can be reduced from 2,60,98,935 to 1,84,89,173 Mt after implementation of bio-mining. Percentage reduction of methane emission in almost 25 year is 41%.

5.1.2 Estimation of methane generation by using IPCC default method

Another method discussed in IPCC guideline (IPCC, 2006) to estimate methane generation at the landfill is IPCC Default Method. In this method methane emission from solid waste disposal site can be estimated with a simple equation requiring waste disposal data only for the inventory year. An assumption of this method is that all CH_4 emissions are generated in the year in which the waste is disposed. Methane generation by default method can be computed by using the following equation:

Methane emissions (Gg/year)

$$= (MSW_T * MSW_F * MCF * DOC * DOC_F * F * 16/12 - R) * (1 - OX)$$

Where, MSW_T: total MSW generated (Gg/year)

MSW_F: fraction of MSW disposed to solid waste disposal sites

MCF: methane correction factor (fraction); MCF=0.8 for Unmanaged, deep sites ($\geq$ 5m) (IPCC guidelines). As Dhapa is unsanitary landfill and its height is around 20m($\geq$5m), MCF=0.8 is taken for calculation.

DOC: DOC stands for degradable organic carbon (fraction), or kg C/kg SW. The following equation is provided by IPCC standards for DOC value computation.

DOC = 0.4 * (A) + 0.17 * (B) + 0.15 * (C) + 0.30 * (D);

Where, A is Paper and textiles (% portion in SW); B is Garden and park waste, and other (non-food) organic putrescibles (% portion in SW); C is Food waste (% portion in SW); D is Wood and straw waste (% portion in SW). A, B, C, D value can be found out from table 4.1 and hence DOC value can be computed.

DOC_F: fraction DOC dissimilated; The IPCC default value of DOC_F is 0.77 as suggested by Bingemer and Crutzen (1987).

F: fraction of CH4 in landfill gas (IPCC default is 0.5)

16/12: conversion of C to CH_4

R: recovered CH_4 (Gg/year); As Dhapa is non-engineered landfill, there is no gas collection system so R is taken as 0.

OX: oxidation factor; A standard value of OX is taken as 0.1 (IPCC guidelines)

Putting all the input parameter in the equation, methane emission in Gg/year is calculated and presented in table 5.4.

Table 5.4: Methane generation of individual year by default method

Year	**Methane Generation (Gg/Yr.)**	**Cumulative Methane Generation (Gg/Yr.)**	**Year**	**Methane Generation (Gg/Yr.)**	**Cumulative Methane Generation (Gg/Yr.)**
1987	*26.25*	*26.25*	*2002*	*41.25*	*531.42*
1988	*27.04*	*53.29*	*2003*	*42.49*	*573.91*
1989	*27.85*	*81.14*	*2004*	*43.77*	*617.68*
1990	*28.69*	*109.83*	*2005*	*42.82*	*660.5*
1991	*29.55*	*139.38*	*2006*	*33.75*	*694.25*
1992	*30.43*	*169.81*	*2007*	*34.77*	*729.02*

1993	*31.34*	*201.15*	*2008*	*35.81*	*764.83*
1994	*32.29*	*233.44*	*2009*	*36.88*	*801.71*
1995	*33.25*	*266.69*	*2010*	*49.65*	*851.36*
1996	*34.55*	*301.24*	*2011*	*49.52*	*900.88*
1997	*35.59*	*336.83*	*2012*	*51.01*	*951.89*
1998	*36.65*	*373.48*	*2013*	*52.54*	*1004.43*
1999	*37.75*	*411.23*	*2014*	*54.11*	*1058.54*
2000	*38.89*	*450.12*	*2015*	*55.73*	*1114.27*
2001	*40.05*	*490.17*			

Methane generation from solid waste disposal site is highest the first few years after deposition and then decreases as the available carbon is consumed. Default method considers that all the methane is generated in the year in which waste is disposed and creates inaccuracies in actual annual methane emission. This method, besides, does not account for the rate of waste degradation over time. In actuality, there is a delay before methane emissions start, and methane emissions might last for decades after waste is disposed of. On the other hand, FOD models gives more accurate emission estimate as it takes cumulative effect of methane generation over years. The degradation pattern of waste in landfill is also reflects in FOD model which gives proper justification of using this model over default method. For the comparative study of these two methods a graph has been plotted and shown in figure 5.3. As waste disposal is increasing, default method gives overestimate value of methane emission.

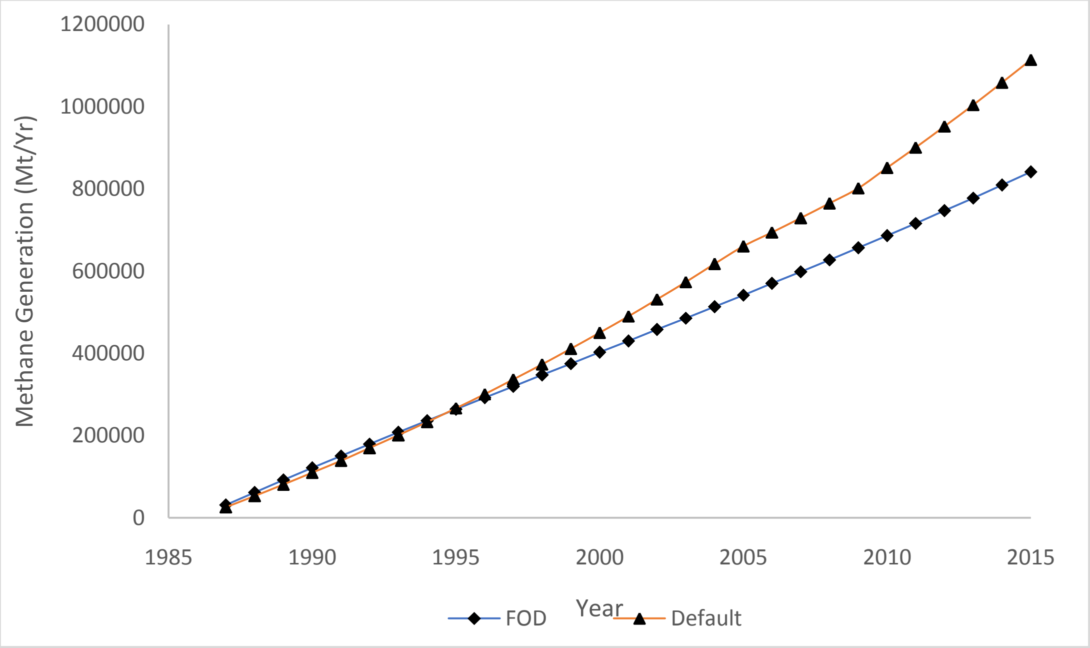

Fig 5.3: Comparison of methane generation by FOD model and IPCC default method

As FOD model gives more accurate results than default method, for further analysis the methane generation has been taken from FOD models only which is presented in table 5.3. The percentage distribution of all gases emitting from landfill are presented in table 5.1. The amount of methane generation and its percentage contribution is known and from there the generation of other landfill gases can be calculated. The gas generation only in the year 2020 and 2022 is presented in Table 5.5. The gas generation from year 1987-2050 are represented in figure no. 5.4, 5.5 and 5.6.

Table 5.5: Landfill Gas generation from landfilled legacy waste in 2020 and 2022

Gases	**Gas Generation in 2020 (MT/Yr.) (Before Bio-mining Scenario)**	**Gas Generation in 2022 (MT/Yr.) (During Bio-mining Scenario)**
Methane (CH_4)	655071	592733
Carbon di-oxide (CO_2)	1737698	1572335
Hydrogen Sulfide (H_2S)	257	233
Ammonia (NH_3)	14637	13244
Carbon Monoxide (CO)	2311	*2091*
Nitrogen (N_2)	*88850*	*80395*
Oxygen (O_2)	*22084*	*19983*
Hydrogen (H_2)	*257*	*232*

Acetone	*2311*	*2091*
Benzene	*1027*	*929*
Chloroform	*257*	*232*
Dichloromethane	12069	*10921*
Ethyl benzene	*4365*	*3950*
Toluene	*17462*	*15800*
Tetrachloroethylene	4879	*4415*
Vinyl chloride	*1284*	*1162*
Styrene	770	*697*
Vinyl acetate	2568	*2324*

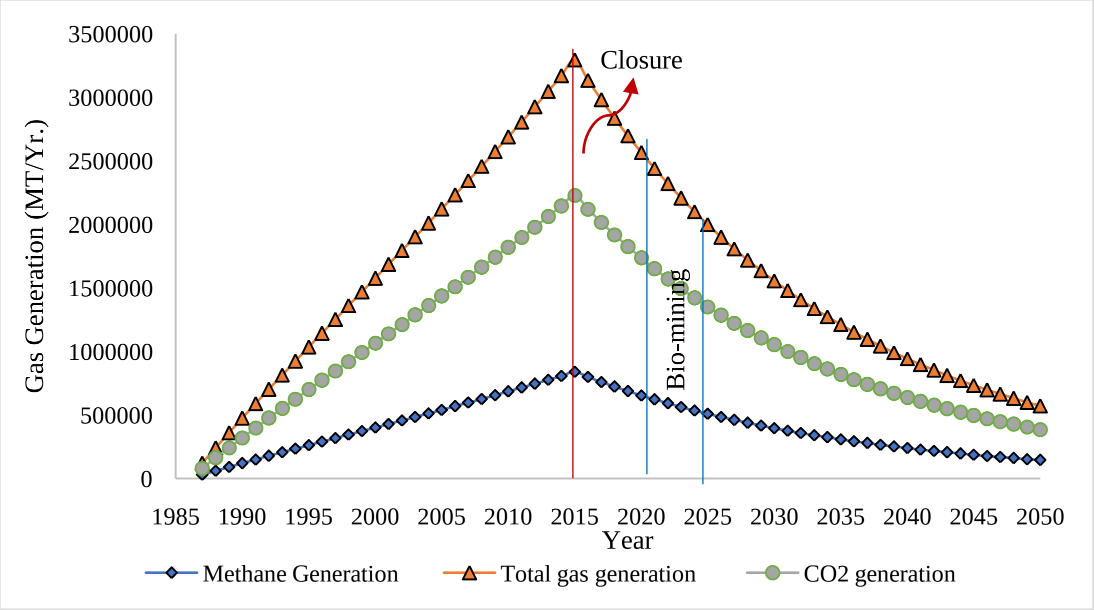

Fig 5.4: Year wise gas generation from landfilled legacy waste

From the above curve of FOD model, total landfill gas generation, CO_2generation, methane generation up to 2050 will be 10,23,08,673 MT, 6,92,32,313 MT and 2,60,98,935 MT (73,07,70,180 MT of CO_2-eq) respectively. But bio-mining period is up to 2024 starting from 2021. Hence, total landfill gas (LFG), CO_2 and methane emission up to 2024 will be 7,24,78,156 MT, 4,90,45,988 MT and 1,84,89,173 MT respectively. So, total LFG, CO_2 and CH_4 generation can be reduced by around 41% in 25 years potential after implementation of bio-mining treatment.

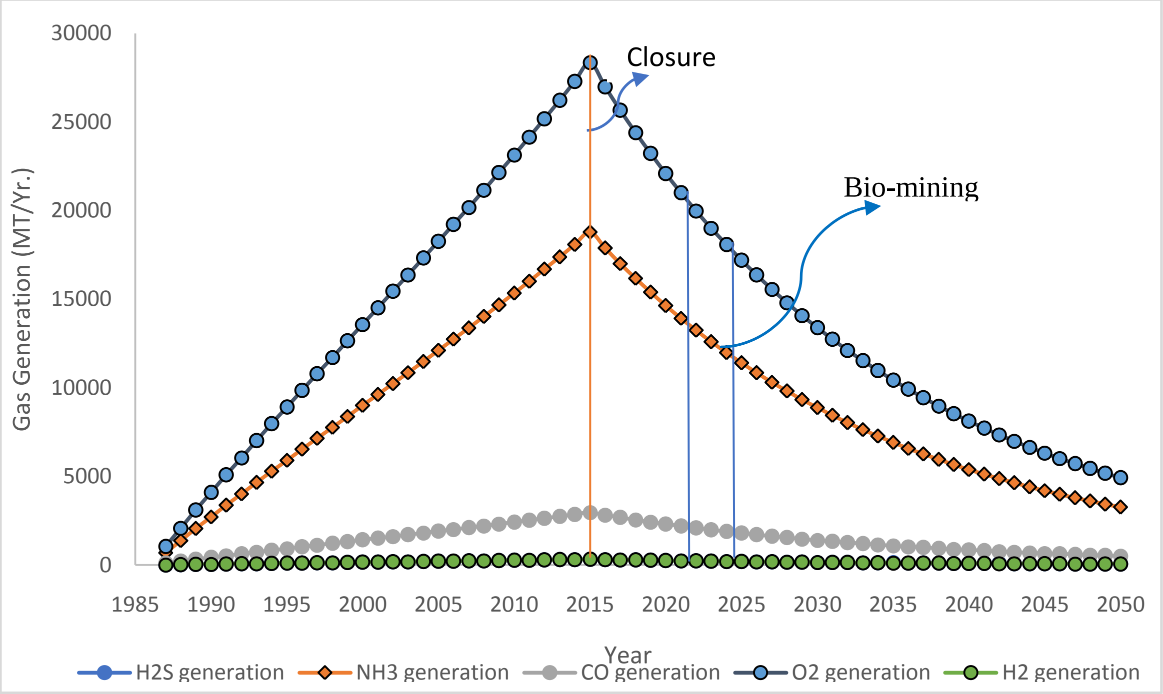

Fig 5.5: Year wise LFG component generation from landfilled legacy waste

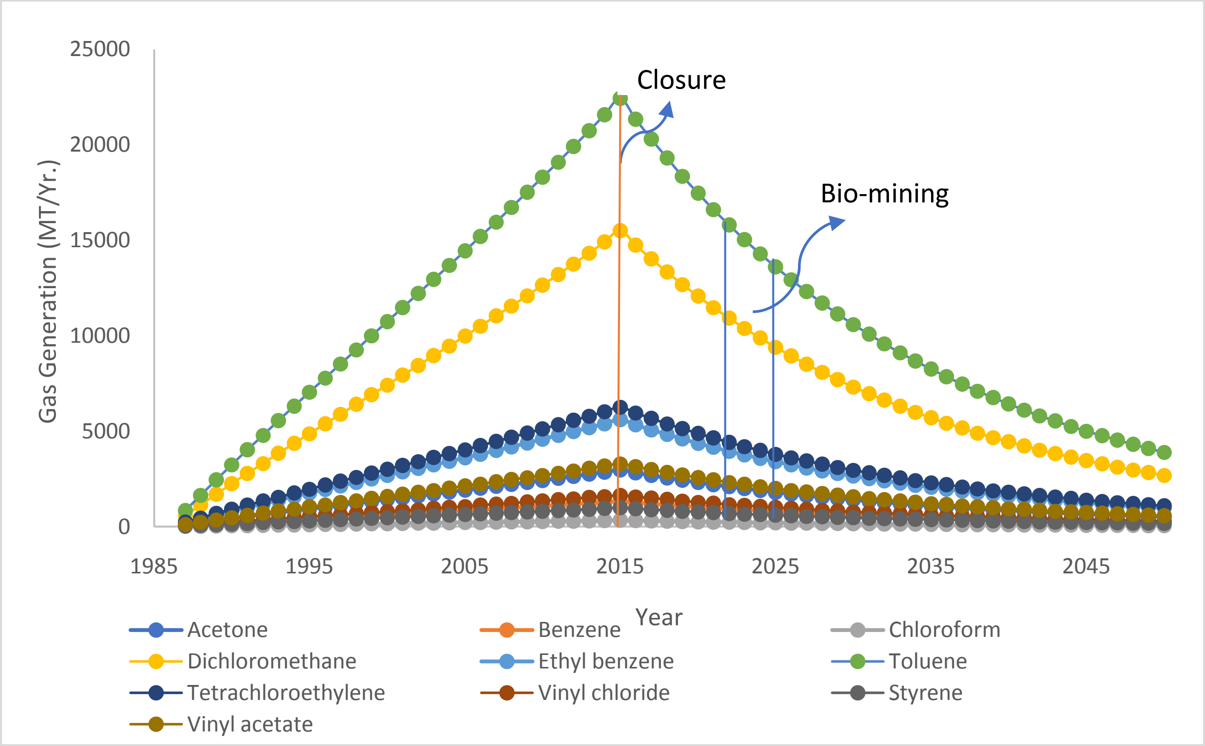

Fig 5.6: Year wise LFG trace component generation from landfilled legacy waste

5.2 LAND AREA RECLAMATION

Total estimated quantity of legacy waste in Dhapa landfill is 40 lakh MT. This huge amount of legacy waste will be processed in 3 consecutive years i.e., in 2021-22, 2022-23, 2023-24. The quantity of legacy waste processing in these three bio-mining year will be 9 lakh MT, 13 lakh MT, 18 lakh MT respectively. The average height of Dhapa landfill site is around 20 m (Chattopadhyay et. al., 2007b). As most of the waste deposited in Dhapa is biodegradable, the density of the waste has been taken as 850 kg/m3 (CPHEEO, 2000). Land area reclamation in each bio-mining year has been calculated below.

1st Bio-mining Year: Quantity of legacy waste has to be processed= 9 lakh MT= 900000 MT

Density of legacy waste= 850 kg/m^3 = 0.85 MT/m^3

Volume of legacy waste= (900000/0.85) m^3= 1058824 m^3

Area reclamation= (1058824/20) m^2= 52941 m^2 = 5.29 ha

2nd Bio-miming year: Quantity of legacy waste has to be processed=13 lakh MT=1300000 MT

Density of legacy waste= 850 kg/m^3 = 0.85 MT/m^3

Volume of legacy waste= (1300000/0.85) m^3= 1529412 m^3

Area reclamation= (1529412/20) m^2= 76471 m^2 = 7.65 ha

3rd Bio-mining year: Quantity of legacy waste has to be processed= 18 lakh MT= 1800000 MT

Density of legacy waste= 850 kg/m^3 = 0.85 MT/m^3

Volume of legacy waste= (1800000/0.85) m^3= 2117647 m^3

Area reclamation= (2117647/20) m^2= 105882 m^2 = 10.59 ha

Total land area reclamation after bio-mining = (5.29+7.65+10.59) ha= 23.5 ha

5.3 LANDFILL LEACHATE GENERATION

Due to increasing environmental consciousness, sustainable development in material management, the push for recycling and reusing materials, as well as global economic and space limits, waste management is becoming more and more complex.Though in the solid waste management hierarchy landfilling is least preferred option, it is still the most practiced approach of waste management as it has the advantage of requirement of cheapest capital and exploitation costs. But it generates highly contaminated liquid called leachates which is drains out from the waste material, consists of both dissolved and suspended materials.Leachate is generated mainly due to the precipitation filters through a solid waste disposal site and from the decomposition of the landfilled waste.The leachate from landfills contains toxic chemicals including volatile organic compounds (VOCs), nitrogen compounds, inorganic macro components (common cations and anions including sulfate, chloride, iron, aluminium, zinc and ammonia), heavy metals (Cr, Cd, Pb, Ni, Cu, Hg), and xenobiotic organic compounds such as halogenated organics, (PCBs, dioxins, etc) (Tchobanoglous, 1993; Kjeldsen et al., 2002; Kathpalia and Alappat, 2003; Mor et al., 2006). Volume of leachate generated in a landfill depends on a number of factors including climate conditions, stage and age of landfill and waste characteristics and site-specific parameters.Dhapa landfill in Kolkata is a non-engineered disposal site**,** there is no liners and no leachate management facility.Huge quantity of rainfall in Kolkata (1850 mm/year) causes huge amount of leachate generation which pollutes surrounding soil, surface water and ground water. A study conducted by CPCB in and around Dhapa landfill in Kolkata found that leachate is highly polluted with organic and inorganic pollutants (Saha et. al., 2003).Leachate generation estimation becomes important inquantifying pollution potential and managing the landfill site. There is no direct method available for estimation of leachate generation in case of existing landfills with no proper leachate collection system like Dhapa.One of the best available well validated models for such purpose is EPA’s Hydrologic Evaluation of Landfill Performance (HELP) model. HELP model is based on modelling the site water balance, used to measure daily water inflows and outflows and storage changes for a unit area of the system over a certain period of time. A study has been done with the HELP model to quantify the leachate generation from the existing open dumping ground at Dhapa, Kolkata (Basak, 2011). For leachate estimation, the model uses various input parameters including daily climate data, soil data, landfill design data, waste characteristics. From there, a graph was plotted showing yearly variation of leachate generation that was in the range of 900-1000 L/m^2/year. From that variation we got year-wise leachate generation which is shown in table 5.6 and presented in figure 5.7. For ease of calculation the average value of leachate generation has been taken over 38 year (1987-2024). The average value of leachate generation is 968 L/m^2/year.

Table 5.6: Year wise leachate generation

Year	**Leachate Generation ($L/m^2/yr.$)**
1987	*900*
1988	*920*
1989	*940*
1990	*780*
1991	*1180*
1992	*860*
1993	*880*
1994	*950*
1995	*930*
1996	*820*
1997	*1020*
1998	*880*
1999	*1040*
2000	*1300*
2001	*1000*
2002	*640*
2003	*680*
2004	*840*
2005	*820*

Year	**Leachate Generation ($L/m^2/yr.$)**
2006	*780*
2007	*760*
2008	*940*
2009	*940*
2010	*1020*
2011	*1120*
2012	*950*
2013	*1100*
2014	*1080*
2015	*1050*
2016	*1000*
2017	*1180*
2018	*1120*
2019	*1000*
2020	*1400*
2021	*1250*
2022	*800*
2023	*900*
2024	*1000*

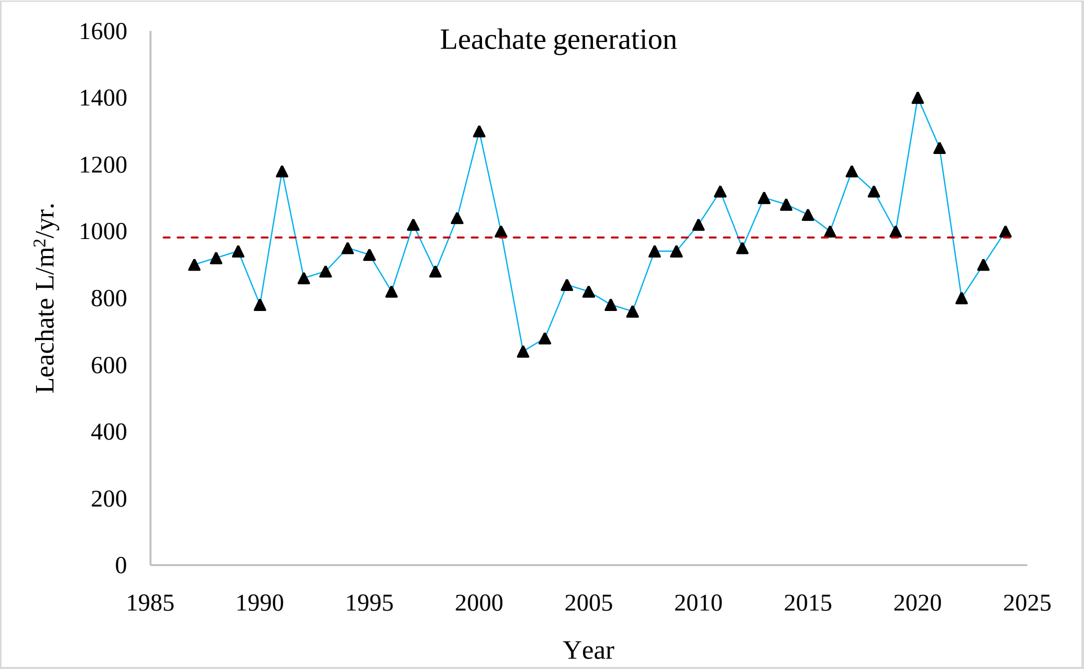

Fig 5.7: Year wise leachate generation

Leachate generation in bio-mining years

In 1st bio-mining year i.e., 2021-22 the generation is 800 L/m^2/year (table 5.6)

Land area reclamation= 5.29 ha= 52900 m^2

Leachate generation in 2022= (800*52900) L= 4.232*10^7 L

After bio-mining in 2021-22, leachate generation reduction will be 4.232*10^7 L

In 2nd bio-mining year i.e., 2022-23 the generation is 900 L/m^2/year (table 5.6)

Land area reclamation= 7.65 ha= 76500 m^2

Leachate generation in 2022-23= (900*76500) L= 6.885*10^7 L

After bio-mining in 2022-23, leachate generation reduction will be 6.885*10^7 L

In 3rd bio-mining year i.e., 2023-24 the generation is 1000 L/m^2/year (Table 5.6)

Land area reclamation= 10.59 ha= 105900 m^2

Leachate generation in 2023-24= (1000*105900) L= 10.59*10^7 L

After bio-mining in 2023-24, leachate generation reduction will be 10.59*10^7 L

Total reduction in 3 bio-mining year= 21.7*10^7 L

Average reduction per year= $7.23*10^7$ L/year.

Average leachate generation= 968 L/m^2/year.

Total landfill area= 23.5 ha= 235000 m^2.

Average leachate generation from whole landfill area= (968*235000) = $22.7*10^7$ L/year.

So, percentage reduction= $[(22.7*10^7-7.23*10^7)/22.7*10^7]*100 = 68\%$

Estimated leachate generation reduction for three consecutive years is 21.7 x 10^7litre. From figure 5.7, average leachate generation from whole land area is 22.7 x 10^7 litre. Hence, for bio-mining period, an estimated reduction of leachate by 68% is achievable. However, in post bio-mining period, due to reclamation of whole land area will be done and no such MSW will be there, leachate generation tends to net zero emission.

Chapter 6

IMPACT ASSESSMENT OF BIO-MINING OF LEGACY WASTE

There are two suitable approaches are available for assessing the environmental impact based on availability of data, these are Life Cycle Impact Assessment (LCIA) Approach; and (2) Waste Reduction (WAR) Algorithm.WARapproach is used to assess the environmental impact and eco-friendliness of manufacturing process. This approach also uses the Impact Potential method and/or TPBP for finding out the environmental impact of chemicals in different environmental categories (Young and Cabezas,1999; Young et al., 2000).In this study, potential environmental impact is calculated based on LCIA approaches which is a part of LCA (Life Cycle Assessment). LCA is usually used to find out the total environmental impact of product or process from the different activities throughout its life cycle.It offers a very efficient and useful tool which effectively supports the decision-making of a waste management policy, schemes and practices.

According to the International Organisation for Standardisation (ISO) an environmental Life Cycle Assessment (LCA) studies the environmental interventions and potential impacts throughout a product’s life (i.e., from cradle-to grave) from raw material acquisition through production, use and disposal.The United States Environmental Protection Agency (USEPA) considers life cycle assessment (LCA) as one of the markers on the way to sustainability. The USEPA defines LCA as a method for assessing the environmental aspects and potential impacts related to a product or process by creating an inventory of pertinent energy and material inputs and environmental releases, assessing the potential environmental impacts related to identified inputs and releases, and then interpreting the results to help with decision-making. Use of resources, human health, and ecological issues are the three broad areas of environmental impacts that need to be taken into account. The term "product" in the definition of LCA can refer to both product and service systems, for example solid waste management systems (Clift et al., 2000, Goran Finnveden, 1999).

6.1 LIFE CYCLE IMPACT ASSESSMENT (LCIA)

6.1.1History of LCA

LCA i.e., life cycle assessment was introduced in the late 1960s and early 1970s. The first implementation of LCA can be tracked back to 1969, which was done out by Coca-Cola for the evaluation of the resource consumption and emissions associated with beverage containers to assess the feasibility of replacing disposable plastic containers with returnable glass bottles (Fan, 2014). This study is considered recognized as one of the first studies of LCA and recognized for basis for life cycle inventory analysis (Environmental Protection Agency, 1993). More companies in the United States and Europe started similar life cycle inventory analyses in 1970s. For example, the Japan Nomura Research Institute, multinational food packaging and processing company, conducted a packaging LCA study for Tetra Pak in 1975 (Imura, et al., 1997); and after that Franklin Associates performed an LCA for soft-drink containers for Goodyear (Franklin Associates Inc., 1978). In this period the studies commonly used the energy analysis method (quantification method of resource use and environmental release), which was known as the Resource and Environmental Profile Analysis (REPA). This method was used more during late 1970s to the mid-1980s with the emergence of the global problem of solid waste (Fan, 2014). And later on, some consultant companies in Europe and the United States further developed this method for a range of waste management purposes. Similar method was also developed by some European researchers (as represented by Ian Boustead, United Kingdom) which is also called as ‘Eco-balance’ (based on the balance of energy vs. mass, coupled with an ecological test). After the late 1980’s, due to global awareness of sustainable development and environmental protection, the LCA studies was in boom. To develop a unified specification of LCA, in 1989, the Dutch National Living, Planning and the Environment Ministry first proposed a product-oriented environmental policy instead of the traditional terminal environmental control policy which covered the all aspects of a product life cycle including the consumption and disposal phases. The Society of Environmental Toxicology and Chemistry (SETAC) hosted the International LCA Seminar for thefirst time in 1990 and the specifications of LCA were officially recognized. A unified regulation was finally determined in 1993 at the Portugal Sesimbra Seminar, and the final name was officially designated as the Life Cycle Assessment (LCA) (SETAC, 1993). Still today, LCA methodology is being researched and developed. Now, SETAC and the International Organization for Standardization (ISO) are actively promoting the international standards for the LCA methodology. ISO has made LCA one of the most important steps of the ISO14000 environmental management system. In June 1993, ISO formally founded the Environmental Management Standards Technical Committee (TC-207), which was responsible for the standardization of the environmental management system. The TC207 Technical Committee has reserved 10 standard numbers (ISO14040-ISO14049) for LCA from the ISO14000 family of environmental management standards (Saunders, 1996; Fan, 2014). The evaluation of large-scale projects' environmental impacts has gained importance due to the global increase in interest in environmental issues.Forinstance, it is often necessary to conduct study for a landfill mining project to be able to demonstrate the environmental impacts in order to obtain permits from the government. Utilizing an analytical tool called Life Cycle Assessment (LCA) is a standard method of carrying out such an evaluation.

6.1.2 Phases of LCA

According to ISO 14044, 'LCA addresses the environmental aspects and potential environmental impacts (e.g., use of resources and environmental consequences of releases) throughout a product's life cycle from raw material acquisition through production, use, end-of-life treatment, recycling and final disposal (i.e., cradle-to-grave).'

The methodological framework of LCA consists of four phases (ISO, 2006; PRéConsultants, 2016)

I. Goal and scope definition phase,
II. Inventory analysis phase,
III. Impact assessment phase, and
IV. Interpretation phase

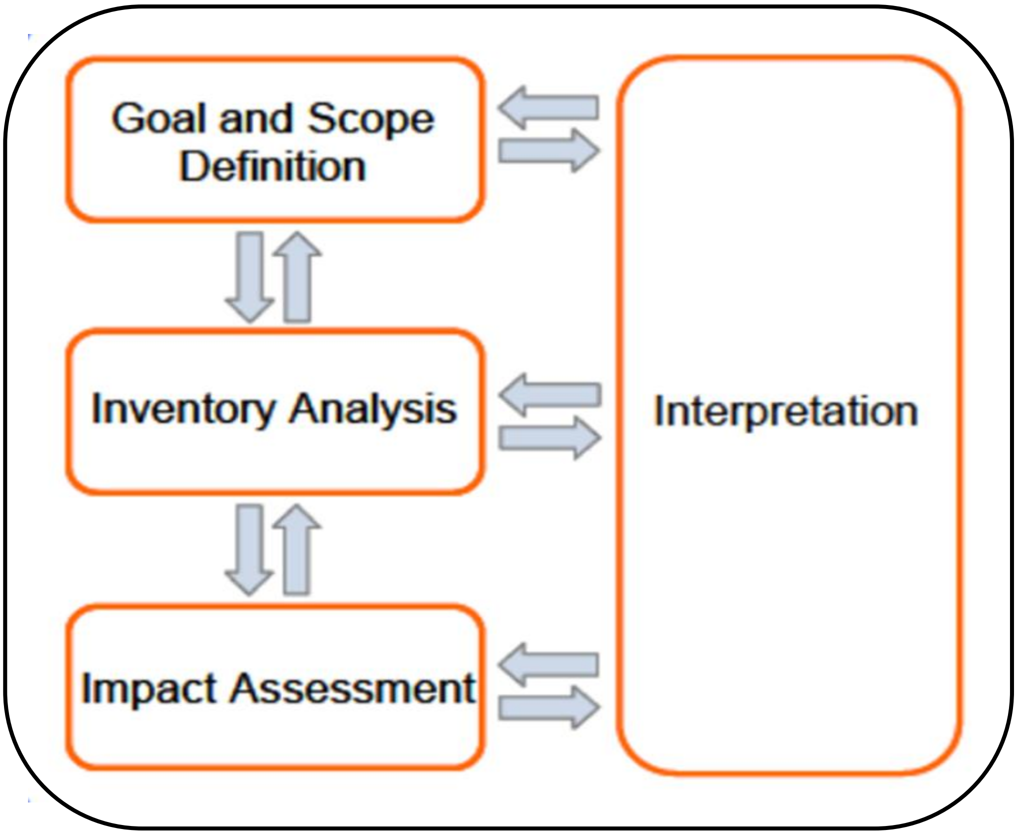

Figure 6.1: The methodological framework for LCA (ISO, 2006a)

Ⅰ. Goal and scope definition

The purpose of the LCA study, the intended audience, and the intended application are all part of defining the goal. While defining the scope involves setting the system boundaries and the level of detail. For example, in this study the goal can be defined as the evaluation of potential environmental impacts of bio-mining operation within specific system boundary shown in figure 6.2.

Ⅱ. Inventory analysis

The second phase of the LCA, the life cycle inventory analysis (LCI) phase, deals with collecting the necessary data to meet the objectives of the LCA study by inventorying the input and output data of the studied system. Possible data sources include for example measurements on the production site, existing databases and bibliographic research (Lehtinen et al. 2011).

Ⅲ. Impact assessment

Third phase of LCA is life cycle impact assessment (LCIA) which is used to transform the LCI results into the associated environmental impacts, including effects on resource usage, the environment, and human health (Lehtinen et al. 2011). There are many methodologies for LCA which differs due to the impact categories or environmental indicator focuses. The methodology used for combining the effect of multiple pollutants is based on the concept of impact potential(Heijungs et al., 1992a; EPA 1995b, 1998). It is expressed in terms of the total potential environmental impact (PEI) score, which quantitatively combines the effects of each pollutant release after scaling the environmental effects of various pollutants to the same quantitative scale. The PEI score considering all pollutants and all streams of pollutant discharges would represent the aggregate environmental effect of an action or an operation. Such a combined score will be useful for comparing the polluting effect of different processes and methods etc.

Ⅳ. Interpretation

The final phase of LCA i.e., life cycle interpretation phase involves summarising and discussing the result to give a basis for conclusions, recommendations, and decision-making, based on the goal and scope definition (Lehtinen et al. 2011).

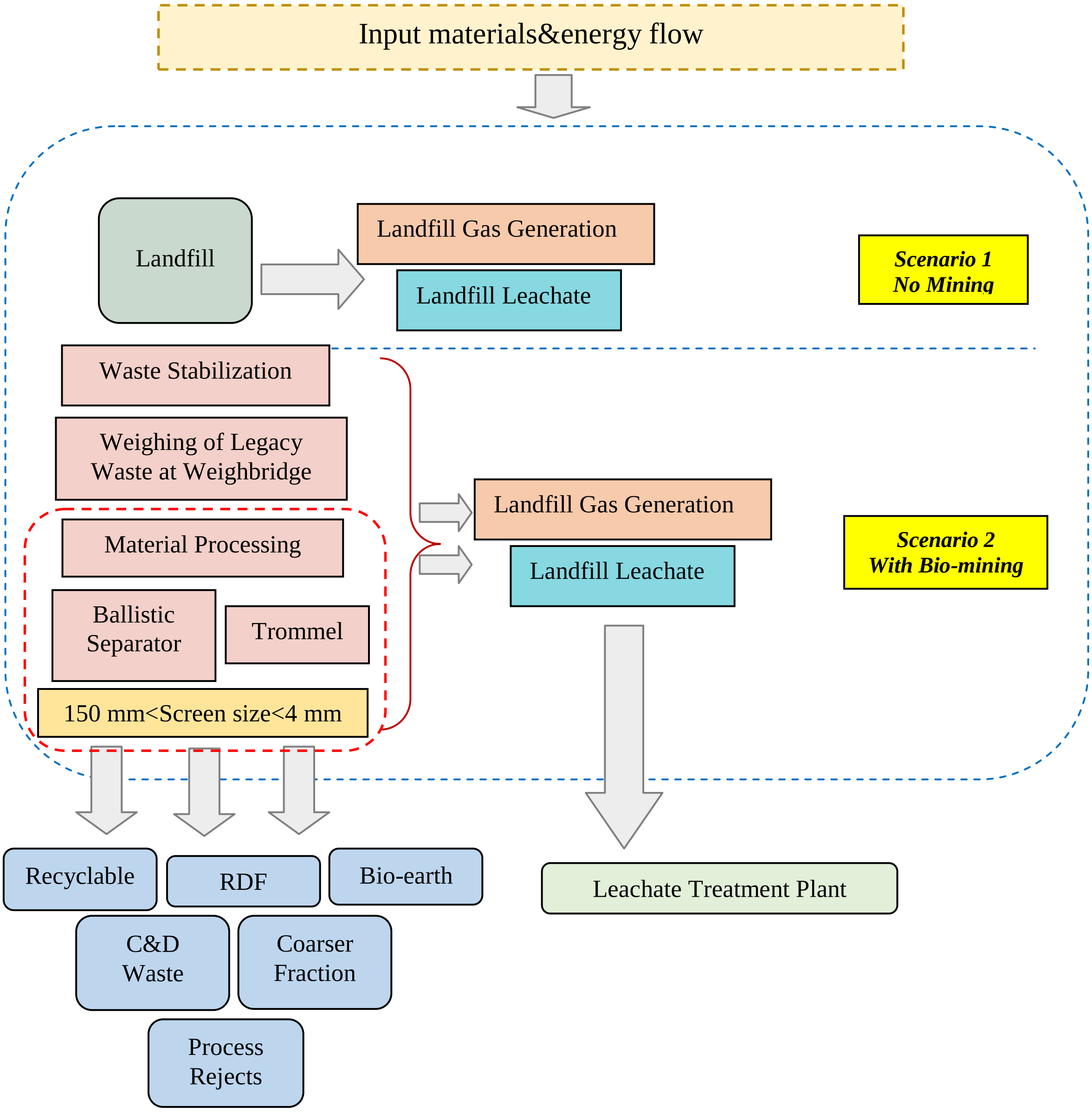

Fig 6.2: Schematic diagram of system boundary of the study area for LCIA analysis.

The above figure depicts the inputs, outputs and processing of the considered research area. Inputs suggest only the legacy waste at the landfill site excluding the incoming waste transportation and their dozing at the time of dumping. The system boundary has two scenarios. Scenario 1 represents no mining scenario i.e., if the landfill site was as it is there with legacy waste from where outputs like landfill gas and landfill leachate were generated. Scenario 2 proposes the legacy waste processing with bio-mining. Here, waste excavation, waste stabilization, weighing of waste and further processing through trammel and ballistic separator. Here, system boundary excludes the negligible electricity consumption because consideration of diesel generator for proper usage have been made for the same purpose. Only the emission during the whole processing from excavation to output material processing is considered within the system boundary. However, the emission regarding output material transportation, their alternative usage, have been excluded from the system. Impact from manpower, office operation on the system boundary is considered to be negligible but it can be assessed in future study.

6.1.3 Estimation of PEI_{LCIA}

In the present work, the estimation of PEI based on LCIA approach considering three impact categories (EPA, 1998): (1) global, (2) regional and (3) local. Global category primarily refers to the concern of the whole world and appropriate worldwide pollutant inventories are considered for evaluating the PEI component from this impact category. Similarly, regional category refers to the region (state) in which landfill is situated. Local category refers to the locality (Bandyopadhyay et. al., 2001, Dutta and Koshti, 2002).

Under global impact category, the sub-categories considered are Global Warming Potential (GWP), Resource Depletion Potential (RDP) and Ozone Depletion Potential (ODP). Under regional categories, the sub-categories are Acidification Potential (AP) and Photochemical Ozone Conversion Potential (POCP). Under local category, the sub-categories are Human, Terrestrial and Aquatic Toxicity. Human Toxicity is again sub-divided into Human Toxicity Potential by Ingestion (HTPI) and Human Toxicity Potential by Inhalation (HTPE). HTPI is considered only for solid and liquid pollutants while HTPE is for gaseous pollutants only. Terrestrial Toxicity is also sub-divided into Terrestrial Toxicity Potential by Liquids (TTPL) and Terrestrial Toxicity Potential by Gases (TTPG). Aquatic Toxicity is expressed in terms of Aquatic Toxicity Potential (ATP). The categories / sub-categories of impact considered in this work are shown in figure 6.3.

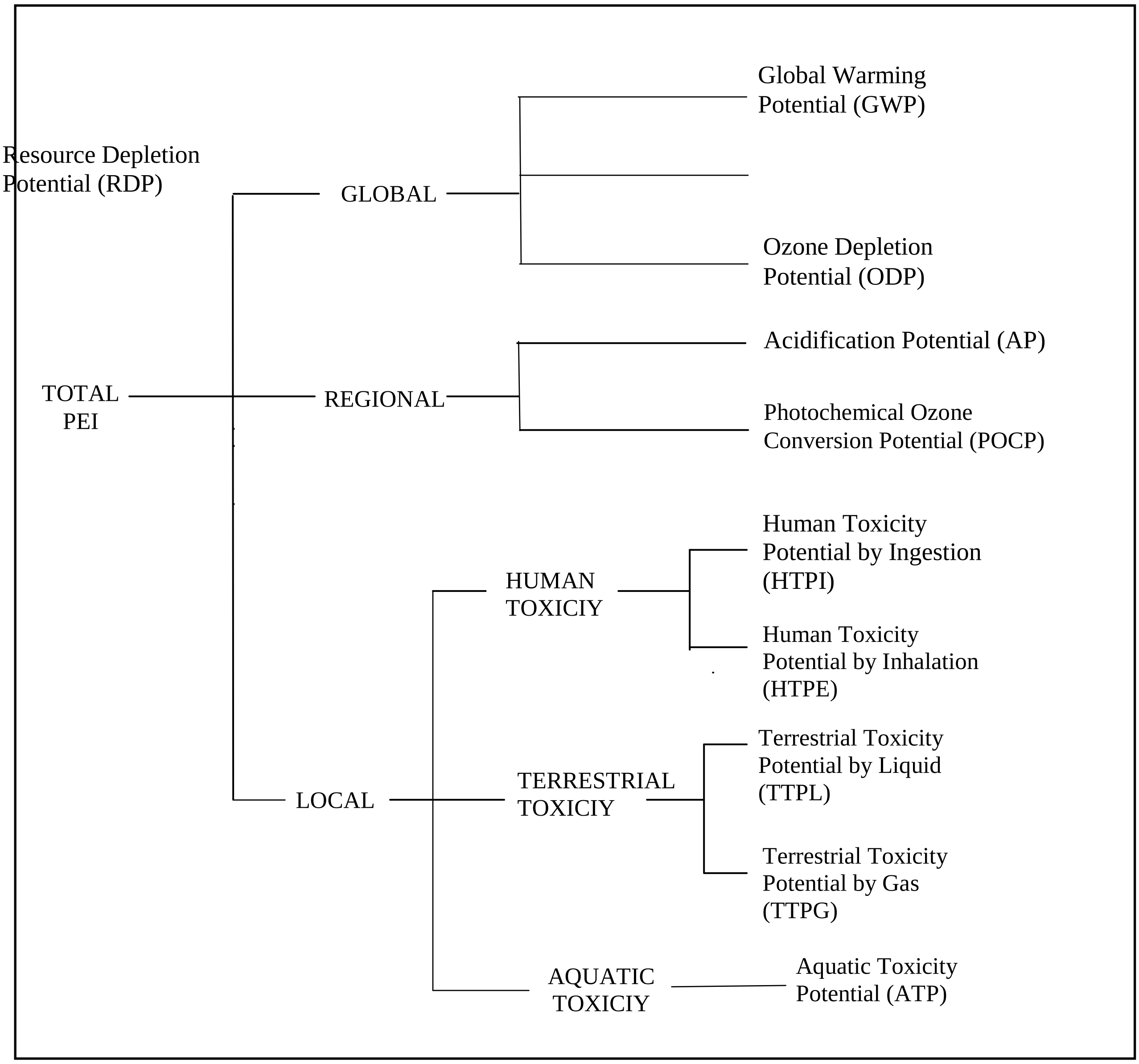

Fig 6.3: A Typical Potential Environmental Impact Category Hierarchy considering Environmental Factors

6.1.4 Computation of PEI_{LCIA}

The potential environmental impact based on the LCIA approach (PEI_{LCIA}) is computed as

$$PEI_{LCIA} = \sum_j [w_j \times \{\sum_i (m_i \times EF_{ij}) \; / \; N_j\}]$$

Where w_j is weightage of impact sub-category *j*; m_i is discharge rate of pollutant *i* (kg/ year); EF_{ij} is equivalency factor for pollutant *i* in impact sub-category *j*; and N_j is normalizing value for impact sub-category *j*.

The normalizing value N_j is estimated separately for global, regional and local categories as follows.

For all global impact sub-category *j*,

$$N_j = \sum_k (I_{kj} \times EF_{kj})$$

Where I_{kj} is the global annual inventory of pollutant *k* with effect in global sub-category *j*; and $\sum_k$ denotes all pollutants for the global sub-category *j*, whether included in this study or not.

For all regional impact sub-category *j*,

$$N_j = \sum_k (I_{kj} \times \text{Regional scale factor} \times EF_{kj})$$

Where I_{kj} is the maximum annual inventory of pollutant *k* in the region (state) responsible for impact sub-category *j*; and $\sum_k$ denotes summationover all pollutants responsible for impact sub-category *j* included in this study.

(Regional factors are related to sensitivity of the region to the impact sub-category. In the present work pertaining to India, regional factors are taken as unity.)

For all local impact sub-category *j*,

$$N_j = \sum_k (I_{kj} \times \text{Cluster multiplier} \times EF_{kj})$$

Where I_{kj} is the largest annual facility emission of pollutant *k* responsible for impact sub-category *j* in the region; Cluster multiplier is 1.5, to account for facility clustering effect; and $\sum_k$ denotes the summationover all pollutants responsible for impact sub-category *j* included in this study.

Figure 6.3shows the impact categories and sub-categories considered in this study.

6.2 COMPUTATION OF WEIGHTAGE FOR DIFFERENT IMPACT CATEGORIES

In a quantitative multi-criteria analysis, the various environmental effects are added after multiplication with the weighting factors assigned to each environmental problem. The weightage factors are determined using the Analytic Hierarchy Process (AHP) - a multicriteria analysis technique developed by Saaty(1977, 1980, 1990). US EPA (EPA, 1998) has also recommended the use of AHP for this purpose.

A team was asked to reach a consensus on the inputs to be used for the AHP procedure. The group of decision-makers included two process engineers, two environmental engineers, one chemist and one ecologist. The inputs were to be generated with a 'local perspective'.The team were asked to fill the pairwise comparison matrix based on following scale:

1 = equally important or preferred
3 = slightly more important or preferred
5 = strongly more important or preferred
7 = very strongly more important or preferred
9 = extremely more important or preferred
Intermediate values (2, 4, 6 and 8) are used to reflect compromise.
To reflect the dominance of the other element, the reciprocals are used.

Potential environmental impact category hierarchy for the Analytic Hierarchy Process (AHP) problem is shown in figure 6.3. It is a 3-tier problem. The first step is finding the weightages of global, regional and local impact categories. The second step is finding the weightages for sub-categories of the three categories. In the next step, the weightages for the items under the sub-categories Human Toxicity Potential (HTP) and Terrestrial toxicity Potential (TTP) are found. The weightages of the three levels are combined to generate weightages of each of the nine sub-categories of impact.

The pairwise comparison matrix of importance of environmental impacts between global, regional and local with respect to the local perspective is shown in Table 6.1.

Table 6.1 The pairwise comparison matrix of importance of environmental impacts between Global, Regional and Local with respect to the local perspective.

	Global	Regional	Local
Global	1	1/3	1/9
Regional	3*	1	1/5
Local	9**	5***	1

* Regional is Slightly more important or preferred than Global (3)

** Local is Extremely more important or preferred than Global (9)

*** Local is Strongly more important or preferred than Regional (5)

Saaty's method (Harker, 1989) computes W as the principle right eigenvector of the matrix A:

$A_W = \lambda_{max} W$

where λ_{max} is the maximum eigen value of the matrix,

or, $W_i = \dfrac{\sum_{j=1}^{n} a_{ij} W_j}{\lambda_{\max}}$ for all $i = 1 \ldots n$

The computation of the principal right eigenvector is accomplished by raising the matrix A to increasing power k and then normalizing the resulting system:

$$W = \underset{K \to \alpha}{Lim} \frac{A^k e}{e^T A^k e}$$

where, e is unit column vector and e^T represents the transpose of vector

$W^1 = A^1 e / e^T A^1 e$

The pairwise comparison matrix A for the categories was taken as follows:

$$A = \begin{bmatrix} 1 & 0.33 & 0.11 \\ 3 & 1 & 0.2 \\ 9 & 5 & 1 \end{bmatrix}$$

The weightages for each of the element is found out as

$$A^1 e = \begin{bmatrix} 1.444 \\ 4.2 \\ 15 \end{bmatrix} \text{ and } e^T A^1 e = 20.644$$

$$W^1 = \begin{bmatrix} 0.07 \\ 0.203 \\ 0.727 \end{bmatrix}; W^2 = \begin{bmatrix} 0.06935 \\ 0.1773 \\ 0.7533 \end{bmatrix}; W^3 = \begin{bmatrix} 0.0704 \\ 0.178 \\ 0.7516 \end{bmatrix};$$

Check for consistency (with n =3)

$$\lambda_{max} = \frac{\sum_{j=1}^{n} a_{ij} W_j}{W_i}$$

$$\text{So, } \lambda_{max} = \frac{\sum_{j=1}^{3} a_{1j} W_j}{W_1} = \frac{a_{11}W_1 + a_{12}W_2 + a_{13}W_3}{W_1}$$

$= \{1 \times 0.0704 + (1/3) \times 0.1780 + (1/9) \times 0.7516\} / 0.0704$

$= 3.029$

Consistency index, $C.\ I. = \dfrac{\lambda_{\max} - n}{(n-1)}$ = (3.029 – 3)/(3 – 1) = 0.0145

The consistency ratio is found out by,

$C.\,R. = \dfrac{C.I.}{R.I.}$, where, $R.I.$ = Random index = 0.58, for n =3

[ref. Table 22 of Harker, P.T., (1989)]

So, $C.R. = 0.025 < 0.1$ Hence o.k.

Hence, the relative weightages of the global, regional and local categories are: ***0.0704, 0.1780*** *and* ***0.7516*** *respectively.*

Under 'Global' category, the pairwise comparison matrix of RDP, GWP and ODP with respect to the local perspective is shown in table 6.2.

Table 6.2 The pairwise comparison matrix of RDP, GWP and ODP with respect to the local perspective

	RDP	GWP	ODP
RDP	1	6	9
GWP	1/6	1	2
ODP	1/9	1/2	1

$$W^4 = A^4\, e \,/\, e^T A^4\, e \quad \text{or, } W^4 = \begin{bmatrix} 0.7780 \\ 0.1440 \\ 0.0780 \end{bmatrix};$$

$\lambda_{max} = 3.013$; $C.I. = 0.0065$; $C.R. = 0.011 < 0.1$ Hence o.k.

Hence, the relative weightages of the RDP, GWP, and ODP are: ***0.7780****,* ***0.1440*** *and* ***0.0780*** *respectively.*

As an example, the individual weightage of GWP found out from the weightages of the different tiers = (0.0704 × 0.1440) = 0.0101.

Under 'local' category, the pairwise comparison matrix of HTP, TTP and ATP with respect to the local perspective is shown in Table 6.3.

Table 6.3: The pairwise comparison matrix of HTP, TTP and ATP with respect to the local perspective

	HTP	TTP	ATP
HTP	1	3	2
TTP	1/3	1	1/2
ATP	1/2	2	1

$$W^4 = A^4\, e \,/\, e^T A^4\, e \quad \text{or, } W^4 = \begin{bmatrix} 0.5396 \\ 0.1634 \\ 0.2970 \end{bmatrix};$$

λ_{max}= 3.009; *C.I.* = 0.0045; *C.R.* = 0.0078 < 0.1 Hence o.k.

Hence, the relative weightages of the HTP, TTP, ATP are: ***0.5396****,* ***0.1634*** *and* ***0.2970*** *respectively.*

As an example, the individual weightage of HTP found out from the weightages of the different tiers = (0.7516 × 0.5396) = 0.4056

Similarly, under ‘regional’ category, the components are AP and POCP and the relative weightages were found out to be **0.4** and **0.6**, respectively.

Also, under HTP, the components are HTPI and HTPE and their relative weightages were found out to be **0.5** and **0.5**, respectively.

Under TTP, the components are TTPL and TTPG and their relative weightages were found out to be **0.6** and **0.4**, respectively.

As an example, the individual weightage of HTPI found out from the relative weightages of the different tiers

$$W_{HTPI} = (0.7516 \times 0.5396 \times 0.5) = 0.2028$$

Similarly, the weightages for the other eight sub-categories are found out and are shown in table 6.4, below.

Table 6.4: Relative Weightages of the Impact Categories in Local Perspective

Impact Category	**Global**			**Regional**		**Local**				
Sub-Category	*GWP*	*ODP*	*RDP*	*AP*	*POCP*	*HTPI*	*HTPE*	*TTPL*	*TTPG*	*ATP*
Relative Weightage	*0.0704*			*0.178*		*0.7516*				
	0.0101	*0.0055*	*0.0548*	*0.0712*	*0.1068*	*0.2028*	*0.2028*	*0.07368*	*0.04912*	*0.2232*

The human toxicity potential has the largest weightage of 40.56% which is equally divided into its sub- categories Human Toxicity Potential by Ingestion (HTPI) and Human Toxicity Potential by Inhalation (HTPE). Aquatic Toxicity Potential (ATP) has the largest weightage of 22.32% among all the sub- categories. Weightage of global category is 7.04% which is small compare with the local category has the largest weightage of 75.16%. The weightages of all these categories are quite comparable with those derived in EPA report (1998) considering local perspectives.

6.3 COMPUTATION OF EQUIVALENCY FACTOR FOR DIFFERENT IMPACT CATEGORIES

Equivalency factors for an impact category can be evaluated based on level II (Equivalency assessment) or level III (Toxicity, Persistence and Bioaccumulation Profile, i.e., TPBP) impact assessment depending upon availability of data.

Equivalency assessment includes approaches that translate inventory items into common units (via the use of equivalency factors) of impact that can either be evaluated to compare the individual contributions of inventory items to impacts or resulting equivalency units to assess the collective contribution of items of impacts. Equivalency factor are based on mechanisms of impact that relate the group of inventory items to specific impacts. Equivalency units can be aggregated within impact categories to provide an estimate of the total level of impact. This method essentially consists of multiplying the values for groups of inventory items (e.g., greenhouse gases) by the appropriate equivalency factors, thus expressing the inventory items in equivalency units (e.g., global warming potential).

Toxicity, persistence, and bioaccumulation assessment includes those approaches that are more comprehensive than the Tier 2 (level II) assessment approach because they take into account not only hazard but also ecosystem and organism exposure information. Specifically, these models often focus on properties such as toxicity as an indicator of hazard; and persistence and bioaccumulation as indicators of exposure. The main premise of these models is to use information on the inherent properties of substances to assess the potential impacts of chemical substances on the environment (EPA 1995b).

In this case, level II is used for GWP, AP, HTPI, HTPE, TTPL and TTPG, while level III is used for ATP. The choice is made based on availability of data. The basis of computation of ‘equivalency factors’ for the different pollutants for various impact (sub) categories is shown in the following table 6.5.

Table 6.5: Equivalency factors (EF) for the impact (sub) categories

Impact category (sub-category)	**Equivalency factor (Impact potential function)**	**Description**	**Reference and Remarks**
Global-GWP (Global Warming Potential)	$\dfrac{\int_0^T a_i C_i(t)\,dt}{\int_0^T a_{CO2} C_{CO2}(t)}$	a_i and a_{CO2} = Radiativeforcing per unit concentration increase of greenhouse gas i and that of CO_2. $C_i(t)$ and $C_{CO2}(t)$ = Concentration of greenhouse gas i and that of CO_2 at time t after release T = Number of years over which integration was made.	Heijungs (1992) Potential value is relative to CO_2.
Global-ODP (Ozone Depletion Potential)	$\dfrac{\delta[O_3]_i}{\delta[O_3]_{CFC\text{-}11}}$	$\delta[O_3]_i$ and $\delta[O_3]_{CFC\text{-}11}$ = Ozone breakdown in equilibrium state due to annual emissions (kg per year) of substance, i and that of CFC-11 released into atmosphere.	-do- Potential value is relative to CFC-11.
Regional-AP (Acidifica-tion Potential)	$\dfrac{\eta_i}{\eta_{SO2}}$	η_i and η_{SO2} = Number of H^+ ions (mole/kg) which can be produced per kg of substance i and that of SO_2.	-do- Potential value is relative to SO_2.
Regional-POCP (Photoch-emical Ozone	$\dfrac{a_i / b_i}{a_{C2H4} / b_{C2H4}}$	a_i and a_{C2H4} = Change in O_3 concentration due to change in emission of i^{th} VOC and that of C_2H_4. b_i and b_{C2H4} = Integrated emission of i^{th} VOC and that of C_2H_4 up to that time.	-do- Potential value is relative to

Conversion Potential)			C_2H_4

Continued……..

Table 6.5: Equivalency factors (EF) for the impact (sub) categories *[continued]*

Impact category / sub-category	**Equivalency factor (Impact potential function)**	**Description**	**Reference and Remarks**
Local-HTPI (Human Toxicity Potential by Ingestion)	$\frac{1}{(LD_{50})}$	LD_{50} = Median lethal dose at which 50% of test population die during a specified time period (14 days). Considered only for those pollutants, which exist as solid or liquid at 0^0 C and atmospheric pressure.	Young and Cabezas (1999) Here rat oral data is used.
Local-HTPE (Human Toxicity Potential by Inhalation)	$\frac{1}{(TLV)}$	TLV =Time weighted average of threshold limit value i.e., the maximum amount of substance a worker can be exposed to over an 8hour work day without any health damage. Considered only for those pollutants which exist as gas at 0^0 C and atmospheric pressure	-do-
Local-TTPL (Terrestrial Toxicity Potential by Liquid)	$\frac{1}{(LD_{50})}$	Same as HTPI.	-do-
Local-TTPG (Terrestrial Toxicity Potential by Gas)	$\frac{1}{(TLV)}$	Same as HTPE.	-do-
Local-ATP (Aquatic Toxicity Potential)	$HV_{toxicity} \times (HV_{BOD} + HV_{HYD} + HV_{BCF})$	LC_{50} = Lethal concentration at which 50% of total population under test die after certain time period (96 hr). $HV_{toxicity}$ = Aquatic LC_{50} hazardvalue. HV_{BOD} = BOD half-life hazard value. HV_{HYD} = Hydrolysis half-life hazard value. HV_{BCF} = bio-concentration factor hazard value.	EPA pub. 600R94177 and 600R98070

6.3.1 Global Category

- **Global Warming Potential (GWP)**

A substance's global warming potential (GWP) is determined by comparing the contribution to heat radiation absorption resulting from the instantaneous release of 1 unit mass of a greenhouse gas to an equivalent quantity of CO_2 emission integrated over time.The substances which contribute in amplifying the greenhouse effect parameters, they have been developed in the form of global warming potential (GWP). This is used to express the potential direct contribution towards GHG effects.

In this present work, contributing gases for GWP is Carbon Dioxide (CO_2), Methane(CH_4) and Dichloromethane (CH_2Cl_2). Heatradiation absorption of CO_2 with respective to CO_2 is 1. So, equivalency factor of CO_2 for global warming potential is 1.Global Warming Potential of CH_4 and CH_2Cl_2relative to CO_2, with time horizon of 100 years are given in table 6.6.In the present system, Global Warming Potential (GWP) is calculated for 100 years. So, the value of Equivalency Factor (EF) of 100 years is taken for calculation of Global Warming Potential (GWP).

Table 6.6: Equivalency Factor for Global Warming Potential

Gases	Equivalency Factor (100 Years)
CO_2	*1*
CH_4	*28*
CH_2Cl_2	*9*

This data is adapted from the IPCC Fifth Assessment Report, 2014 which is the latest assessment report.

- **Ozone Depletion Potential (ODP)**

The substances which contribute to the depletion of ozone layer parameters in a single effect score, they have been considered as Ozone Depletion Potential (ODP). The ODP is a relative parameter which uses CFC-11 as a reference. The steady state ozone depletion per unit mass of gas emitted to the atmosphere annually is calculated relative to that unit mass of CFC level.

In the landfill of Dhapa, there are no such gases are generated which can cause the breakdown of ozone layer. So, ODP cannot be calculated.

6.3.2 Regional Category

- **Acidification Potential (AP)**

The ratio of potential H+ equivalents per unit mass of substance release to potential H+ equivalents per unit mass of SO_2 is known as the AP.The contributing chemicals to AP are SO_2, NO_2 and NH_3. The equivalency factors for AP are shown in table 6.7. This data is taken from Heijungs (1992b) and Hua Li et al, 2015.

Table 6.7: Equivalency Factor for Acidification Potential

Gases	Reaction equation	No. of potential H^+	Mass (kg / mole)	No. of poten-tial H^+ per unit mass	Equi-valency factor (EF)
SO_2	$SO_2 + H_2O + O_3 = 2H^+ + SO_4^{2-} + O_2$	2	64	1/32	1.0
NO_2	$NO_2 + ½ H_2O + ¼ O_2 = H^+ + NO_3^-$	1	46	1/46	0.7
NH_3	$NH_3 + 2O_2 = H^+ + NO_3^- + H_2O$	1	17	1/17	1.88

- **Photo-chemical Ozone Conversion Potential (POCP)**

POCP parameters have been developed for some substances which contribute to the photochemical oxidant formation. The Photo- chemical Ozone Conversion Potential (POCP) is a relative measure to ethylene (C_2H_4). Contributing gases which are responsible for the changes of ozone concentration in the atmosphere are methane (CH_4), Dichloromethane (CH_2Cl_2) and Toluene ($C_6H_5CH_3$). As the amount of generation of other gases like acetone, benzene is less in the existing system, so, for calculation contribution of these gases is not considered.

Table 6.8: Equivalency Factor for Photo- chemical Ozone Conversion Potential

Gases	Equivalency Factor (EF)
CH_4	0.007
CH_2Cl_2	0.010
$C_6H_5CH_3$	0.563

Data is taken from Heijungs (1992b)

6.3.3 Local Category

In local category, consideration of human toxicity and terrestrial toxicity have been made in this study. Human toxicity is assessed correlating the emissions to the tolerable daily intake, acceptable daily intake, tolerable concentration in air, maximum tolerable risk level and air quality guidelines. Human toxicological classification depends on the substance and the environmental medium concerned e.g., for atmosphere (HTPE) and for water (HTPI). The assessment of ecotoxic substances on species in the ecosystem is based on maximum tolerable concentration. Terrestrial toxicological classification depends on the substance and the environmental medium concerned e.g., for atmosphere (TTPG) and for water (TTPL).

- **Human Toxicity Potential by Ingestion (HTPI) and Terrestrial Toxicity Potential by Liquids (TTPL)**

The equivalency factors for HTPI and TTPL are the same (which is shown in table 6.9) as both are based on the LD_{50} value (Young and Cabezas, 1999). LD_{50} is the amount of a chemical that, when given orally as a single dose, will kill 50% of a group of rodents within 14 days. Dose is defined as the mass of the chemical per kilogramme of the animal's body weight (i.e., rat). The information for the rat LD50 has been obtained from several websites and is provided below.

Arsenic& Chloride: *Whs.rocklinusd.org*;The LD_{50} of chloride is that for sodium chloride. Mercury& Cyanide: *chem.libretexts.org;* Lead:*Inchem.org*; Cadmium: *Chemistry LibreTexts*; Total Chromium: *assets.publishing.service.gov.uk*; Copper: *Npic.orst.edu*; The LD_{50} of copper is that for copper sulphate pentahydrate and the average of 450 to 790 mg/kg is taken.Zink:(Egorova *&Ananikov, 2017*); Nickel:*pubmed.ncbi.nlm.nih.gov*;Fluoride:*Euro.who.int*;Nitrate: *Atsdr.cdc.gov*; The LD_{50} of nitrate is that for sodium nitrate.Sulphate: *Finarchemicals.com*;Phenolic Compounds:*Ncbi.nlm.nih.gov*;Ammoniacal Nitrogen: *Rsc.aux.eng.ufl.edu*.

Table 6.9: The equivalency factors for HTPI and TTPL

Chemical Components	LD_{50} for rat, oral (mg/kg of body weight of rat)	Equivalency Factor ($1/LD_{50}$)
Arsenic (As)	*15*	*0.0667*
Mercury (Hg)	*1*	*1*

Lead (Pb)	*1.2*	*0.8333*
Cadmium (Cd)	*7080*	*0.00014*
Total Chromium (Cr)	*399*	*0.0025*
Copper (Cu)	*620*	*0.0016*
Zink (Zn)	*725*	*0.00138*
Nickel (Ni)	*705*	*0.00142*
Cyanide (CN)	*6.4*	*0.1563*
Chloride (Cl)	*3000*	*0.00033*
Fluoride (F)	*51.6*	*0.01938*
Nitrate (NO3)	*1267*	*0.00079*
Sulphate (SO4)	*1288*	*0.00078*
Phenolic Compounds (Phn)	*525*	*0.0019*
Ammoniacal Nitrogen as (N)	*350*	*0.00286*

- **Human Toxicity Potential by Inhalation (HTPE) and Terrestrial Toxicity Potential by Gas (TTPG)**

The equivalency factors for HTPE and TTPG are the same (Table 6.10) as both are based on the TLV value (Young and Cabezas, 1999). The threshold limit value, or TLV is the maximum amount of substance to which a worker can be exposed for eight hours a day without experiencing any negative health effects.These data are taken from *www.cdc.gov/niosh/* (NIOSH);*www.osha.gov*(OSHA); *www.safeopedia.com;www.Nj.gov*; The TLV in mg/m^3 unit are the approximate value.

Chemicals' TLVs are described as concentrations in the air, usually for inhalation or skin contact. For gases, it is measured in parts per million (ppm), while for particles like dust, smoke, and mist, it is measured in milligrams per cubic metre (mg/m^3).The basic formula for gases converting between ppm and mg/m^3 is

ppm = (mg/m^3) x 24.45 / molecular weight.

This formula is not applicable to airborne particles.

Table 6.10: Equivalency Factor for HTPE and TTPG

Compound	**TLV (ppm)**	**TLV (mg/m3)**	**Equivalency Factor (EF)=(1/TLV)**
Methane (CH_4)	*1000*	*654.396*	*0.00153*
Carbon Dioxide (CO_2)	*5000*	*8997.955*	*0.000111*
Sulphur Dioxide (SO_2)	*5*	*13.0879*	*0.0764*
Nitrogen Dioxide (NO_2)	*5*	*9.407*	*0.1063*
Ammonia (NH_3)	*50*	*34.765*	*0.02876*
Hydrogen Sulphide (H_2S)	*10*	*13.9059*	*0.07191*
Carbon Monoxide (CO)	*50*	*57.2597*	*0.01746*
Methylene Chloride (CH_2Cl_2)	*25*	*86.912*	*0.01151*
Toluene ($C_6H_5CH_3$)	*200*	*752.556*	*0.001329*
Acetone	*1000*	*2372.188*	*0.00042*
Benzene	*1*	*3.19018*	*0.3135*
Chloroform	*50*	*244.376*	*0.00409*
Ethyl Benzene	*100*	*433.538*	*0.00231*
Tetrachloroethylene	*100*	*678.937*	*0.001473*
Vinyl Chloride	*1*	*2.55624*	*0.3912*
Styrene	*100*	*425.3579*	*0.00235*
Vinyl Acetate	*10*	*35.1738*	*0.02843*

- **Aquatic Toxicity Potential (ATP)**

The contributing chemicals and their aquatic toxicity potential values are shown is table 6.11**.**The aquatic toxicity potential of these chemicals calculated considering “Toxicity, Persistence and Bioaccumulation Profile (TPBP)”and required data are taken directly from table 4.1 of EPA 1998 document. The sample calculation for phenol has been discussed below.

Table 6.11: Equivalency Factor for ATP

Contributing Chemicals	**ATP equivalency factor**
Arsenic (As)	*16.78*
Mercury (Hg)	*29.8*
Lead (Pb)	*24.53*

Cadmium (Cd)	*36.25*
Total Chromium (Cr)	*16.386*
Copper (Cu)	*30*
Zink (Zn)	*20.615*
Nickel (Ni)	*16.443*
Cyanide (CN)	*0*
Chloride (Cl)	*22.5*
Fluoride (F)	*5.718*
Nitrate (NO_3)	*15.822*
Sulfate (SO_4)	*15.054*
Phenolic Compounds (Phn)	*11.4*
Ammonical Nitrogen as (N)	*21.36*

Sample Calculation:

Equivalency factor based on TPBP (EPA, 1998) is defined as

$EF = HV_{toxicity} \times (HV_{BOD} + HV_{HYD} + HV_{BCF})$

where, $HV_{toxicity}$ is toxicity hazard value for LC_{50} or LD_{50} whichever is applicable, calculated following the procedural steps shown in figure 6.4;

HV_{BOD} is biological oxygen demand hazard value, calculated from BOD half-life following the procedural steps shown in figure 6.5. The BOD half-life is the number of days needed for a chemical to biodegrade to the point where its BOD in water is reduced to half of what it was initially.

HV_{HYD} is hydrolysis hazard value, calculated from Hydrolysis half-life following the procedural steps shown in figure 6.6. Hydrolysis half-life is the time required in days for the amount of substance to decrease to half of the original amount through hydrolysis reaction in water at pH 7.

HV_{BCF} is bio-concentration factor hazard value, calculated from Aquatic Bio-concentration factor following the procedural steps shown in figure 6.7. Bio-concentration factor is a measure of a chemical's ability to bio-accumulate and is defined as the ratio of a chemical in fish to its concentration in water at steady state condition.

ATP of phenol considering “Toxicity, Persistence and Bioaccumulation Profile” can be estimated as follows:

LC_{50} fish for phenol = 34 mg/l (EPA, 1994c)

So, $HV_{toxicity} = – 1.67 \times \log LC_{50} + 5.0$

$= - 1.67 \times \log (34) + 5.0 = 2.4$

BOD half-life = 9 days (EPA, 1994c)

So, $HV_{BOD} = 0.311 \times \ln (\text{BOD half life}) + 0.568 = 0.311 \times \ln (9) + 0.568$

$= 1.25$

Hydrolysis half-life = 1000 days > 500 days (EPA, 1994c)

So, $HV_{HYD} = 2.5$

log BCF = 0.6 < 1.0 (EPA, 1994c)

So, $HV_{BCF} = 1.0$

So, ATP of phenol:

$ATP_{PHENOL} = HV_{toxicity} \times (HV_{BOD} + HV_{HYD} + HV_{BCF}) = 2.4 \times (1.25 + 2.5 + 1.0)$

$= 11.4$

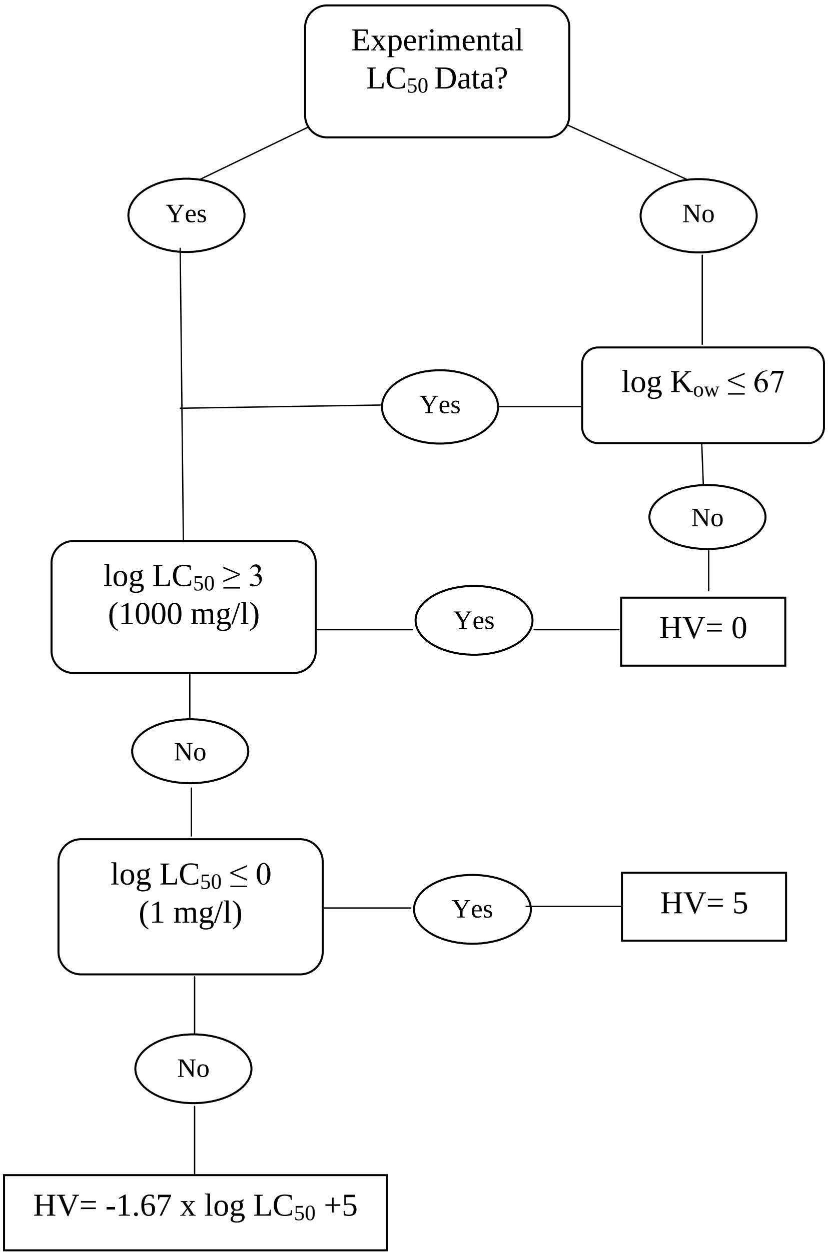

Figure 6.4: Decision tree for aquatic LC_{50} hazard value (EPA, 1994c)

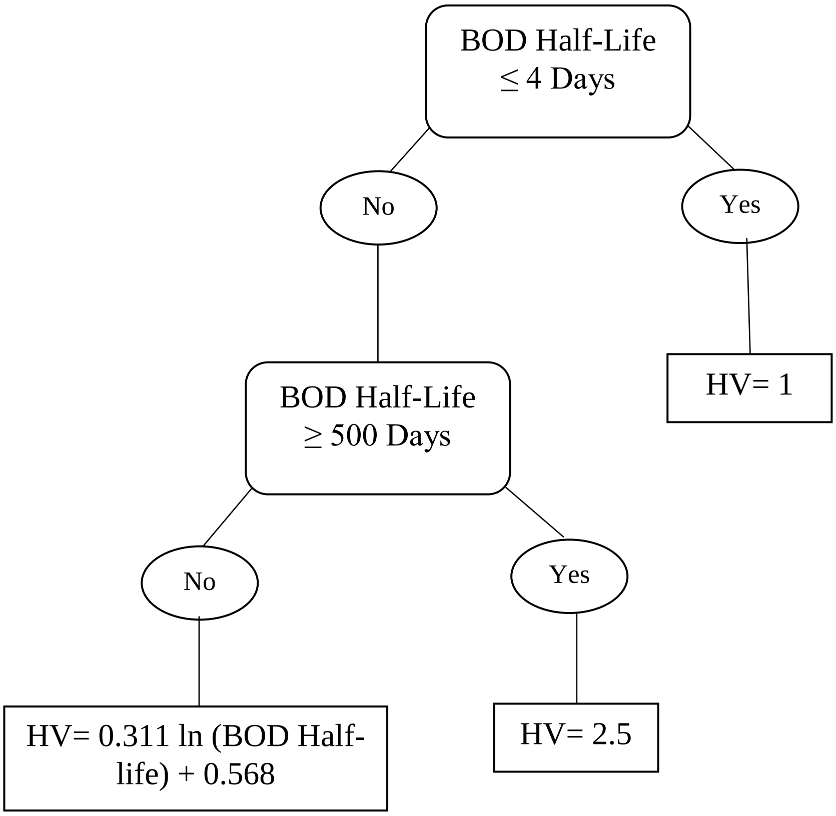

Figure 6.5: Decision tree for BOD half-life hazard value (EPA, 1994c)

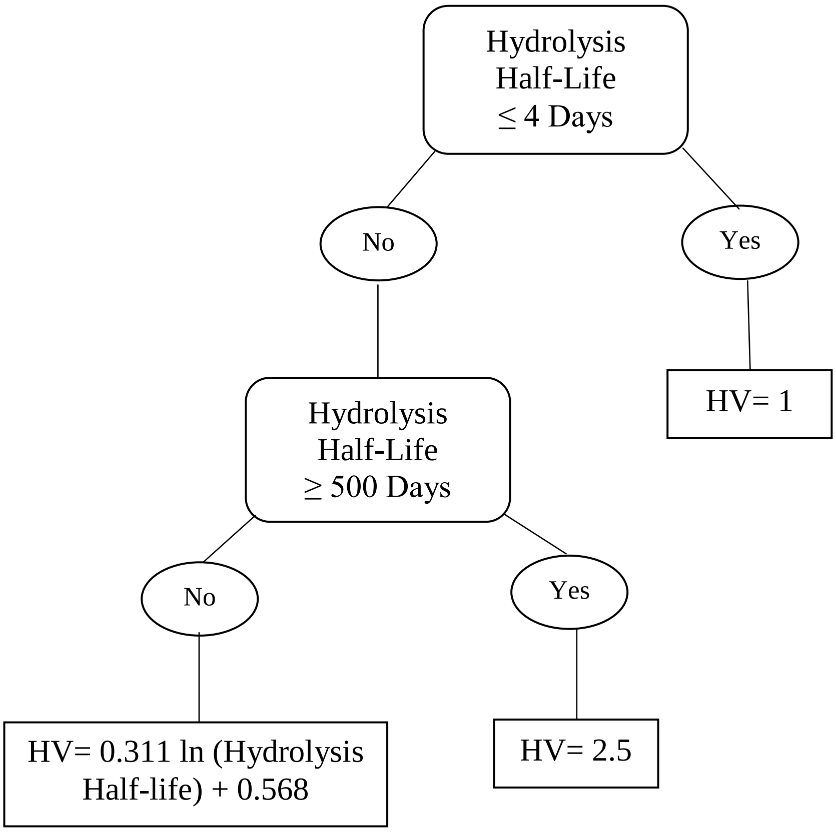

Figure 6.6: Decision tree for hydrolysis half-life hazard value (EPA, 1994c)

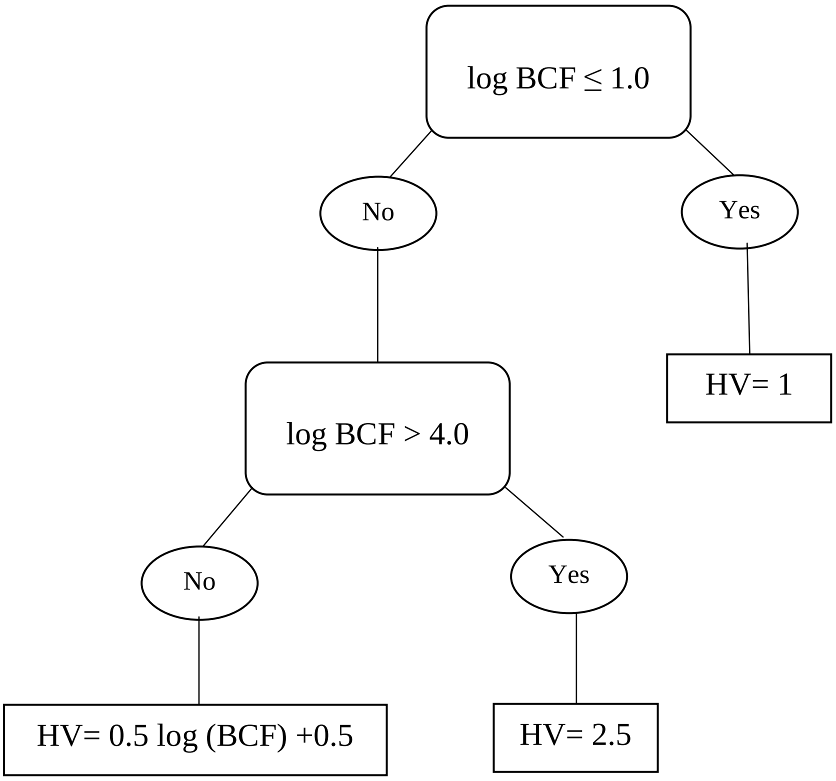

Figure 6.7: Decision tree for BCF hazard value (EPA, 1994c)

All Figures6.4 to 6.7 are based on following source: *Chemical Hazard Evaluation Management Strategies: A Method For Ranking and Scoring Chemicals By Potential Human Health and Environmental Impacts*.1994c, EPA /600/R-94/177, Office of Research and Development, Washington DC

The equivalency factors of all the gaseous and liquid pollutants are tabulated below.

Table 6.12: Equivalency Factors (EF_{ij}) of Gaseous Pollutants

Impact sub-category j	**Gaseous Pollutant**															
	CO_2	**CH_4**	**SO_2**	**NO_2**	**NH_3**	**H_2S**	**CO**	**CH_2Cl_2**	**Toluene**	**Acetone**	**benzene**	**Chloroform**	**Ethyl benzene**	**Tetrachloro ethylene**	**vinyl chloride**	**styrene**	**vinyl acetate**
GWP	*1*	*28*						*9*									
ODP																	
RDP																	
AP			*1*	*0.7*	*1.88*												
POCP		*0.007*						*0.01*	*0.563*								
HTPI																	
HTPE	*0.000111*	0.00153	0.0764	0.1063	0.02876	0.07191	0.01746	0.01151	0.00133	0.00042	0.3135	0.00409	0.00231	0.001473	0.3912	0.00235	0.02843
TTPL																	
TTPG	*0.000111*	0.00153	0.0764	0.1063	0.02876	0.07191	0.01746	0.01151	0.001329	0.00042	0.3135	0.00409	0.00231	0.001473	0.3912	0.00235	0.02843
ATP																	

Table 6.13: Equivalency Factors (EF_{ij}) of Liquid Pollutants

Liquid Pollutant	**Impact Sub-category**		
	HTPI	TTPL	ATP
Arsenic (As)	*0.0667*	*0.0667*	*16.78*
Mercury (Hg)	*1*	*1*	*29.8*
Lead (Pb)	*0.8333*	*0.8333*	*24.53*
Cadmium (Cd)	*0.00014*	*0.00014*	*36.25*
Total Chromium (Cr)	*0.0025*	*0.0025*	*16.386*
Copper (Cu)	*0.0016*	*0.0016*	*30*
Zink (Zn)	*0.00138*	*0.00138*	*20.615*
Nickel (Ni)	*0.00142*	*0.00142*	*16.443*
Cyanide (CN)	*0.1563*	*0.1563*	*0*
Chloride (Cl)	*0.00033*	*0.00033*	*22.5*
Fluoride (F)	*0.01938*	*0.01938*	*5.718*
Nitrate (NO_3)	*0.00079*	*0.00079*	*15.822*
Sulfate (SO_4)	*0.00078*	*0.00078*	*15.054*
Phenolic Compounds (Phn)	*0.0019*	*0.0019*	*11.4*
Ammonical Nitrogen as (N)	*0.00286*	*0.00286*	*21.36*

6.4 COMPUTATION OF NORMALIZING VALUES FOR DIFFERENT IMPACT CATEGORIES

Equivalency factor (EF_{ij}) for a pollutant i and impact (sub) category j has already been estimated. The procedure for calculation of normalizing values has been presented along with sample calculations.

6.4.1 Global Category

Under global impact category, for all sub-category *j*, the normalizing value is given by

$$N_j = \sum_k (I_{kj} \times EF_{kj})$$

where, I_{kj} is the global annual inventory of pollutant *k* with effect in global (sub) category *j*; and $\sum_k$ includes all pollutants for the global (sub) category *j*, whether included in this study or not.

- **Global Warming Potential (GWP)**

The pertinent details for various pollutants responsible for the GWP are adopted from (Page-ES5) of U.S. Environmental Protection Agency, (EPA, 2010).The annual emission of Methane, Carbon-dioxide, Nitrous Oxide and other gasesare taken from different websites, details are given below.

Table 6.14: Normalizing Value for Global Warming Potential

Gases	World total annual emission (Mt/year) (I_{kj})	GWP equivalency factor (EF_{kj})**	GWP impact (I_{kj} x EF_{kj})
*Carbon dioxide**	36.4×10^{9}	1	36.4×10^{9}
Methane@	570×10^{6}	28	1.6×10^{10}
Nitrous oxide$	12.6×10^{6}	265	3.3×10^{9}
All CFCs#	240×10^{3}	4660	1.1×10^{9}
HCFC-22#	473×10^{3}	1760	8.3×10^{8}
Carbon tetrachloride#	20.8×10^{3}	1730	3.6×10^{7}
Methyl chloroform#	128×10^{3}	160	20.5×10^{6}
Normalizing value for GWP = 5.77×10^{10} Mt/year = 5.77×10^{13} kg/year			

*Annual CO_2 emissions worldwide 1940-2020 | Statista

@ Methane Tracker 2020 – Analysis - IEA

$ N_2O emissions globally 2050 | Statista

Emissions Scenarios for the IPCC: an Update

All CFCs includes CFC-11, CFC-12, CFC-113, CFC-114 and CFC-115

**Value of equivalency factors are taken from the IPCC Fifth Assessment Report, 2014 which is the latest assessment report.

- **Resource Depletion Potential (RDP)**

After completion of biomining operation total land area will be reclaimed completely. The cleared land area can be used for other purposes. So, in terms of resource depletion potential it has a positive impact. RDP has to be calculated as how much land is cleared with respect to total urban land area of the world. Total land area of the world is 129949283 sq. Km and out of this urban area occupy almost 2.7% of total land area i.e., 3629312 sq. Km. (Data.worldbank.org; Newgeography.com)

6.4.2 Regional Category

Under regional impact category, for all sub-category *j*, the normalizing value is given by

$N_j = \sum_k (I_{kj} \times \text{Regional scale factor} \times EF_{kj})$

where, I_{kj} is the maximum annual inventory of pollutant *k* in the region (state) responsible for impact (sub) category *j*; Regional scale factors are related to sensitivity of the region to the impact (sub) category. In the present work pertaining to India, since no such factors are yet defined, all regional scale factors are taken as unity; and $\sum_k$ denotes summationover all pollutants responsible for impact (sub) category *j* included in this study.

- **Acidification Potential (AP)**

The region considered is the state of West Bengal. The gaseous pollutant SO_2, NO_x and NH_3 are responsible for acidification potential impact sub-category. Emission data for SO_2, NO_x and NH_3 in the West Bengal state are required as inventory of pollutants in the region.

As the emission data are not available directly, a calculated approach has been considered as described below.From the *Urbanemissions.info*, the annual emission of SO_2 from all sectors of Kolkata and Asansol in the year 2018 reported 10,400 and 12700 MT respectively. And the annual emission of NO_2 from all sectors of Kolkata and Asansol in the year 2018 reported 143650 and 160350 MT respectively. Considering sector wise area of Kolkata and Asansol and their corresponding ambient air concentration calculating total emissions of West Bengal using weightage average method is justified. From 2020 onwards due to covid 19 lockdown, various sector was not operational so on an average of 7-10% increase of SO_2 emission in West Bengal region as on 2022 have been estimated. As the emission data is as on 2017-18, a 7.68% increased trend have been followed(STATE ENVIRONMENT PLAN: WEST BENGAL).Hence net calculated SO_2 emission as on 2022 is 24.4×10^8 kg/year. The calculation is shown in annexure 1**.** As per the trend of growth in vehicle numbers from 2018-2022, it is increased by 14-27% (The Economic Times). However, from recent trends, percentage growth of NO_2 with respect to 2003 for West Bengal lies in between 3.37±1.18% i.e., around 5%. So, for 2022 an increasing trend of 15-20% for NO_2 may be assumed. So calculated NO_2 emission for West Bengal region is 40.1×10^{10} kg/year. The calculation is shown in annexure 2.

NH_3 generation from Dhapa landfill site in 2022 is 13244×10^3 kg/year. As the total solid waste generation in West Bengal is 3 times more than waste generated from Kolkata, NH_3

emission from all landfill of West Bengal can be estimated as 3 times NH_3 generation of Dhapa i.e., (3 x 13244 x 10^3)=39732 x 10^3 kg/yr. Considering other sources of NH_3 emission like agricultural field, industrial process and vehicular emission, the net NH_3 generation have been calculated by multiplying 2 times more than the amount which is emitting from the landfill. Net NH_3 generation = (2 x 39732 x 10^3) = 0.79 x 10^8 kg/yr.

Table6.15: Normalizing Value for Acidification Potential

Chemical	**Max regional emission x scaling factor* (kg/yr.)**	**Acid rain equivalency factor**	**AP impact (Kg/Yr.)**
SO_2	*24.4*x 10^8	*1*	*24.4*x 10^8
NOx as (NO_2)	*4.01* x 10^{10}	*0.7*	*2.807*x 10^{10}
NH_3	*0.79* x 10^8	*1.88*	*1.485*x 10^8
Normalizing value for AP = 3.066 x 10^{10}kg/year			

* All regional scale factors are taken as unity (Heijungs, 1992a)

- **Photo-chemical Ozone Conversion Potential (POCP)**

The region considered is the state of West Bengal. Methane (CH_4), Methylene Chloride (CH_2Cl_2) and Toluene ($C_6H_5CH_3$) are responsible for photo- chemical ozone conversion potential impact sub-category. Emission data for CH_4, CH_2Cl_2 and $C_6H_5CH_3$ in the West Bengal state are required as inventory of pollutants in the region. For West Bengal region maximum regional emission for CH_4 is not given directly. However, GHG emissions from the state of West Bengal grew from 114.5 Mt CO2-e to 171.7 Mt CO_2-e at an estimated CAGR of 5.19% from 2005 to 2013. Assuming 80% CO_2 and 20% CH_4 as a major contributing GHG gas, calculated methane emission as on 2022 is 0.845 x 10^{10} kg/year (GHG Platform, 2013), (Our World in Data). The detailed calculation is shown in annexure 3.

The maximum regional emission for CH_2Cl_2 and $C_6H_5CH_3$ are not given directly for West Bengal. CH_2Cl_2 and $C_6H_5CH_3$ emission from Dhapa landfill site in 2022 is 10921 x 10^3 kg/year and 15800 x 10^3 kg/year respectively. As the total solid waste generation in West Bengal is 3 times more than waste generated from Kolkata, CH_2Cl_2 emission from all landfill of West Bengal can be estimated as 3 times CH_2Cl_2 generation of Dhapa i.e., (3 x 10921 x 10^{10}) = 32763 x 10^3. Considering other sources of CH_2Cl_2 emission like industrial process, energy sector, the net CH_2Cl_2 generation have been calculated by multiplying 2 times more than the amount which is emitting from the landfill. Net CH_2Cl_2generation = (2 x 32763 x 10^3) = 0.655 x 10^8 kg/yr. The same way, net $C_6H_5CH_3$ emission = (3 x 2 x 15800 x 10^3)= 0.948 x 10^8.

Table 6.16: Normalizing Value for Photo- chemical Ozone Conversion Potential

Chemical	Max regional emission x scaling factor* (kg/yr)	POCP equivalency factor	POCP impact (kg/yr)
CH_4	*84.5*x10^8	*0.007*	*59.15*x 10^6
CH_2Cl_2	*0.655* x 10^8	*0.01*	*0.655* x10^6
$C_6H_5CH_3$	*0.948* x 10^8	*0.563*	*53.37*x10^6
Normalizing value for POCP = 1.132 x 10^8 kg/year			

*All regional scale factors are taken as unity (Heijungs, 1992a)

6.4.3 Local Category

Under local impact category, for all sub-category *j*, the normalizing value is given by

$$N_j = \sum_k (I_{kj} \times \text{Cluster multiplier} \times EF_{kj})$$

where I_{kj} is the largest annual facility emission of pollutant *k* responsible for impact (sub) category *j* in the region; Cluster multiplier is 1.5, to account for facility clustering effect; and $\sum_k$ denotes summationover all pollutants responsible for impact (sub) category *j* included in this study.

The local sub-categories are Human Toxicity Potential by Ingestion (HTPI), Human Toxicity Potential by Inhalation (HTPE), Terrestrial Toxicity Potential by Liquid (TTPL), Terrestrial Toxicity Potential by Gas (TTPG) and Aquatic Toxicity Potential (ATP).CO_2, CH_4, SO_2, NO_2, NH_3, H_2S CH_2Cl_2, $C_6H_5CH_3$, CO, Acetone, benzene, chloroform, ethyl benzene, tetrachloroethylene, vinyl chloride, styrene and vinyl acetate contributes to HTPE and TTPG while Arsenic, Mercury, Lead, Cadmium, Total Chromium, Copper, Zinc, Nickel, Cyanide, Chloride, Fluoride, Nitrate, Sulphate, Ammoniacal Nitrogen and phenol contributes to HTPI, TTPL, and ATP.

- **Human Toxicity Potential by Ingestion (HTPI)**

Kolkata and its surrounding area are considered as the Local category. The maximum facility discharges of chemicals contributing HTPI are not given directly. Dhapa landfill have been considered as a point source of maximum facility discharge of liquid pollutant. The contributing compounds responsible for this category are the chemicals including heavy metals which emitting from the landfill leachate. The maximum facility discharge calculation is shown in annexure 4.

Table 6.17: Normalizing Value for Human Toxicity Potential by Ingestion (HTPI)

Contributing Chemicals	**Max facility discharge (kg/yr)**	**HTPI Equivalency factor**	**Facility clustering multiplier**	**HTPI impact (kg/yr)**
Arsenic (As)	*8.94*	*0.0667*	*1.5*	*0.8944*
Mercury (Hg)	*343.2*	*1*	*1.5*	*514.8*
Lead (Pb)	*171.6*	*0.8333*	*1.5*	*214.49*
Cadmium (Cd)	*1.5*	*0.00014*	*1.5*	*0.00032*
Total Chromium (Cr)	*1288.8*	*0.0025*	*1.5*	*4.83*
Copper (Cu)	*98.4*	*0.0016*	*1.5*	*0.2362*
Zink (Zn)	*3158.4*	*0.00138*	*1.5*	*6.5379*
Nickel (Ni)	*120*	*0.00142*	*1.5*	*0.2556*
Cyanide (CN)	*7.08*	*0.1563*	*1.5*	*1.6599*
Chloride (Cl)	*1060560*	*0.00033*	*1.5*	*524.98*
Fluoride (F)	*312*	*0.01938*	*1.5*	*9.069*
Nitrate (NO_3)	*2033.28*	*0.00079*	*1.5*	*2.4094*
Sulphate (SO_4)	*95894.4*	*0.00078*	*1.5*	*112.196*
Phenolic Compounds (Phn)	*60*	*0.0019*	*1.5*	*0.171*
Ammoniacal Nitrogen as (N)	*525360*	*0.00286*	*1.5*	*2253.79*
Normalizing value for HTPI = 3646.33 kg/year				

- **Human Toxicity Potential by Inhalation (HTPE)**

Farakka Thermal Power Plant is the largest emitter of SO_2, NO_x, and CO_2 with largest thermal power generation capacity of 2100 MW in the region (En.wikipedia.org). Based on the coal consumption norm [specified by Minimal National Standards for Thermal Power Plant, India (CPCB, 1986)] and the composition of the coal used by above power plant [(Pit et al., 2016), (Composition-of-lignite-coal)], SO_2, NO_x and CO_2 emissions from the plant are estimated as 26488×10^3, 28741×10^3 and 2.456×10^{10} kg/year, respectively. The detailed calculation is shown is annexure 5.

The normalizing value of contributing gases of human toxicity potential by inhalation is shown in table 6.18. The emitting amount of all contributing gases except SO_2, NO_2 and $CO_2$are taken from the landfill as max facility emission was not directly given for a particular industry.

Table 6.18: Normalizing Value for Human Toxicity Potential by Inhalation (HTPE)

Contributing Gas	Max facilityemission(kg/yr)	HTPE equivalency Factor	Facility clustering multiplier	HTPE impact (Kg/yr
Methane (CH_4)	$5.927 \text{ x } 10^8$	*0.00153*	*1.5*	1360246
Carbon Dioxide (CO_2)	$2.456 \text{ x } 10^{10}$	*0.000111*	*1.5*	408924
Sulphur Dioxide (SO_2)	$26.488 \text{ x } 10^6$	*0.0764*	*1.5*	3035524
Nitrogen Dioxide (NO_2)	$28.741 \text{ x } 10^6$	*0.1063*	*1.5*	4582752.
Ammonia (NH_3)	$13.244 \text{ x } 10^6$	*0.02876*	*1.5*	571346.
Hydrogen Sulphide (H_2S)	$0.233 \text{ x } 10^6$	*0.07191*	*1.5*	25132.54
Carbon Monoxide (CO)	$2.091 \text{ x } 10^6$	*0.01746*	*1.5*	54763.2
Methylene Chloride (CH_2Cl_2)	$10.921 \text{ x } 10^6$	*0.01151*	*1.5*	188551.0
Toluene ($C_6H_5CH_3$)	$15.8 \text{ x } 10^6$	*0.001329*	*1.5*	31497.3
Acetone	$2.091 \text{ x } 10^6$	*0.00042*	*1.5*	1317.33
Benzene	$0.929 \text{ x } 10^6$	*0.3135*	*1.5*	436862.2
Chloroform	$0.232 \text{ x } 10^6$	*0.00409*	*1.5*	1423.32
Ethyl Benzene	$3.95 \text{ x } 10^6$	*0.00231*	*1.5*	13686.7
Tetrachloroethylene	$4.415 \text{ x } 10^6$	*0.001473*	*1.5*	9754.942
Vinyl Chloride	$1.162 \text{ x } 10^6$	*0.3912*	*1.5*	681861.
Styrene	$0.697 \text{ x } 10^6$	*0.00235*	*1.5*	2456.92
Vinyl Acetate	$2.324 \text{ x } 10^6$	*0.02843*	*1.5*	99106.9
Normalizing value for HTPE= $15.19 \text{ x } 10^6$ Kg				

- **Terrestrial Toxicity Potential by Liquids (TTPL)**

Normalizing value for TTPL of contributing chemicals are same as HTPI, because impact potentials of these chemicals are the same as HTPI (Ref. table 6.17).

- **Terrestrial Toxicity Potential by Gas (TTPG)**

The largest annual facility emission of the gases which are responsible for this category and the normalizing value of the sub category are same as HTPE (Ref. table 6.18)

- **Aquatic Toxicity Potential (ATP)**

ATP impact value for the contributing chemicals are shown in table 6.19. The calculation of maximum facility discharge is shown in annexure 4.

Table 6.19: Normalizing value for Aquatic Toxicity Potential (ATP)

Contributing Chemicals	**Max facility discharge (kg/yr)**	**ATP equivalency factor**	**Facility clustering multiplier**	**ATP impact (kg/yr.)**
Arsenic (As)	*8.94*	*16.78*	*1.5*	*225.02*
Mercury (Hg)	*343.2*	*29.8*	*1.5*	*15341.04*
Lead (Pb)	*171.6*	*24.53*	*1.5*	*6314.02*
Cadmium (Cd)	*1.5*	*36.25*	*1.5*	*81.56*
Total Chromium (Cr)	*1288.8*	*16.386*	*1.5*	*31677.42*
Copper (Cu)	*98.4*	*30*	*1.5*	*4428*
Zink (Zn)	*3158.4*	*20.615*	*1.5*	*97665.6*
Nickel (Ni)	*120*	*16.443*	*1.5*	*2959.74*
Cyanide (CN)	*7.08*	*0*	*1.5*	*0*
Chloride (Cl)	*1060560*	*22.5*	*1.5*	*35793900*
Fluoride (F)	*312*	*5.718*	*1.5*	*2676.02*
Nitrate (NO_3)	*2033.28*	*15.822*	*1.5*	*48255.83*
Sulfate (SO_4)	*95894.4*	*15.054*	*1.5*	*2165391.45*
Phenolic Compounds (Phn)	*60*	*11.4*	*1.5*	*1026*
Ammoniacal Nitrogen as (N)	*525360*	*21.36*	*1.5*	*16832534*

Normalizing value for ATP = 5.5×10^7 kg/yr

The normalizing values of different sub- categories are shown in table 6.20

Table 6.20: Normalizing Values (Nj) for different Sub- categories

Impact Sub-Category	**Normalizing Value (kg/yr)**
GWP	5.77×10^{10}
ODP	-
RDP	*3629312**
AP	3.066×10^{10}
POCP	1.132×10^{8}
HTPE	15.19×10^{6}
HTPI	*3646.33*
TTPG	15.19×10^{6}
TTPL	*3646.33*
ATP	5.5×10^{7}

*Value of RDP in Sq. Km.

Due to the large global emission has considered for the respective pollutants, the normalizing value for GWP is substantially the highest. Higher value of AP is also due to large amount of SO_2, NO_x and NH_3 emissions with respect to maximum annual emission for the state under consideration. Next large value for POCP is also due to contribution of state wise maximum annual emission of CH_4, CH_2Cl_2 and $C_6H_5CH_3$. ATP has normalizing value 3 times more than HTPE and TTPG. HTPE and TTPG values are based on the local largest facility gaseous emission like SO_2 NO_x, CO_2, CH_4 etc. However larger liquid emission from local largest facility is responsible for ATP. Under local category, normalizing value HTPI and TTPL are less as the impact of HTPI and TTPL in localis much more than other global and regional category.

6.5 CALCULATION OF PEI

The equivalency factors (Ref. table 6.12& table 6.13), normalizing values (Ref. table 6.20), relative weightages (Ref. table 6.4) and the emission of the pollutants (Ref. table 5.5

&annexure 4) are used to calculate the PEI_{LCIA}. PEI of individual subcategory is calculated along with sample calculation and presented in table below. Table 6.29&6.30, summarize all the results of PEI value. For calculation of PEI, the usual discharge rate is considered in Kg/yr. (EPA, 1998 and Young and Cabezas, 1999).

6.5.1 Global Category

- **Global Warming Potential (GWP)**

Table 6.21:PEI calculation of GWP

Pollutant (i)	**Weightage (W_j)**	**Discharge rate (kg/yr.) (m_i)**	**EF_{ij}**	**N_j**	**PEI**
CO_2	*0.0101*	*1572335000*	*1*	5.77×10^{10}	2.75×10^{-4}
CH_4	*0.0101*	*592733000*	*28*	5.77×10^{10}	29.05×10^{-4}
CH_2Cl_2	*0.0101*	*10921000*	*9*	5.77×10^{10}	0.172×10^{-4}
				Total	**31.972×10^{-4}**

Sample calculation:
The PEI based on the LCIA approach is computed as

$$PEI_{LCIA} = \sum_j [w_j \times \{\sum_i (m_i \times EF_{ij}) \ / \ N_j\}]$$

PEI for CO_2 = 0.0101 x {(1575335000 x 1)/5.77 x 10^{10}}
=2.75 x 10^{-4}

- **Resource Depletion Potential (RDP)**

RDP has to be calculated as how much land is cleared with respect to total urban land area of the world. Weightage of RDP in global category is 0.0548 (Table 6.4). Total bio-mining area = 24ha = 0.24 sq. Km. Urban area in the world is 3629312 sq. Km.
PEI = 0.0548 x (0.24/3629312)
= 3.624 x 10^{-9}

6.5.2 Regional Category

- **Acidification Potential (AP)**

Table 6.22:PEI calculation of AP

Pollutant	**Weightage**	**Discharge rate**	**EF_{ij}**	**N_j**	**PEI**

(i)	(W_j)	(kg/yr.) (m_i)			
SO_2	*0.0712*	*238.68*	*1*	*$3.066 x10^{10}$*	*$5.543 \text{ x } 10^{-10}$*
NO_2	*0.0712*	*169.24*	*0.7*	*$3.066 \text{ x } 10^{10}$*	*$2.751 \text{ x } 10^{-10}$*
NH_3	*0.0712*	*13244000*	*1.88*	*$3.066 \text{ x } 10^{10}$*	*$5.782 \text{ x } 10^{-05}$*
				Total	**$5.7822 \text{ x } 10^{-05}$**

Sample calculation:

PEI for SO_2 = 0.712 x {(238.68 x 1)/ $3.066 \text{ x } 10^{10}$}

=$5.543 \text{ x } 10^{-10}$

- **Photo-chemical Ozone Conversion Potential (POCP)**

Table 6.23: PEI calculation of POCP

Pollutant (i)	Weightage (W_j)	Discharge rate (kg/yr.) (m_i)	EF_{ij}	N_j	PEI
CH_4	*0.1068*	*592733000*	*0.007*	*$1.132 \text{ x } 10^8$*	*$39.15 \text{ x } 10^{-4}$*
CH_2Cl_2	*0.1068*	*10921000*	*0.01*	*$1.132 \text{ x } 10^8$*	*$1.03 \text{ x } 10^{-4}$*
$C_6H_5CH_3$	*0.1068*	*15800000*	*0.563*	*$1.132 \text{ x } 10^8$*	*$83.92 \text{ x } 10^{-4}$*
				Total	**$124.1 \text{ x } 10^{-4}$**

Sample calculation:

PEI for CH_4 = 0.1068 x {(592733000 x 0.007)/ $1.132 \text{ x } 10^8$}

=$39.15 \text{ x } 10^{-4}$

6.5.3 Local Category

- **Human Toxicity Potential by Ingestion (HTPI)**

Table 6.24:PEI calculation of HTPI

Pollutant (i)	Weightage (W_j)	Discharge rate (kg/yr.) (mi)	EF_{ij}	N_j	PEI
Arsenic (As)	*0.2028*	*6.97*	*0.0667*	*3646.33*	*2.586×10^{-05}*
Mercury (Hg)	*0.2028*	*267.55*	*1*	*3646.33*	*1488×10^{-05}*

Lead (Pb)	*0.2028*	*133.78*	*0.8333*	*3646.33*	620×10^{-05}
Cadmium (Cd)	*0.2028*	*1.17*	*0.00014*	*3646.33*	0.0009×10^{-05}
Total Chromium (Cr)	*0.2028*	*1004.73*	*0.0025*	*3646.33*	13.97×10^{-05}
Copper (Cu)	*0.2028*	*76.71*	*0.0016*	*3646.33*	0.68×10^{-05}
Zink (Zn)	*0.2028*	*2462.24*	*0.00138*	*3646.33*	18.9×10^{-05}
Nickel (Ni)	*0.2028*	*93.55*	*0.00142*	*3646.33*	0.739×10^{-05}
Cyanide (CN)	*0.2028*	*5.52*	*0.1563*	*3646.33*	4.798×10^{-05}
Chloride (Cl)	*0.2028*	*826794.9*	*0.00033*	*3646.33*	1517.5×10^{-05}
Fluoride (F)	*0.2028*	*243.23*	*0.01938*	*3646.33*	26.22×10^{-05}
Nitrate (NO_3)	*0.2028*	*1585.11*	*0.00079*	*3646.33*	6.96×10^{-05}
Sulphate (SO_4)	*0.2028*	*74757.68*	*0.00078*	*3646.33*	324.31×10^{-05}
Phenolic Compounds (Phn)	*0.2028*	*46.78*	*0.0019*	*3646.33*	0.494×10^{-05}
Ammoniacal Nitrogen as (N)	*0.2028*	*409561.9*	*0.00286*	*3646.33*	6514.7×10^{-05}
				Total	**0.105399**

Sample calculation:

PEI for Arsenic (As)= 0.2028 x {(6.97 x 0.0667)/3646.33}

=2.586 x 10^{-05}

- **Human Toxicity Potential by Inhalation (HTPE)**

Table 6.25: PEI calculation of HTPE

Pollutant (i)	**Weightage (W_j)**	**Discharge rate (kg/yr.) (m_i)**	**EF_{ij}**	**N_j**	**PEI**
Methane (CH_4)	*0.2028*	*592700000*	*0.00153*	15.19×10^{6}	1210.7×10^{-5}
Carbon Dioxide (CO_2)	*0.2028*	*1572300000*	*0.000111*	15.19×10^{6}	233×10^{-5}
Sulphur Dioxide (SO_2)	*0.2028*	*238.68*	*0.0764*	15.19×10^{6}	0.0243×10^{-5}
Nitrogen Dioxide (NO_2)	*0.2028*	*169.24*	*0.1063*	15.19×10^{6}	0.024×10^{-5}
Ammonia (NH_3)	*0.2028*	*13244000*	*0.02876*	15.19×10^{6}	508.53×10^{-5}

Hydrogen Sulphide (H_2S)	*0.2028*	*233000*	*0.07191*	*15.19 x 10^6*	*22.37 x 10^{-5}*
Carbon Monoxide (CO)	*0.2028*	*2091000*	*0.01746*	*15.19 x 10^6*	*48.74 x 10^{-5}*
Methylene Chloride (CH_2Cl_2)	*0.2028*	*10921000*	*0.01151*	*15.19 x 10^6*	*167.82 x 10^{-5}*
Toluene ($C_6H_5CH_3$)	*0.2028*	*15800000*	*0.001329*	*15.19 x 10^6*	*28.03 x 10^{-5}*
Acetone	*0.2028*	*2091000*	*0.00042*	*15.19 x 10^6*	*1.173 x 10^{-5}*
Benzene	*0.2028*	*929000*	*0.3135*	*15.19 x 10^6*	*388.83 x 10^{-5}*
Chloroform	*0.2028*	*232000*	*0.00409*	*15.19 x 10^6*	*1.267 x 10^{-5}*
Ethyl Benzene	*0.2028*	*3950000*	*0.00231*	*15.19 x 10^6*	*12.18 x 10^{-5}*
Tetrachloroethylene	*0.2028*	*4415000*	*0.001473*	*15.19 x 10^6*	*8.68 x 10^{-5}*
Vinyl Chloride	*0.2028*	*1162000*	*0.3912*	*15.19 x 10^6*	*606.89 x 10^{-5}*
Styrene	*0.2028*	*697000*	*0.00235*	*15.19 x 10^6*	*2.19 x 10^{-5}*
Vinyl Acetate	*0.2028*	*2324000*	*0.02843*	*15.19 x 10^6*	*88.21 x 10^{-5}*
				Total	**0.033287**

Sample calculation:

PEI for Methane (CH_4) = 0.2028 x {(592700000x 0.00153)/ 15.19 x 10^6}

=1210.7 x 10^{-5}

- **Terrestrial Toxicity Potential by Liquids (TTPL)**

Table 6.26:PEI calculation of TTPL

Pollutant (i)	**Weightage (W_j)**	**Discharge rate (kg/yr.) (m_i)**	**EF_{ij}**	**N_j**	**PEI**
Arsenic (As)	*0.07368*	*6.97*	*0.0667*	*3646.33*	*0.939 ×10^{-05}*
Mercury (Hg)	*0.07368*	*267.55*	*1*	*3646.33*	*540.6 ×10^{-05}*
Lead (Pb)	*0.07368*	*133.78*	*0.8333*	*3646.33*	*225.3 ×10^{-05}*
Cadmium (Cd)	*0.07368*	*1.17*	*0.00014*	*3646.33*	*0.00033 ×10^{-05}*
Total Chromium (Cr)	*0.07368*	*1004.73*	*0.0025*	*3646.33*	*5.075 ×10^{-05}*
Copper (Cu)	*0.07368*	*76.71*	*0.0016*	*3646.33*	*0.248 ×10^{-05}*
Zink (Zn)	*0.07368*	*2462.24*	*0.00138*	*3646.33*	*6.87 ×10^{-05}*
Nickel (Ni)	*0.07368*	*93.55*	*0.00142*	*3646.33*	*0.268 ×10^{-05}*

Cyanide (CN)	*0.07368*	*5.52*	*0.1563*	*3646.33*	1.743×10^{-05}
Chloride (Cl)	*0.07368*	*826794.9*	*0.00033*	*3646.33*	551.3×10^{-05}
Fluoride (F)	*0.07368*	*243.23*	*0.01938*	*3646.33*	9.52×10^{-05}
Nitrate (NO_3)	*0.07368*	*1585.11*	*0.00079*	*3646.33*	2.53×10^{-05}
Sulphate (SO_4)	*0.07368*	*74757.68*	*0.00078*	*3646.33*	117.83×10^{-05}
Phenolic Compounds (Phn)	*0.07368*	*46.78*	*0.0019*	*3646.33*	0.179×10^{-05}
Ammonical Nitrogen as (N)	*0.07368*	*409561.9*	*0.00286*	*3646.33*	2366.9×10^{-05}
				Total	**0.03829**

Sample calculation:

PEI forArsenic (As)= 0.07368 x {(6.97x 0.0667)/ 3646.33}

=0.939 x 10^{-05}

- **Terrestrial Toxicity Potential by Gas (TTPG)**

Table 6.27:PEI calculation of TTPG

Pollutant (i)	**Weightage (W_j)**	**Discharge rate (kg/yr.) (m_i)**	**EF $_{ij}$**	**N_j**	**PEI**
Methane (CH_4)	*0.04912*	*592700000*	*0.00153*	15.19×10^{6}	293.24×10^{-05}
Carbon Dioxide (CO_2)	*0.04912*	*1572300000*	*0.000111*	15.19×10^{6}	56.44×10^{-05}
Sulphur Dioxide (SO_2)	*0.04912*	*238.68*	*0.0764*	15.19×10^{6}	0.0059×10^{-05}
Nitrogen Dioxide (NO_2)	*0.04912*	*169.24*	*0.1063*	15.19×10^{6}	0.0058×10^{-05}
Ammonia (NH_3)	*0.04912*	*13244000*	*0.02876*	15.19×10^{6}	123.17×10^{-05}
Hydrogen Sulphide (H_2S)	*0.04912*	*233000*	*0.07191*	15.19×10^{6}	5.418×10^{-05}
Carbon Monoxide (CO)	*0.04912*	*2091000*	*0.01746*	15.19×10^{6}	11.8×10^{-05}
Methylene Chloride (CH_2Cl_2)	*0.04912*	*10921000*	*0.01151*	15.19×10^{6}	40.65×10^{-05}
Toluene ($C_6H_5CH_3$)	*0.04912*	*15800000*	*0.001329*	15.19×10^{6}	6.79×10^{-05}
Acetone	*0.04912*	*2091000*	*0.00042*	15.19×10^{6}	0.284×10^{-05}
Benzene	*0.04912*	*929000*	*0.3135*	15.19×10^{6}	94.18×10^{-05}

Chloroform	*0.04912*	*232000*	*0.00409*	*15.19 x 10^{6}*	*0.307 x 10^{-05}*
Ethyl Benzene	*0.04912*	*3950000*	*0.00231*	*15.19 x 10^{6}*	*2.95 x 10^{-05}*
Tetrachloroethylene	*0.04912*	*4415000*	*0.001473*	*15.19 x 10^{6}*	*2.103 x 10^{-05}*
Vinyl Chloride	*0.04912*	*1162000*	*0.3912*	*15.19 x 10^{6}*	*147 x 10^{-05}*
Styrene	*0.04912*	*697000*	*0.00235*	*15.19 x 10^{6}*	*0.53 x 10^{-05}*
Vinyl Acetate	*0.04912*	*2324000*	*0.02843*	*15.19 x 10^{6}*	*21.37 x 10^{-05}*
				Total	**0.0080624**

Sample calculation:

PEI for Methane (CH_4) = 0.04912 x {(592700000 x 0.00153)/ 15.19 x 10^{6}}

=293.24 x 10^{-05}

- **Aquatic Toxicity Potential (ATP)**

Table 6.28: PEI calculation of ATP

Pollutant (i)	**Weightage (W_j)**	**Discharge rate (Kg/yr.) (m_i)**	**EF_{ij}**	**N_j**	**PEI**
Arsenic (As)	*0.2232*	*6.97*	*16.78*	*5.5 x 10^{7}*	*0.047 ×10^{-05}*
Mercury (Hg)	*0.2232*	*267.55*	*29.8*	*5.5 x 10^{7}*	*3.24 ×10^{-05}*
Lead (Pb)	*0.2232*	*133.78*	*24.53*	*5.5 x 10^{7}*	*1.33 ×10^{-05}*
Cadmium (Cd)	*0.2232*	*1.17*	*36.25*	*5.5 x 10^{7}*	*0.017 ×10^{-05}*
Total Chromium (Cr)	*0.2232*	*1004.73*	*16.386*	*5.5 x 10^{7}*	*6.68 ×10^{-05}*
Copper (Cu)	*0.2232*	*76.71*	*30*	*5.5 x 10^{7}*	*0.934 ×10^{-05}*
Zink (Zn)	*0.2232*	*2462.24*	*20.615*	*5.5 x 10^{7}*	*20.6 ×10^{-05}*
Nickel (Ni)	*0.2232*	*93.55*	*16.443*	*5.5 x 10^{7}*	*0.62 ×10^{-05}*
Cyanide (CN)	*0.2232*	*5.52*	*0*	*5.5 x 10^{7}*	*0*
Chloride (Cl)	*0.2232*	*826794.9*	*22.5*	*5.5 x 10^{7}*	*7549.4 ×10^{-05}*
Fluoride (F)	*0.2232*	*243.23*	*5.718*	*5.5 x 10^{7}*	*0.564 ×10^{-05}*
Nitrate (NO_3)	*0.2232*	*1585.11*	*15.822*	*5.5 x 10^{7}*	*10.18 ×10^{-05}*
Sulphate (SO_4)	*0.2232*	*74757.68*	*15.054*	*5.5 x 10^{7}*	*456.7 ×10^{-05}*
Phenolic Compounds	*0.2232*	*46.78*	*11.4*	*5.5 x 10^{7}*	*0.216 ×10^{-05}*

(Phn)					
Ammonical Nitrogen as (N)	*0.2232*	*409561.9*	*21.36*	*5.5 x* 10^{7}	*3550.2* ×10^{-05}
				Total	**0.116**

Sample calculation:

PEI for Arsenic (As)= 0.2232 x {(6.97 x 16.78)/*5.5 x*10^{7}}

=*0.047*x 10^{-05}

The following table 6.29 and table 6.30 are showing total quantitative PEI with respect to both category and pollutants.

Table 6.29: Pollutant and category wise PEI of differ impact subcategory of gaseous pollutant

Gaseous Pollutants (i)	**Impact Sub- category (j)**							**Pollutant wise Total PEI**
	GWP	**ODP**	**RDP**	**AP**	**POCP**	**HTPE**	**TTPG**	
Methane (CH_4)	*29.05 x* 10^{-4}				*39.15 x* 10^{-4}	*1210.7 x* 10^{-5}	*293.24 x* 10^{-05}	**2185.89 × 10^{-05}**
Carbon Dioxide (CO_2)	*2.75 x* 10^{-4}					*233 x* 10^{-5}	*56.44 x* 10^{-05}	**316.94 × 10^{-05}**
Sulphur Dioxide (SO_2)				*5.543 x* 10^{-10}		*0.0243 x* 10^{-5}	*0.0059 x* 10^{-05}	**0.0303 × 10^{-05}**
Nitrogen Dioxide (NO_2)				*2.751 x* 10^{-10}		*0.024 x* 10^{-5}	*0.0058 x* 10^{-05}	**0.0298 × 10^{-05}**
Ammonia (NH_3)				*5.782 x* 10^{-5}		*508.53 x* 10^{-5}	*123.17 x* 10^{-05}	**637.49 × 10^{-05}**
Hydrogen Sulphide (H_2S)						*22.37 x* 10^{-5}	*5.418 x* 10^{-05}	**27.788 × 10^{-05}**
Carbon Monoxide (CO)						*48.74 x* 10^{-5}	*11.8 x* 10^{-05}	**60.55 × 10^{-05}**
Methylene Chloride (CH_2Cl_2)	*0.172 x* 10^{-4}				*1.03 x* 10^{-4}	*167.82 x* 10^{-5}	*40.65 x* 10^{-05}	**220.49 × 10^{-05}**
Toluene ($C_6H_5CH_3$)					*83.92 x* 10^{-4}	*28.03 x* 10^{-5}	*6.79 x* 10^{-05}	**874.07 × 10^{-05}**
Acetone						*1.173 x* 10^{-5}	*0.284 x* 10^{-05}	**1.4565 × 10^{-05}**
Benzene						*388.83 x* 10^{-5}	*94.18 x* 10^{-05}	**483.01 × 10^{-05}**
Chloroform						*1.267 x* 10^{-5}	*0.307 x* 10^{-05}	**1.5737 × 10^{-05}**
Ethyl Benzene						*12.18 x* 10^{-5}	*2.95 x* 10^{-05}	**15.13 × 10^{-05}**
Tetrachloroethylene						*8.68 x* 10^{-5}	*2.103 x* 10^{-05}	**10.79 × 10^{-05}**
Vinyl Chloride						*606.89 x* 10^{-5}	*147 x* 10^{-05}	**753.89 × 10^{-05}**
Styrene						*2.19 x* 10^{-5}	*0.53 x* 10^{-05}	**2.716 × 10^{-05}**
Vinyl Acetate						*88.21 x* 10^{-5}	*21.37 x* 10^{-05}	**109.58 × 10^{-05}**
Category wise Total PEI	**31.972x 10^{-4}**		**3.624 x 10^{-9}**	**5.7822x 10^{-5}**	**124.1x 10^{-4}**	**0.033287**	**0.0080624**	

Table 6.30: Pollutant and category wise PEI of differ impact subcategory of liquid pollutant

Liquid Pollutants (i)	**Impact Sub- category (j)**			**Pollutant wise Total PEI**
	HTPI	**TTPL**	**ATP**	
Arsenic (As)	2.586×10^{-05}	0.939×10^{-05}	0.047×10^{-05}	**3.572×10^{-05}**
Mercury (Hg)	1488×10^{-05}	540.6×10^{-05}	3.24×10^{-05}	**2031.9×10^{-05}**
Lead (Pb)	620×10^{-05}	225.3×10^{-05}	1.33×10^{-05}	**846.61×10^{-05}**
Cadmium (Cd)	0.0009×10^{-05}	0.00033×10^{-05}	0.017×10^{-05}	**0.018×10^{-05}**
Total Chromium (Cr)	13.97×10^{-05}	5.075×10^{-05}	6.68×10^{-05}	**25.73×10^{-05}**
Copper (Cu)	0.68×10^{-05}	0.248×10^{-05}	0.934×10^{-05}	**1.86×10^{-05}**
Zink (Zn)	18.9×10^{-05}	6.87×10^{-05}	20.6×10^{-05}	**46.36×10^{-05}**
Nickel (Ni)	0.739×10^{-05}	0.268×10^{-05}	0.62×10^{-05}	**1.63×10^{-05}**
Cyanide (CN)	4.798×10^{-05}	1.743×10^{-05}	*0*	**6.54×10^{-05}**
Chloride (Cl)	1517.5×10^{-05}	551.3×10^{-05}	7549.4×10^{-05}	**9618.2×10^{-05}**
Fluoride (F)	26.22×10^{-05}	9.52×10^{-05}	0.564×10^{-05}	**36.3×10^{-05}**
Nitrate (NO_3)	6.96×10^{-05}	2.53×10^{-05}	10.18×10^{-05}	**19.67×10^{-05}**
Sulphate (SO_4)	324.31×10^{-05}	117.83×10^{-05}	456.7×10^{-05}	**898.85×10^{-05}**
Phenolic Compounds (Phn)	0.494×10^{-05}	0.179×10^{-05}	0.216×10^{-05}	**0.89×10^{-05}**
Ammoniacal Nitrogen as (N)	6514.7×10^{-05}	2366.9×10^{-05}	3550.2×10^{-05}	**12431.8×10^{-05}**
Category wise Total PEI	**0.105399**	**0.03829**	**0.116**	

6.6 RESULT AND DISCUSSION

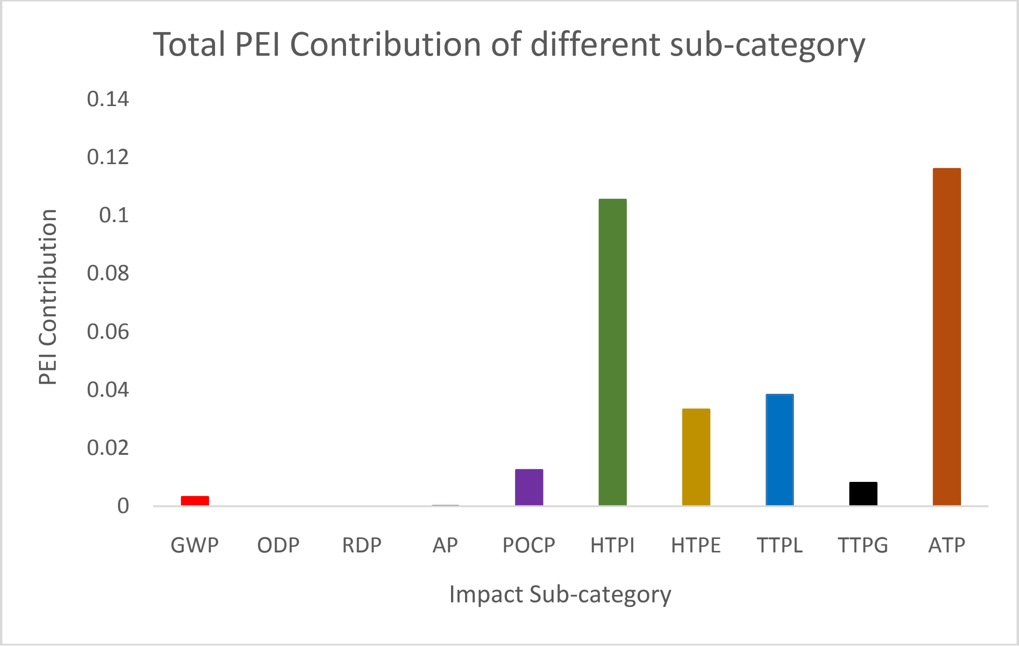

Fig 6.8: Total PEI Contribution of different Impact Sub- categories

Fig 6.8 depicts total PEI contribution of different sub-category. ATP is the highest PEI contributor (36.63%) among all sub-category due to its high weightage value (22.32%) and relatively higher equivalency factor. PEI contribution of HTPI and TTPL are 33.28% and 12.09%. Higher value of HTPI and TTPL are due to local impact of liquid pollutants is much more than gaseous pollutant. Percentage of PEI contribution of HTPE and TTPG are 10.51% and 2.55% respectively. In sub- category acidification potential (AP), PEI is very less due to emission of PEI contributing pollutants in this sub-category is substantially lower in quantity. But, POCP has a significant impact potential (3.92%) majorly due to toluene (67.62%). The impact sub-category ODP did not contribute any PEI value as no pollutant is generated to breakdown the ozone layer in this system.The PEI value of GWP is less (1.01%) in local perspective as the relative weightage value is less compared to other impact sub- category but it is very significant in global perspective.The resource is recovered in the form of land though the PEI value of RDP is not much but it has a significant positive impact in local perspective.

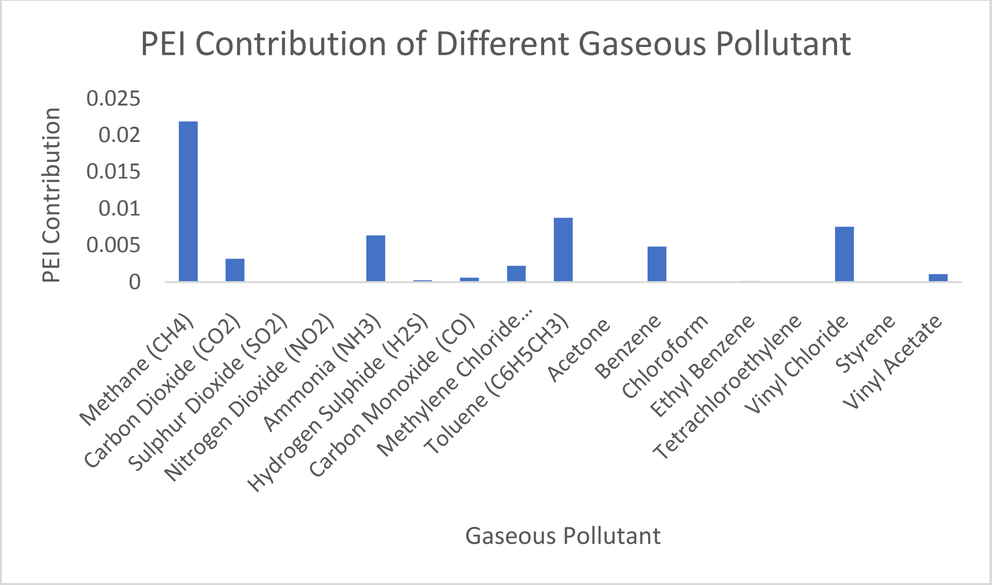

Fig 6.9: Total PEI Contribution of different Gaseous Pollutants

The Fig 6.9 shows the variation of PEI contribution of different gaseous pollutants. It is evident from this figure that CH_4 is the highest PEI contributor (38.34%) among all other pollutants. Toluene (15.33%), vinyl chloride (13.22%) and ammonia (11.18%) are also contributing significant amount of PEI. Though the emission of CO_2 is much more than other pollutants but the PEI contribution is less (5.55%) compared to other pollutants.

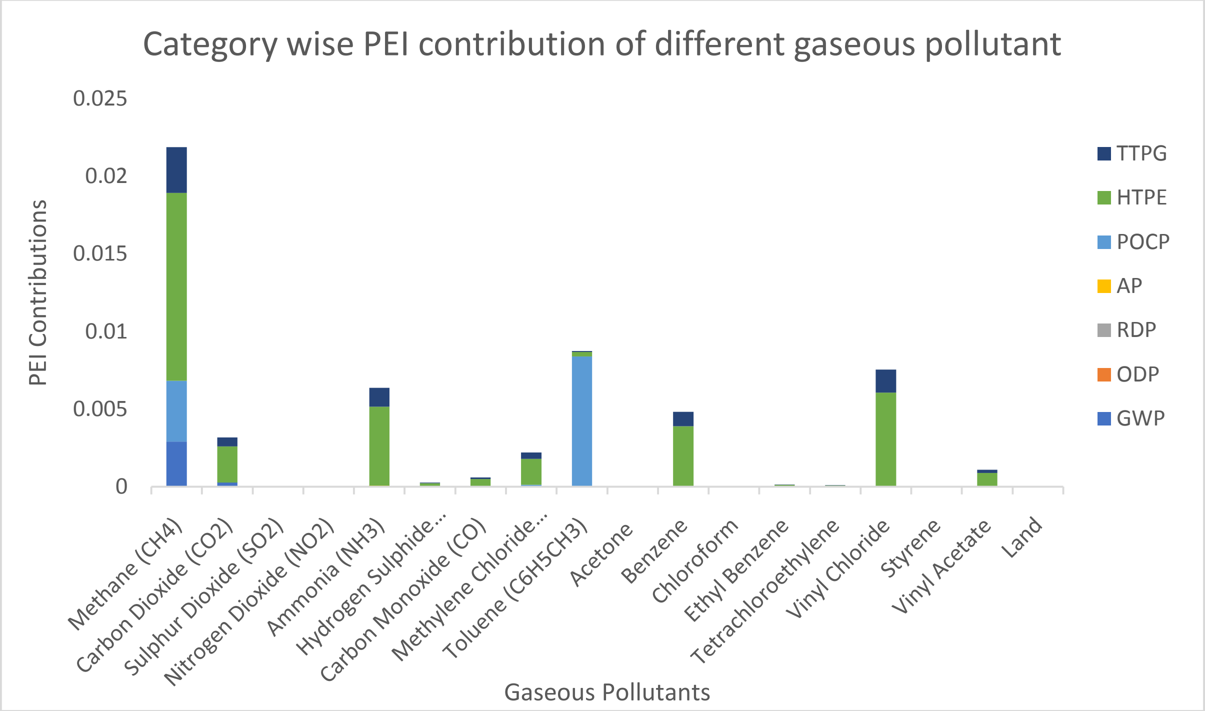

Fig 6.10: Category wise PEI Contribution of Gaseous Pollutants and Land Recovery.

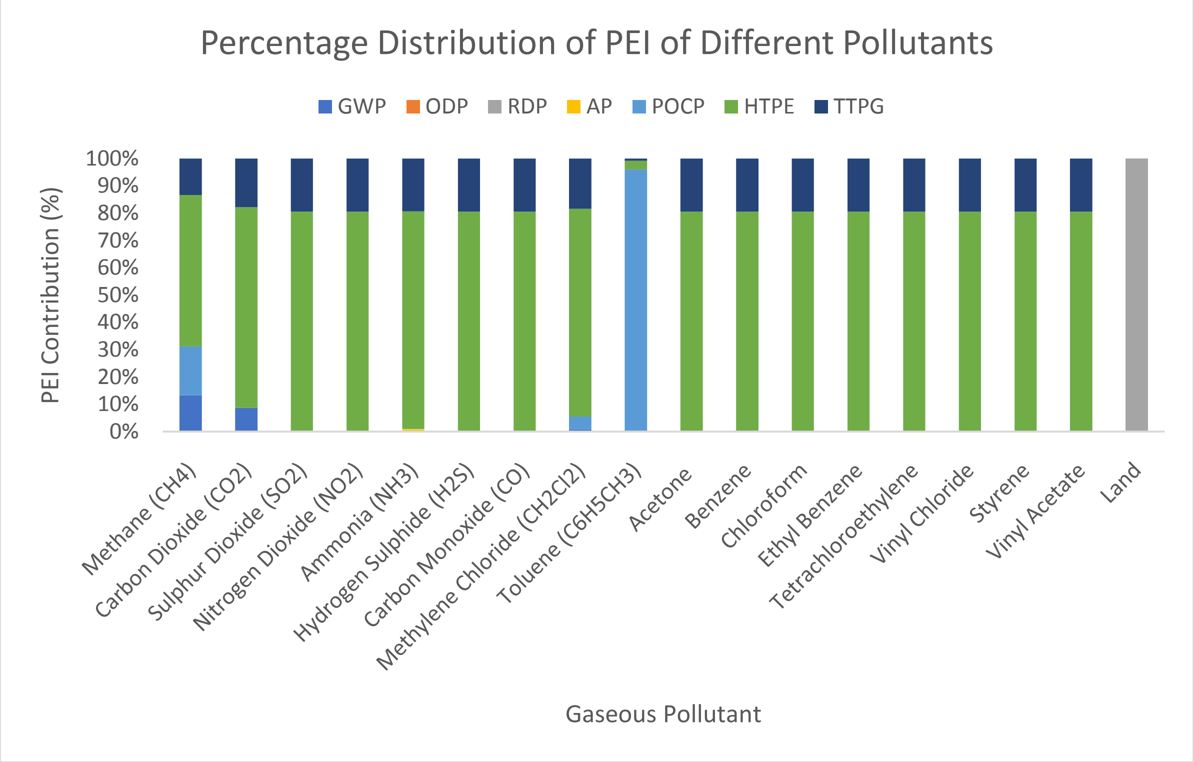

Fig 6.11: Category wise percentage distribution of PEI of different pollutants

It is observed from the figure 6.10 that CH_4 is the major contributing gaseous pollutant in relation to PEI contributor (38.34%). In sub-category human toxicity potential by inhalation (HTPE), methane has highest impact (36.37%).Other than this, Vinyl Chloride (18.23%), Benzene (11.68%) and Ammonia (15.28%) are having impact potential in HTPE sub-category. The contribution of Toluene is very significant in the impact sub-category POCP (67.62%). Though the emission of the trace gases liketoluene, methylene chloride, benzene and vinyl chloride are much less than other principal gases but due to their high toxicity level the PEI contribution in impact sub-category POCP, HTPE and TTPG is noticeable. Figure 6.11 shows category wise percentage distribution of PEI of different pollutants, which suggests that almost all the gaseous pollutants are having impacts on HTPE and TTPG i.e., total local impact is higher (72.52%) among others considering only gaseous pollutants.

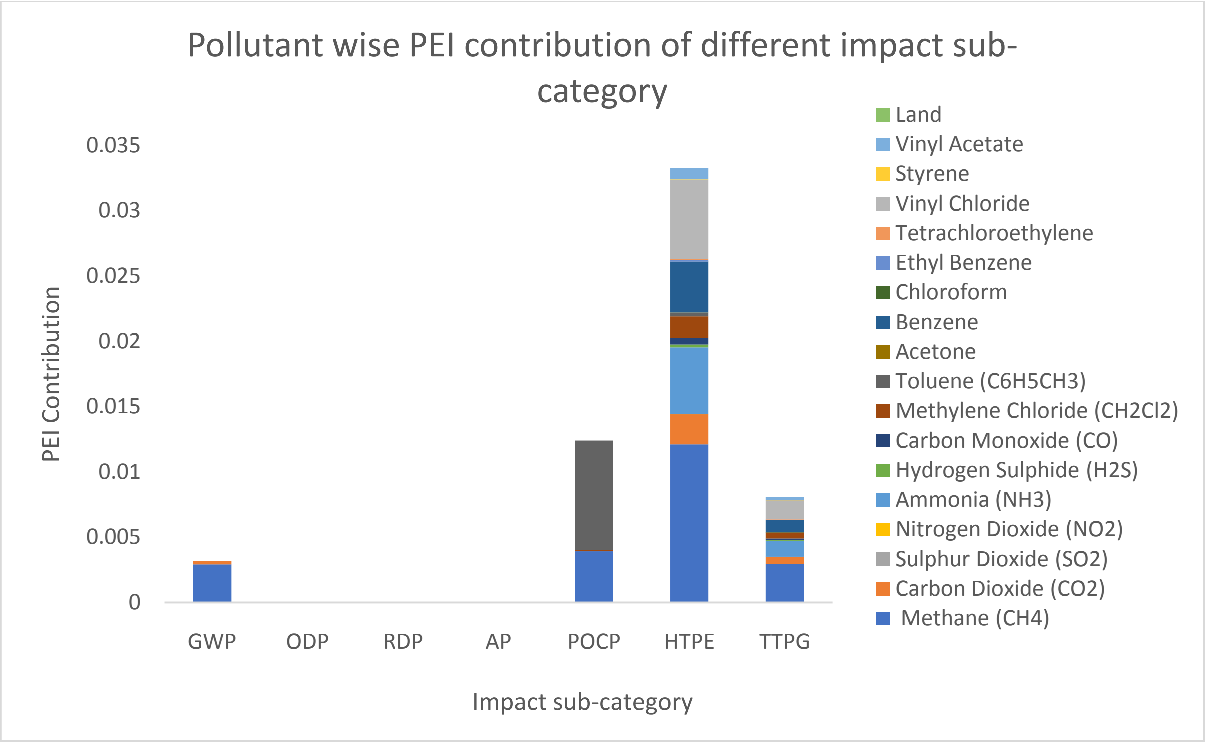

Fig 6.12: Pollutant wise PEI Contribution of different Impact Sub- categories.

It is seen from the figure 6.12 that among all the impact sub- category, HTPE contribute the highest PEI value. It is because all the gaseous pollutant are responsible to increase the impact value. The PEI value of GWP is less in local perspective as the relative weightage value is less compared to other impact sub- category but it is very significant in global perspective. The impact of RDP is not much corresponding to acquired land areabut it has a significant positive impact in local perspective. In sub-category acidification potential (AP), PEI of pollutants is very less. POCP has significat impact due to methane and toluene.

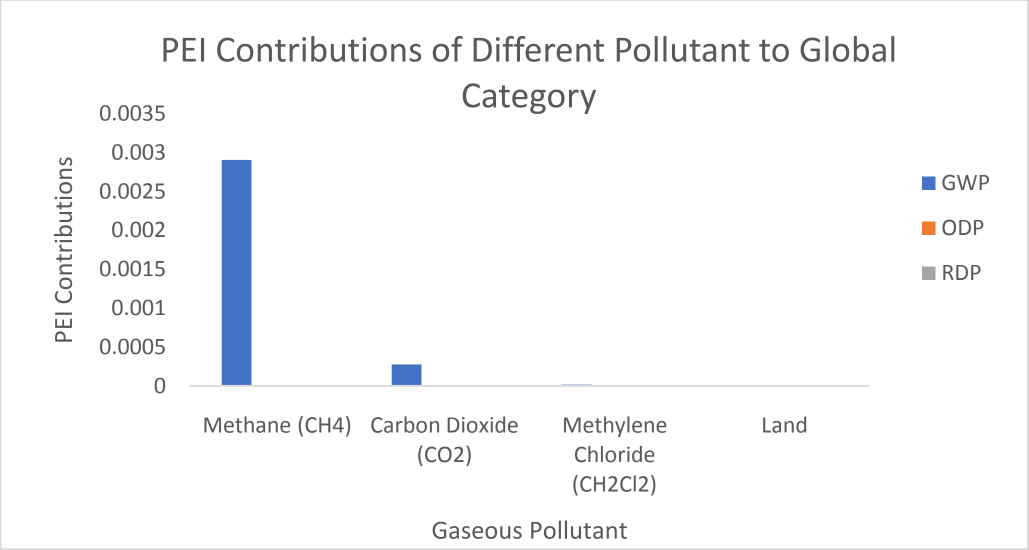

Fig 6.13: PEI Contribution of different gaseous pollutant and land recovery of global category

It is seen from figure 6.13 that CH_4 (91.07%) is the main gaseous pollutant to GWP followed by CO_2 (8.63%) and Dichloromethane (CH_2Cl_2) (0.54%) originating from landfill legacy waste degradation.Though the generation rate of CO_2 is much more than CH_4,the impact potential is much higher for methane due to its high equivalency factor over carbon dioxide. There is no gas contributing to ODP so the impact of ODP is zero. Though the land recovery with respect to global scenario is very less but it has significant positive impact in local perspective in terms of reclamation of valuable resource in the form of land from the landfill site.

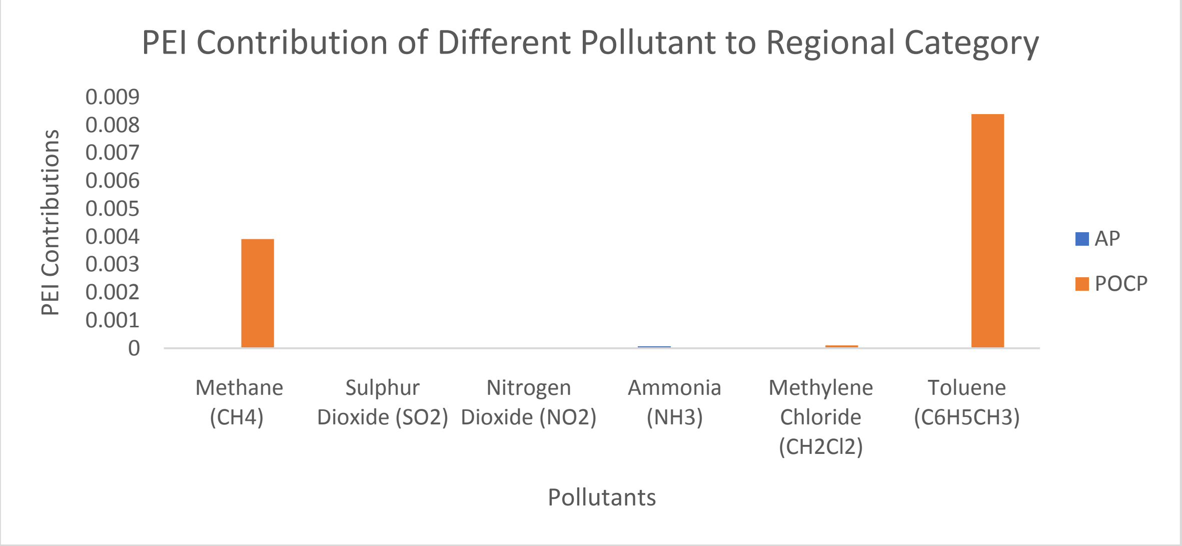

Fig 6.14: PEI Contribution of different Gaseous Pollutants to Regional Category

Under regional category, Fig6.14 shows that ammonia (NH_3) (99.99%) is the main contributing gas in AP sub- category as huge ammonia is being generated from 40 lakh MT legacy waste. In comparison, the impact of SO_2(0.0096%) and NO_2 (0.00048%) in AP sub-category is almost negligible due to their very low discharge rate from site. As, SO_x and NO_x generation have been solely considered from diesel consumption from different bio-mining equipment. Toluene is the main contributing landfill gas in POCP sub-category due to its high equivalency factor over methane and methylene chloride.

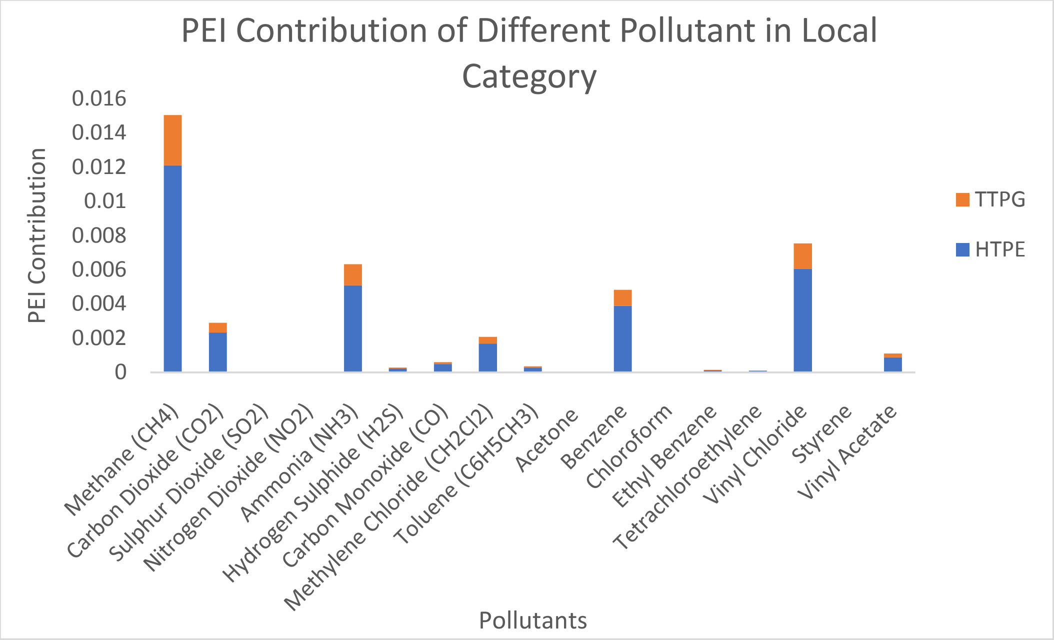

Fig 6.15: PEI Contribution of different Gaseous Pollutants to Local Category

In local category HTPE and TTPG, it is observed from figure 6.15 that CH_4 is the main contributing gas due to its huge generation rate. However, emission of CO_2 is maximum among all other gas components. But, due to lower equivalency factor, impact is less which may be considered to be contributed back to carbon cycle. Ammonia, Benzene and Vinyl Chloride have considerable discharge rate along with higher equivalency factors. So, their impact on HTPE and TTPG is significant. All other pollutants are also contributing to local category but in lesser quantity.

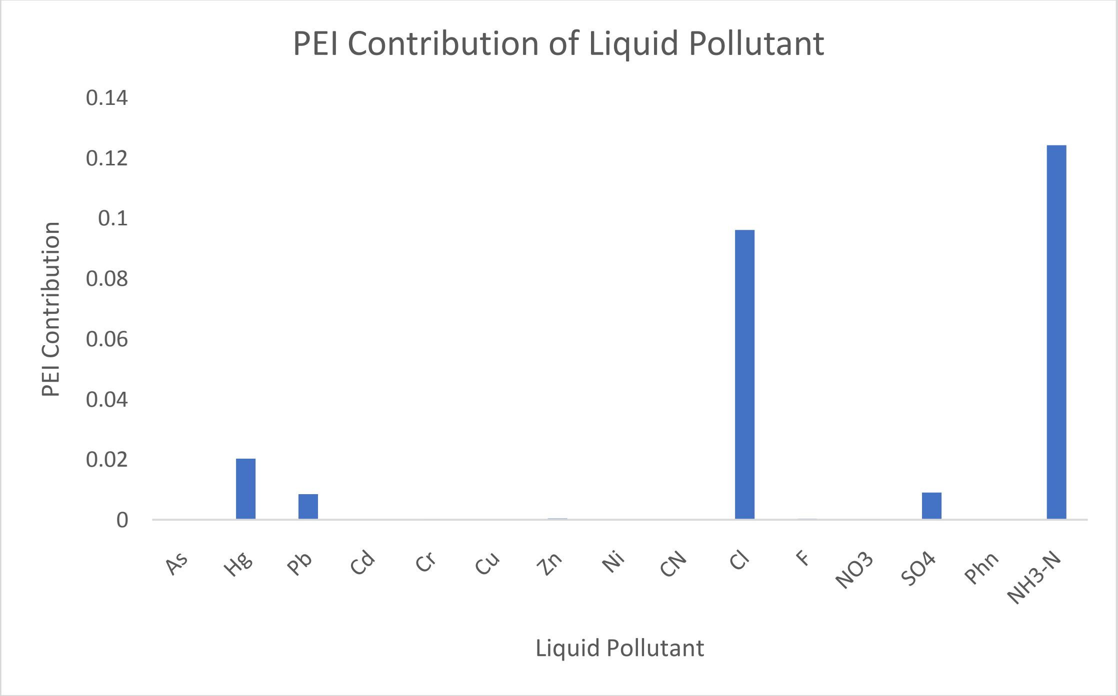

Fig 6.16: Total PEI Contribution of different Liquid Pollutants in Local Category

It is observed from the figure 6.16 that Ammoniacal Nitrogen (47.87%) and Chloride (Cl) (37.03%) is the highest PEI contributor among all liquid pollutants followed by Mercury (7.82%), Sulphate (3.46%) and Lead (3.26%). Other chemicals show very trace amount but due to their higher toxicity value the contribution of these chemicals is very important.

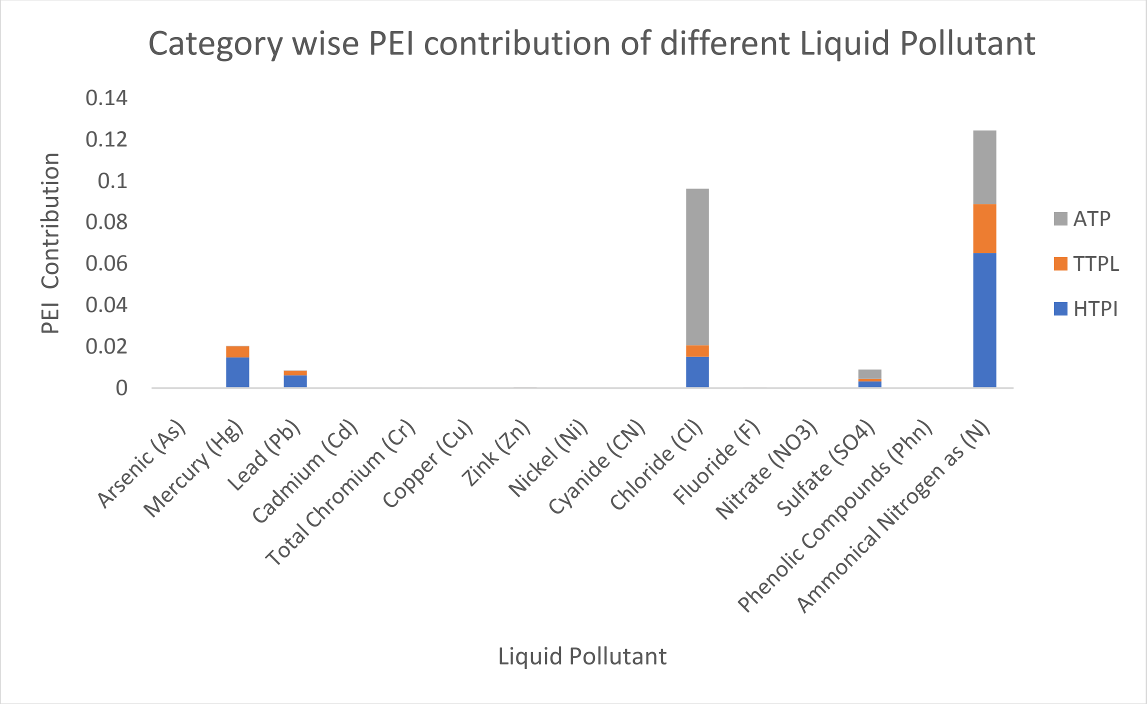

Fig 6.17: Category wise PEI Contribution of different Liquid Pollutants in Local category

It is seen from the Figure 6.17 that the significant amount of impact is generated from Ammoniacal Nitrogen and Chloride (Cl) due to their huge discharge rate. Though the discharge rate of chloride is much higher than ammoniacal nitrogen but due to very less equivalency factor of chloride in HTPI and TTPL sub-category, the impact contribution of chloride is slight less than ammoniacal nitrogen. All other liquid pollutant shows less but significant PEI in all three sub- categories i.e., ATP, TTPL and HTPI.

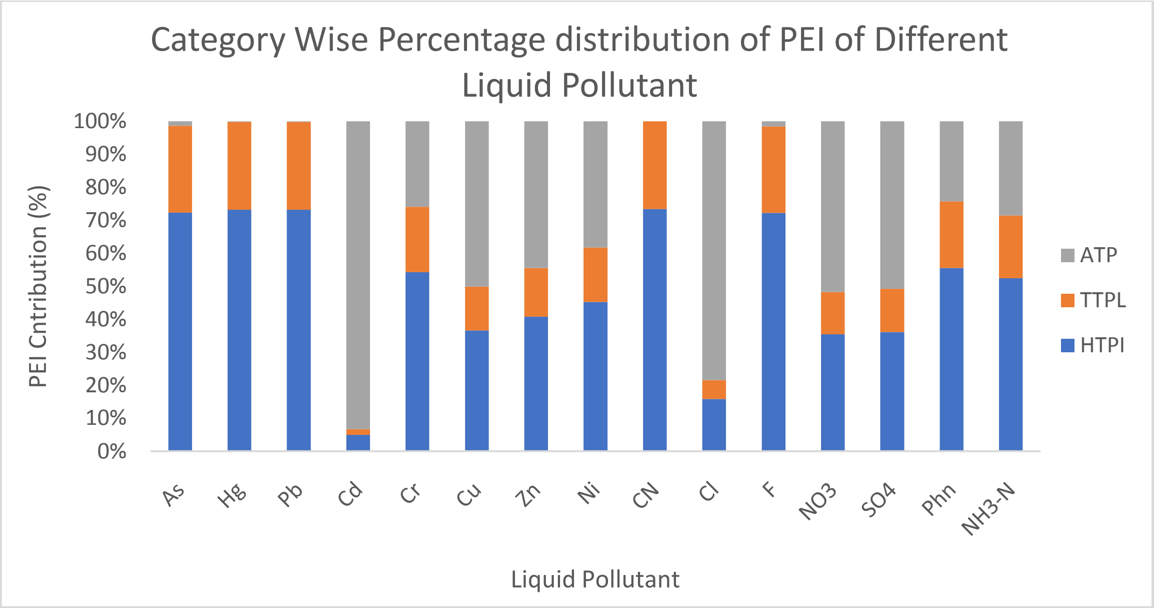

Fig 6.18: Category Wise Percentage distribution of PEI of Different Liquid Pollutant

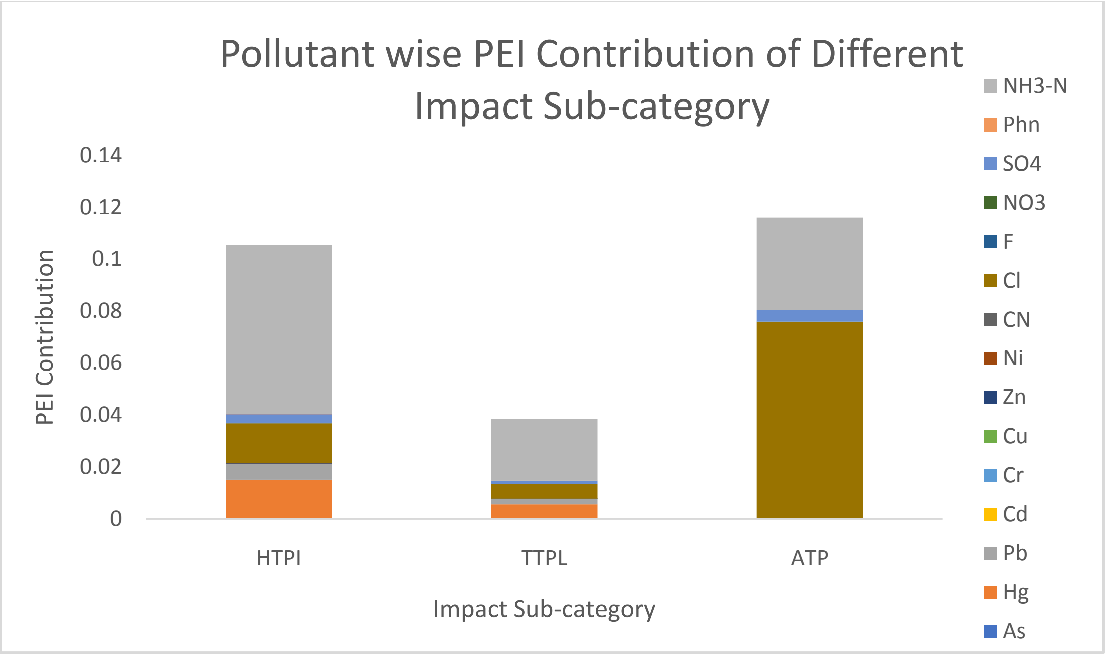

Fig 6.19: Pollutant wise PEI Contributionof different Impact Sub- category in Local Category

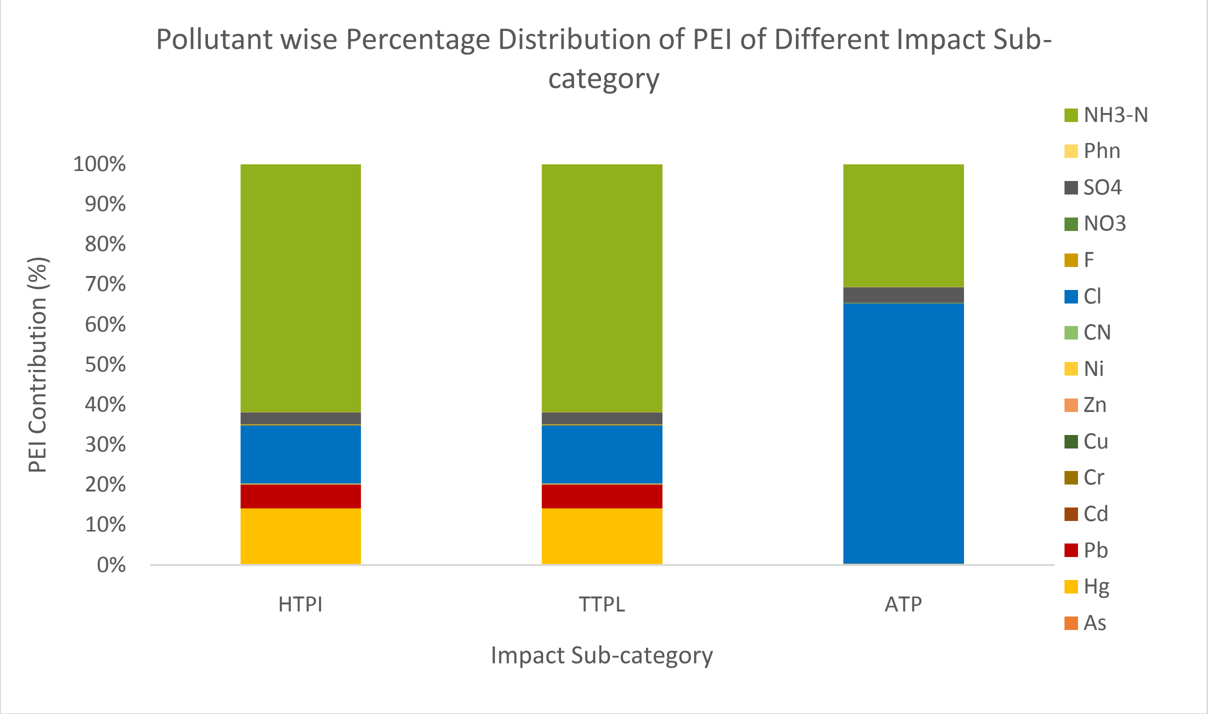

Fig 6.20: Pollutant wise Percentage Distribution of PEI of Different Impact Sub-category

Figure6.18shows Category wise percentage distribution of PEI of different liquid pollutant. HTPI and ATP contributes maximum percentage of impact in almost all liquid pollutant. Figure 6.19 shows pollutant wise PEI contribution of sub-category HTPI, TTPL and ATP. Due to highest weightage value among all impact sub-category and overall higher ATP equivalency factor, ATP contributes highest (44.67%) PEI followed by HTPI and TTPL. Though the equivalency factor, discharge rate, normalizing value is same for both HTPI and TTPL, due to higher weightage in HTPI sub-category leads to higher contribution (40.59%) of impact than TTPL (14.74%). Fig 6.19 also depicts that Chloride (65.08%), NH_3-N (30.6%) and Sulphate (3.94%) are having major PEI corresponding to Aquatic Toxicity Potential (ATP). Major contributing liquid pollutants in both HTPI and TTPL are Ammoniacal Nitrogen (61.76%), Mercury (14.1%), Lead (5.87%), Chloride (14.38%), and Sulphate (3.07%). Figure 6.20 shows pollutant wise percentage distribution of PEI of different impact sub-category.

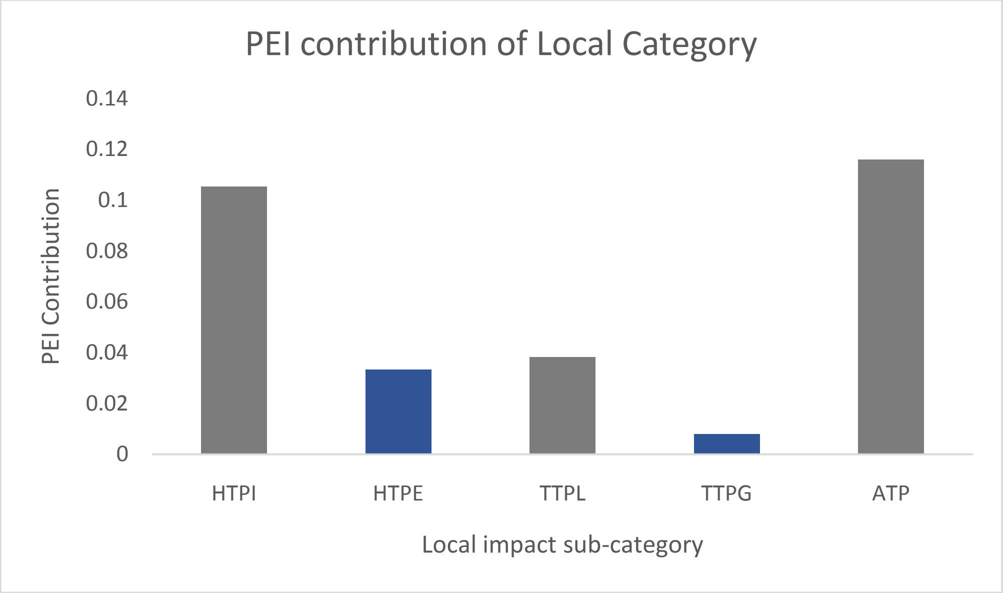

Fig 6.21: Total PEI Contribution of Local Impact Sub- category

Under overall local category, contribution of PEI is maximum for ATP (38.53%) followed by HTPI (35.01%), TTPL (12.72%), HTPE (11.06%) and TTPG (2.68%). It is seen that the liquid pollutantsare contributing more impact than gaseous pollutants. It is due to their higher weightage in impact categories and also their lower normalizing value in local category.

6.7 COMPARISON OF IMPACT WITH DIFFERENT BIO-MINING SCENARIO

Open dumping of waste materials prior any treatment to the dumpsite having no such liner system and landfill cover to curb out huge amount of toxic landfill gases and leachate generation is a major concern. In this study, an estimation of landfill gas like methane and other trace compounds suggest that they remain existing in the environment for more than 50 years after post closure period. Landfill leachates get generated for longer years and disperse both vertically and horizontally by polluting groundwater, surface water and soil medium. It has also put impact on aquatic life, vegetation by bio-accumulation of heavy metals and various POPs. Frequent landfill fires, generation of VOCs have vast impact on landfill workers as well as outskirts of the dumpsite. It is of utmost concern when these kind of potential pollution sources are very near to the city. This study estimates the potential impacts of having dumpsite under different categories causing from both liquid and gaseous pollutants. Implementation of bio-mining in the open dumpsite is supposed to minimize the impacts. This research outcomes focus on a comparative analysis between before, during and after bio-mining scenario.

Potential environmental impact (PEI) during bio-mining period i.e., in 2022 has been calculated and results are discussed above. During bio-mining (2022), quantitative impact i.e., PEI score of Global, Regional and Local category are 0.0032, 0.0125 and 0.301 respectively. The quantitative impact for all gaseous pollutant is 0.057 and for all liquid pollutant is 0.2597 i.e., overall impact obtained is 0.3167.The same methodological framework has been followed to calculate the potential impact in 2020 (scenario before bio-mining). To calculate PEI before biomining,the equivalency factors (Ref. table 6.12 & table 6.13), normalizing values (Ref. table 6.20), relative weightages (Ref. table 6.4) is used same as before. And the emission of the pollutants is taken as for 2020 which is shown in table 5.5 & annexure 4.From the calculation overall PEI score obtained is 0.39 for the scenario before bio-mining. The quantitative impact of PEI for global, regional and local categories are 0.0035, 0.0138,0.374 respectively. And quantitative impact of all gaseous pollutant is 0.063 and for liquid pollutant the impact is 0.333. The comparison graph between before biomining and during bio-mining is shown in figure no. 6.22, 6.23 and 6.24.

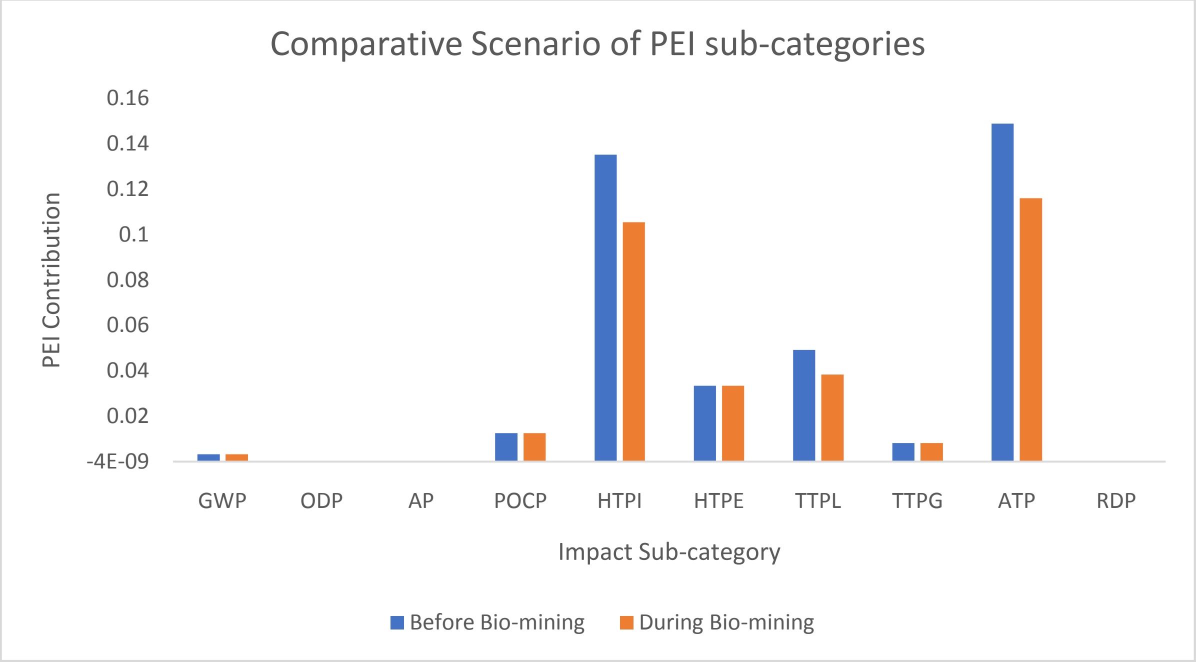

Fig 6.22: Comparison of PEI Contribution of different Impact Sub- categories

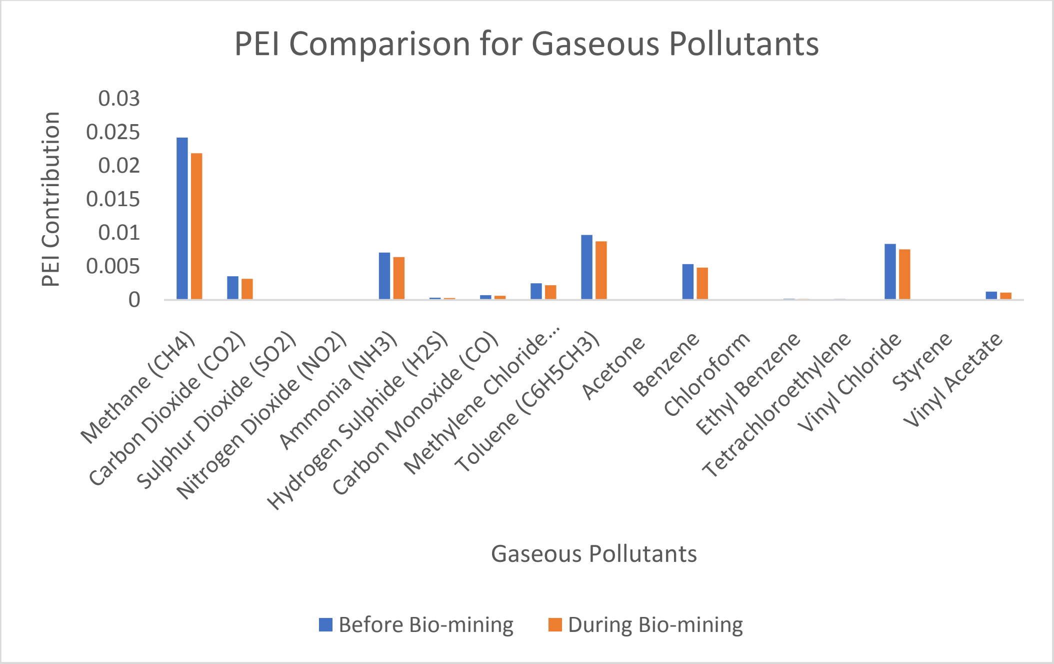

Fig 6.23: Comparison of PEI Contribution of different Gaseous Pollutants

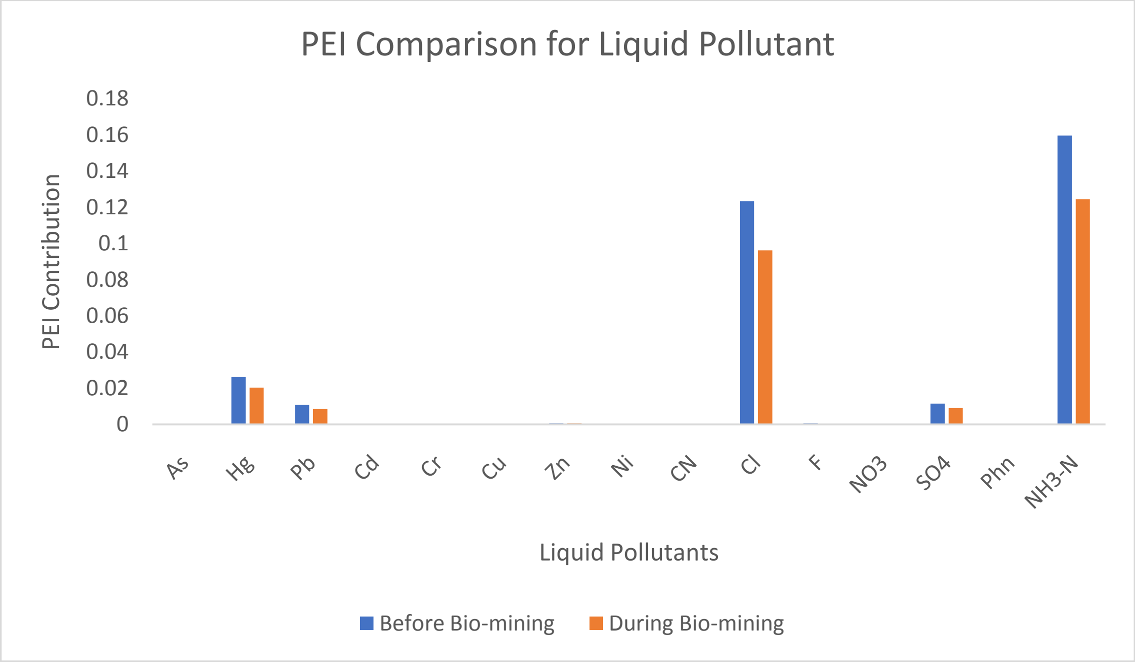

Fig 6.24: Comparison of PEI Contribution of different Liquid Pollutants

The overall impact obtained before bio-mining is 0.39 whereas the impact during bio-mining is 0.3167. So, the percentage reduction of impact is around 19% after one year of implementation of bio-mining operation.

Although, after bio-mining operation all the legacy waste are going to be extracted as secondary resource and huge land area will be reclaimed after bio-mining. So, firstly, from FOD model analysis an estimated 41% reduction in landfill gas after initiation of bio-mining is achievable with an indirect global energy saving against amplified GHG effect and global temperature rise. After that due to inexistence of legacy waste, no gas generation will be there with no such potential impacts. In the aspect of leachate, 68% of leachate generation can be minimized during the bio-mining period and it tends to zero emission after completion. Besides, around 24 ha of land will be reclaimed for other various uses. From the life cycle impact assessment, quantitative potential impact from different category which is mentioned above all will be minimized and tends to zero after completion of bio-mining operation.

Chapter 7

CONCLUSIONS

7.1 SUMMARY OF THE STUDY

With rapid incremental growth of municipal solid waste (MSW) generation transforming the landfills into virtual mountains of old legacy waste. Environmental degradation causing from untreated solid waste disposal in open dumpsites have vast social and environmental impact. Long term methane emission, leaching of toxic and hazardous substances causing pollution to air, surface water, ground water as well as to vegetation. Under the veridiction of National Green Tribunal (NGT) and solid waste management rules 2016, bio-mining and bioremediation needs to be implemented for clearing the legacy waste for open dumpsites. The convergence of sustainable waste material management and environmental protection issues have evolved the demand for the feasibility study of bio-mining. This research work objectifies the quantitative environmental impact study of bio-mining using life cycle assessment tool. In the first part of this study legacy waste characterization followed by its landfill degradation nature, material balancing of different bio-mining components have been studied. From the past 25 years MSW composition analysis, more than 50% of MSW found to be organic in nature. From onsite monthly data analysis of legacy waste, it is found that legacy waste consists of decomposable components such as Waste Soil (55.12%), Wood (0.42%), Coconut (1.01%), Animal Bone (0.66%), Textile Fabric (0.51%) and non-decomposable components such as Plastic (21.16%), Glass (1.21%), Thermocol (0.45%), Ceramic (1.55%), Gravels (9.22%), Kankar (6.61%), Mix (2.08%). From IPCC 1st order decay rate model, the degradation analysis was done for decomposable components for 30 years (both landfill period and post closure period) and it was found that 93±2% of organic food waste,39±2% of wood waste, 88±1% of coconut shell and animal bone, 59±2% of textile fabric, out of which major parts are mixed up with degraded soil like materials (SLM) along with simultaneous gas generation and leachate formation. Remaining percentages are yet to be transformed which can be easily recycled or recovered into different by-products. It is estimated that average physical material compositions have redistributed into six components i.e., Recyclable, Construction and Demolition waste (C & D waste), Refused-Derived-Fuel (RDF), Bio-Earth or Good Earth, Coarser Fraction (Coarser organics mixed with sand and silt), Process Rejects. As per IPCC model, 58-63% wood is recyclable and 37-

42% can be used as RDF; 80-85% of coconut shell can be used as RDF and rest are process reject; 80-85% of bones degrades and form soil like material and 15-20% remains in form of coarser fraction; 40-45% textile can be recycled and 55-60% can be used as RDF. Glass recycling is being done on 75% basis and 25% became coarser fraction.10% plastic can be recycled and 90% can be used as RDF. 80-85% of Ceramic is goes to coarser fraction and rest considered as process rejects. For inert material such as Gravel and Kankar, 5-10% partial degradation may be assumed. 90-95% of it will be treated as C&D waste and 5-10% as coarser fraction. 80-85% of Ceramics are in form of coarser fraction and rest can be treated as process reject. It is assumed 100% thermocol can be used as RDF and 100% mix waste remains as process reject. From the sieve analysis it was obtained that 50% of waste soil was good earth or bio-earth while, 40% was coarser fraction and 10% was C&D waste. Different moisture laden waste components have been reconciled to form different bio-mining components using material balance diagram where total moisture loss from the legacy waste is found to be around 13.89%. The percentage of bio-earth obtained is around 22.484%, recyclable fraction as 3.32%, C&D waste as 18.14%, RDF as 19.747%, Coarser fraction as 19.947% and process reject is found to be 2.477%.

The pollution contributing gases presents in landfill majorly are Methane, Carbon di-oxide, Hydrogen Sulfide, Ammonia, Carbon Monoxide. The degradation pattern of waste in landfill is also reflects in FOD model which gives proper justification of using this model over default method. From the curve of FOD model total methane generation up to 2050 will be 2,60,98,935 MT which is equivalent to 73,07,70,180 MT of CO_2-eq. Percentage reduction of methane emission in almost 25 year is 41%. The generation of all the other gases i.e., carbon dioxide, hydrogen sulphide, ammonia, carbon monoxide and other trace gases can be reduced by around 41% in 25 years potential after implementation of bio-mining treatment. Total land area 23.5 ha can be reclaimed after bio-mining for which an estimated reduction of leachate by 68% is achievable over the bio-mining period. However, in post bio-mining period, due to reclamation of whole land area will be done and no such MSW will be there, leachate generation tends to net zero emission.

LCIA is one of the most effective methods to evaluate the environmental performance of any product or process. In the present work, the estimation of PEI of bio-mining process is done based on LCIA approach considering three impact categories i.e., global, regional and local. Weightage of different categories and sub-categories are calculated based on analytical hierarchy process (AHP). After normalizing different sub-categories respective PEI have been calculated for different bio-mining scenario. During bio-mining the following results are obtained: ATP is the highest PEI contributor (38.14%) among all sub-category due to its high weightage value and relatively higher equivalency factor. PEI contribution of HTPI and TTPL are 34.65% and 12.59%. Higher value of HTPI and TTPL are due to local impact of liquid pollutants is much more than gaseous pollutant. Percentage of PEI contribution of HTPE and TTPG are 8.53% and 2.07% respectively. In sub- category acidification potential (AP), PEI is very less due to emission of PEI contributing pollutants in this sub-category is substantially lower in quantity. But, POCP has a significant impact potential (3.18%) majorly due to toluene. The PEI value of GWP is less (0.81%) in local perspective as the relative weightage value is less compared to other impact sub- category but it is very significant in global perspective.The impact sub-category ODP did not contribute any PEI value as no pollutant is generated to breakdown the ozone layer in this system. The resource is recovered in the form of land though the PEI value of RDP is not much but it has a significant positive impact in local perspective. The overall impact obtained before bio-mining is 0.39 whereas the impact during bio-mining is 0.3167. So, the percentage reduction of impact is around 19% after one year of implementation of bio-mining operation. After completion of the bio-mining operation the mentioned all quantitative impact will be minimized besides around 24 ha of land will be reclaimed.

7.2 BIO-MINING AND CIRCULAR ECONOMY

This study envisages maximum secondary material extraction from the landfill legacy waste. Alternative resources like RDF is being sent to cement manufacturing industries or power plant for co-processing. These RDF can be mixed up with coal due to their high calorific value not only save resource like coal depletion but also maximize the recovery with revenue generation. Besides recyclables like rubber, metal, wood are being recovered and send to respective vendors. Huge C&D waste recovery and their corresponding utilization in various infrastructural work such as basement filling, low line area filling, filling if plinth structure, road bed preparation is being pursued. The recovered coarser organic fraction is a very good quality filler material which is being utilized different non-structural construction applications. Recovery of bio-earth and their utilization as soil conditioner, tree pit filler, landscaping or as compost materials is some of the usages. This material recovery and their secondary usage indirectly saving the amplified GHG effect in terms of global energy conservation, minimizing resource extraction and depletion and their consequent operational environmental impact, generation of revenue from the secondary resources are leading towards circular economy. Since, bio-mining process integrates both waste to material and waste to energy by minimizing impact both environmentally, ecologically and socially, it has been proved as most economic ex-situ management alternatives for legacy waste.

7.3 FUTURE SCOPE OF WORK

The future scope of work may be as follows

1. In thisstudy quantitative environment impact is calculated within a specific system boundary. However, the impact can be calculated with a new extended system boundary. This study only estimates impact after bio-mining of different segregated materials but what will be the use of different bio-mining component, their impact after usage of particular component can be assessed in future work.
2. In this thesis, environmental impact is evaluated but for more precise work economic impact and feasibility can be find out through conduction of cost-benefit analysis, LCC model optimization, sensitivity analysis considering market values of recyclable and reusable materials, processing cost, fuel cost generated from the processing of combustible waste, reuse cost of reclaimed soil as cover material.
3. Social impact of bio-mining operation can also be studied in nearby area of Dhapa landfill site.
4. This this study, LCA model is applied in the bio-mining process excluding the energy flow of the equipment. So, life cycle assessment can also be done for the equipment which is required for the processing of legacy waste.

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ANNEXURE

Annexure 1: Calculation of SO_2 emission in West Bengal Region

From the *Urbanemissions.info*, the annual emission of SO_2 from all sectors of Kolkata and Asansol in the year 2018 reported 10,400 and 12700 MT respectively.

Ambient air concentration of SO_2 in Kolkata (K_a) =8 ug/m3

Ambient air concentration of SO_2 in Asansol (A_a) = 13.5 ug/m3

Ref. (STATE ENVIRONMENT PLAN: WEST BENGAL)

Weightage Average of ambient air conc.= $\frac{K_A * K_a + A_A * A_a}{K_A + A_A}$

$$= \frac{185 * 8 + 326 * 13.6}{185 + 326}$$

$$= 11.5 \text{ ….(Say X)}$$

Where, K_A and A_A are the area of Kolkata and Asansol respectively in km^2.

The same way, weightage avg. of all district except Kolkata and Asansol = $\frac{571710.5}{81000}$

$$= 7.06 \text{ …... (Say Y)}$$

(81,000 is the sum of area of all district except Kolkata and Asansol)

From (185+326) km^2 area, total emission is (10400+12700) MT

From total area 81000 km^2 area, total emission would be = $\frac{10400+12700}{185+326}$ x 81000 x $\frac{7.06}{11.5}$

$$= 2248249 \text{ MT}$$

Total SO_2 emission from West Bengal= (2248249+10400+12700) Mt/yr.

$$= 22.7 \times 10^8 \text{ kg/yr.}$$

From the emission data as on 2017-18, a 7.68% increased trend have been followed from all district in West Bengal (STATE ENVIRONMENT PLAN: WEST BENGAL).

So, net SO_2 emission in 2022= $22.7 \times 10^8 \times 1.0768 = 24.4 \times 10^8$ kg/yr.

Annexure 2: Calculation of NO_2 emission in West Bengal Region

From the *Urbanemissions.info*, the annual emission of NO_2 from all sectors of Kolkata and Asansol in the year 2018 reported 143650 and 160350 MT respectively.

Ambient air concentration of NO_2 in Kolkata (K_a) =42 ug/m3

Ambient air concentration of NO_2 in Asansol (A_a) = 41 ug/m3

Ref. (STATE ENVIRONMENT PLAN: WEST BENGAL)

Weightage Average of ambient air conc.= $\frac{K_A * K_a + A_A * A_a}{K_A + A_A}$

$$= \frac{185 * 42 + 326 * 41}{185 + 326}$$

$$= 41.36 \text{ ….(Say X)}$$

Where, K_A and A_A are the area of Kolkata and Asansol respectively in km^2.

The same way, weightage avg. of all district except Kolkata and Asansol = $\frac{2479230.5}{81000}$

$$= 30.6 \text{ …... (Say Y)}$$

(81,000 is the sum of area of all district except Kolkata and Asansol)

From (185+326) km^2 area, total emission is (143650+160350) MT

From total area 81000 km^2 area, total emission would be = $\frac{143650 + 160350}{185 + 326}$ x 81000 x $\frac{30.6}{41.36}$

$$= 34936203 \text{ MT}$$

Total NO_2 emission from West Bengal= (34936203+143650+160350) Mt/yr.

$$= 3.52 \times 10^{10} \text{ kg/yr.}$$

From the vehicular growth data in West Bengal from 2018-22, a 15% increased trend have been followed.

So, net NO_2 emission in 2022= $3.52 \times 10^{10} \times 1.15 = 4.01 \times 10^{10}$ kg/yr.

Annexure 3: Calculation of CH_4 emission in West Bengal Region

GHG emissions in the state of West Bengal estimated 171.7 Mt CO_2-e in the year 2013 (GHG Platform, 2013).

Assume 80% CO_2 and 20% CH_4 present in total GHG gas (Our World in Data)

Let, the amount of CO_2 is x MT

So, $0.80x + 28x^{*} 0.20 = 171.7$;(28= GWP of Methane)

$x = 26.8$ MT

$CH_4 = 26.8 \times 0.20 = 5.36$ MT

Growth rate of GHG emission is 5.19% CAGR

Time n= 9 years (from 2013 to 2022)

CH_4 emission in 2022 = $5.36(1+0.0519)^9$ MT

$= 0.845 \times 10^{10}$ kg

Annexure 4: Calculation of Maximum facility discharge for HTPI.

The max and min concentration of contributing chemicals except sulphate, nitrate, fluoride and cadmium are taken from (De et. al., 2015). The concentration of Sulphate, nitrate, fluoride and cadmium are taken from onsite leachate characterization data of Dhapa landfill. Leachate generation rate of Dhapa landfill is taken as 1000 L/m^2/yr. Bio-mining are is 24 ha. Max facility discharge is calculated and shown in table 1. One sample calculation is shown below.

Table A-4.I: Max facility discharge for liquid pollutants

Parameter	**Conc. (mg/l)**	**Avg. Conc. (mg/l)**	**leachate generation Rate (L/m^2/yr.)**	**Area (m^2)**	**Max. facility emission (kg/yr)**
Cl	*2103-6735*	*4419*	*1000*	*240000*	*1060560*
NO_3	*8.472*	*8.472*	*1000*	*240000*	*2033.28*
SO_4	*399.56*	*399.56*	*1000*	*240000*	*95894.4*
Phn	*0.16-0.34*	*0.25*	*1000*	*240000*	*60*
As	*0.0045-0.07*	*0.03725*	*1000*	*240000*	*8.94*
Cd	*0.00625*	*0.00625*	*1000*	*240000*	*1.5*
Cr	*0.31-10.43*	*5.37*	*1000*	*240000*	*1288.8*
Cu	*0.14-0.68*	*0.41*	*1000*	*240000*	*98.4*
Hg	*0.21-2.65*	*1.43*	*1000*	*240000*	*343.2*
Ni	*0.23-0.77*	*0.5*	*1000*	*240000*	*120*
Pb	*0.37-1.06*	*0.715*	*1000*	*240000*	*171.6*

Zn	*1.18-25.14*	*13.16*	*1000*	*240000*	*3158.4*
CN	*0.024-0.035*	*0.0295*	*1000*	*240000*	*7.08*
F	*1.3*	*1.3*	*1000*	*240000*	*312*
NH_3-N	*168-4210*	*2189*	*1000*	*240000*	*525360*

Sample Calculation:

Maximum facility discharge for Phenolic Compound = (0.25 x 1000 x 240000) x 10^{-6} kg/yr.

= 60 kg/yr.

Table A-4.II: Emission of liquid pollutant in 2022 (during bio-mining)

Parameter	**Conc. (mg/l)**	**Avg. Conc. (mg/l)**	**leachate generation Rate (L/m^2/yr.)**	**Area (m^2)**	**Emission (kg/yr)**
Cl	*2103-6735*	*4419*	*1000*	*187100*	*826794.9*
NO_3	*8.472*	*8.472*	*1000*	*187100*	*1585.1112*
SO_4	*399.56*	*399.56*	*1000*	*187100*	*74757.676*
Phn	*0.16-0.34*	*0.25*	*1000*	*187100*	*46.775*
As	*0.0045-0.07*	*0.03725*	*1000*	*187100*	*6.969475*
Cd	*0.00625*	*0.00625*	*1000*	*187100*	*1.169375*
Cr	*0.31-10.43*	*5.37*	*1000*	*187100*	*1004.727*
Cu	*0.14-0.68*	*0.41*	*1000*	*187100*	*76.711*
Hg	*0.21-2.65*	*1.43*	*1000*	*187100*	*267.553*
Ni	*0.23-0.77*	*0.5*	*1000*	*187100*	*93.55*
Pb	*0.37-1.06*	*0.715*	*1000*	*187100*	*133.7765*
Zn	*1.18-25.14*	*13.16*	*1000*	*187100*	*2462.236*
CN	*0.024-0.035*	*0.0295*	*1000*	*187100*	*5.51945*
F	*1.3*	*1.3*	*1000*	*187100*	*243.23*
NH_3-N	*168-4210*	*2189*	*1000*	*187100*	*409561.9*

Annexure 5: Calculation of Maximum facility discharge (SO_2, NO_2, CO_2) in Farakka Thermal Power Plant for HTPE.

Farakka is the lignite based thermal generating stations with 2100 MW capacity and operates in three stages.

The composition of lignite coal are as follows:

Moisture 35%	Sulphur 0.54%

Carbon 41.7%

Hydrogen 2.61%

Nitrogen 0.79%

Ash 9.47%

Oxygen 9.90%

Different available components of coal (Kg mole) are C= 41.7/12= 3.475 Kg mole, H2= 2.61/2 =1.305 Kg mole, N_2= 0.79/28=0.028 Kg mole, O_2=9.90/32= 0.309 Kg mole.

O_2 is required with 20% excess air for coal combustion. (Ref: Optimal Combustion Processes - Fuel vs. Excess Air)

C(1 mole) +O_2 (1 mole) =CO_2 (1 mole)

H_2 (1 mole)+ ½ O_2 (0.5 mole) = H_2O (1 mole)

O_2 required including 20% excess air = [(3.475 x1.2) +(1.305 x0.5 x1.2)] = 4.953 Kg mole

But already 0.309 Kg mole of O_2 is present in the fuel.

Then, O_2 required from the air= 4.953- 0.309= 4.644 Kg mole

Considering the other part as N_2 in the air i.e., 78.8% of N_2 and 21.2% of O_2 only.

Hence, N_2 present in the air along with O_2= 78.8 x (4.644/21.2) = 17.26 Kg mole.

Air requirement:

(21.2 x 32/100) Kg of O_2 is equivalent to [(0.212 x 32) +(0.788 x 28)] =28.848 Kg of air

Hence, (14.644 x 32) Kg of O_2 = (28.848 x 4.644 x 32)/ (0.212 x 32) = 631.93 Kg of air.

Again, 21.2 gm mole of O_2 = 100 mole of air

= 22.4 x100 litre of air

4.644 Kg mole of O_2 equivalent to (22.4 x 100 x 4.644 x 100) / (21.2 x 100) Nm^3 of air

= 490.69 Nm^3 of air

Material Balance:

Table A-5: Material balance for gas generation

Element/ component		Input			Output	
		Kg	M.W	Kg mole	Kg mole	Kg
Fuel	C	*41.7*	*12*	*3.475*	-	-
	H_2	*2.61*	*2*	*1.305*	-	-
	N_2	*0.79*	*28*	*0.028*	*0.028*	*0.784*
	O_2	*9.90*	*32*	*0.309*	-	-
Air with 20% excess	O_2	*148.6*	*32*	*4.644*	*0.774*	*24.768*
	N_2	*483.28*	*28*	*17.26*	*17.26*	*483.28*
Flue Gas	H_2O	-	*18*	-	*1.305*	*23.49*
	CO_2	-	*44*	-	*3.475*	*152.9*
Total		**686.18 kg**			**685.222 kg**	

Avg. molecular wt. of the flue gas with 20% excess air = (685.222/22.843) = 29.99

100 Kg of coal generates 685.222 Kg of flue gas

= 685.222 x 10^3 gm of flue gas

= (685.222 x 10^3/29.99) mole

= 22848.3 mole

= (22848.3x 22.4/ 1000) Nm^3

= 511.8 Nm^3

Table A-6: Farakka coal consumption and emission data (Pit et al., 2016).

Stage	Coal Consumption (MT)	Emission (mg/m^3)	
		SO_x	NO_x
1st	*6888666*	*303.7*	*331.3*
2nd	*6888666*	*332.8*	*358.7*

3rd	*2282719*	*346.3*	*377.7*

100 Kg of coal generates 511.8 Nm^3 of flue gas

6888666 MT of coal generates $=3.526 \times 10^{10}$ Nm^3 of flue gas

2282719 MT of coal generates $=1.168 \times 10^{10}$ Nm^3 of flue gas

Total SOx emission= $(3.526 \times 10^{10} \times 303.7 + 3.526 \times 10^{10} \times 332.8 + 1.168 \times 10^{10} \times 346.3) \times 10^{-6}$

= 26487774 kg

Total NOx emission = $(3.526 \times 331.3 + 3.526 \times 358.7 + 1.168 \times 377.7) \times 10^4$ kg

= 28740936 kg

Total coal consumption = (6888666+6888666+2282719) = 16060051 MT

Carbon percentage in coal 41.7%

Total Carbon in coal = (160600051 x 0.417) MT

=6697041.3 MT

$C + O_2 = CO_2$

Total CO_2 emission = 6697041.3 x (44/12) MT

$=2.456 \times 10^{10}$ kg