ENVIRONMENTAL AND ECONOMIC ANALYSIS OF LANDFILL BIOMINING PROCESS IN THE CONTEXT OF UTILIZING RDF AS FUEL AND GOOD EARTH AS SUBGRADE MATERIAL FOR FLEXIBLE PAVED ROAD: A LIFE CYCLE AND COST-BENEFIT APPROACH

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I declare that,

a. The work contained in the thesis is original and has been done by myself under supervision and guidance of my supervisor.

b. The work has not been submitted to any other institute for any degree or diploma.

c. Whenever I have used materials (data, theoretical analysis and text) from other sources, I have given due credit to them by citing them in the text of the thesis and giving their details in the references.

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ACKNOWLEDGEMENT

It would not have been possible to write this master thesis without the help and support of the kind people around me. My sincere thanks to one and all, those who at different times have helped me in the development of this thesis, to only some of whom it is possible to give particular mention here.

It gives me great pleasure to express my deep sense of gratitude to my supervisor Dr. Tumpa Hazra for suggesting me the problem as well as giving her continuous guidance and inspiration throughout my research work. In spite of her busy schedule, she has spared lots of her valuable time and given invaluable suggestions in all of my endeavours.

I am also very much thankful to the Civil Engineering Department of Jadavpur University, specially Environmental Engineering Division, Dr. Somnath Mukherjee, Prof. Shibnath Chakrabarty, Dr. Amit Dutta, Dr. Anupam Debsarkar, Dr. Abhisek Roy, Dr. Ankush Majumdar and other supporting staff and personnel for their help and support in many ways to conduct me this study.

My thanks also go to all my friends, classmates and seniors for their help, and of course one of the senior research scholars.

Last but not the least, I am deeply indebted to my family for their constant encouragement and inspiration.

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Abstract

Landfills of municipal solid wastes in India create significant environmental and socio-economic issues due to inadequate maintenance. To address these impacts, Solid Waste Management Rule, 2016 proposes 'Landfill Biomining' as a viable solution. Two landfill sites, Howrah and Durgapur, are examined in this study using Life Cycle Assessment (LCA) and Cost-Benefit Analysis (CBA) models to evaluate the environment and economic performances of this approach by utilising different products of biomining. Four scenarios are considered: the base scenario (Do Nothing Scenario), where biomining occurs but the products are utilized for in-situ filling or covering purpose; Scenario 1, which involves using refuse-derived fuel (RDF) to replace coal in cement factories or brick kilns; Scenario 2, which uses good earth as subgrade material in roads; and a combined scenario incorporating both Scenario 1 and Scenario 2. The environmental analysis reveals that these mining and waste valorization strategies can significantly reduce the global warming potential of landfill waste. In the combined scenario, where RDF is used in cement factories or brick kilns, each site can replace an average of 208 kg of coal by the RDF obtained per ton of legacy waste. This results in a substantial reduction in Global Warming Potential (GWP), with the Durgapur site achieving a 53.92% reduction and the Howrah site achieving a 55.58% reduction. The feasibility of using the good earth as subgrade material has been evaluated through physicochemical, geotechnical, and heavy metals analysis. The results, compared with the literature values and regulatory guidelines, indicate that good earth obtained from both Howrah and Durgapur sites are suitable for subgrade material. Specifically, Howrah's unsoaked California Bearing Ratio (CBR) is 14.18%, while Durgapur's is slightly higher as 15.22%, suggesting marginally better load-bearing capacity in dry conditions. However, good earth of Howrah site has higher heavy metal concentrations compared to Durgapur. Economic performance has been assessed through a Cost-benefit analysis model, which would include the Net Present Value (NPV) and Cost-benefit Ratio, considering direct costs, indirect costs and carbon emission reduction (CER) credits obtained from LandGEM gas emission model as environmental benefit. The NPV analysis has shown positive net benefits for both landfills, with Howrah and Durgapur sites yielding 6,93,22,572.45 INR and 37,25,64,154.68 INR, respectively considering the RDF is utilised in cement factory as replacement of coal and good earth is used as subgrade material of road. The Cost-benefit analysis has identified transportation and coal replacement costs as the major factors influencing economic viability.

Although the environmental and economic performances of biomining of landfill is case specific, the results of this study can be used as a benchmark for the feasibility analysis of future biomining projects considering circular economy and environmental sustainability.

Key words: Landfill biomining, RDF, good earth, life cycle assessment, cost benefit assessment, economic viability, environmental sustainability

LIST OF ABBREVIATIONS

C&D – Construction and Demolition

CBA – Cost-Benefit Analysis

CBR – California Bearing Ratio

CBR – California Bearing Ratio

CER – Carbon Emission Reduction

CO_2e – Carbon-di-Oxide Equivalent

CPCB – Central Pollution Control Board

CRR – Coal Combustion Residual

CTT – Cyclic Triaxial Test

CVM – Contingent Valuation Method

EC – Electrical Conductivity

GHG – Greenhouse Gas

GVW – Gross Vehicle Weight

GWP – Global Warming Potential

INR – Indian Rupee

IRR – Internal rate of Return

IS – Indian Standard

ISWM – Integrated Solid Waste Management

LCA – Life Cycle Assessment

LCCA – Life Cycle Cost Analysis

LFM – Landfill Minning

MCX – Multi Commodity Exchange

MDD – Maximum Dry Density

MoRTH - Ministry of Road Transport & Highways

MRIO – Multi-Regional Input-Output Analysis

MSW – Municipal Solid Waste

MT – Million Tons

NPV – Net Present Value

OMC – Optimum Moisture Content

PCU – Platinum-Cobalt Units

RCRA – Resource Conservation and Recovery Act

RDF – Refused Derived Fuel

SWM – Solid Waste Management

TERI – The Energy and Resources Institute

UNEP – United Nations Environment Programme

USD – United States Dollar

WTA – Willingness to Accept

XRF – X-ray Fluorescence Spectroscopy

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Chapter 1: Introduction

1.1. Motivation

In this modern era, the growing quantity and complexity of generated waste creates critical hazards for both ecosystems and human health. Every year, billion tonnes of solid waste is collected worldwide. Compared to those in developed nations, urban areas are more severely impacted by unsustainably managed waste. In low-income countries, more than 90% of waste is frequently disposed of in unregulated dumps or openly burned, leading to significant health, safety, and environmental consequences (The World Bank, 2022). Inadequately handled waste acts as a breeding ground for disease vectors.

The global waste generation has increased from 635 MT in 1965 to 1999 MT in 2015 and might reach up to 3539 MT by 2050. The current trends show continuous rise in waste production with unsustainable management methods, landfilling being the most dominating one (Chen et al. 2020). The present situation emphasis on 4R's technique, that is, reduce, reuse, recycle, and recovery. But these techniques may require more energy, labour, time, and people's acceptance. Most of the waste that generates cannot be reused, recycled, or treated and eventually ends at landfill (Parul Rawat et al. 2021). A typical landfill is shown in Figure 1. Therefore, to accommodate the untreated, nonrecycled waste either new landfill site should be constructed or existing site should be cleared to reutilize.

Figure 1: Landfill [Howrah,2023]

In developing countries, the accumulation of large quantities of waste in open dumps over the past tens of years has resulted in occupying vast areas of land and reaching heights as tall as 50 m or more (Manoj Datta et al. 2020). According to a report by The Energy and Resources Institute (TERI, 2022), India generates over 62 million tons (MT) of waste in a year. If cities continue to dump the waste at present rate without treatment, it will need 1240 hectares of land per year in India (CPCB, 2019). The maximum permissible limit for the height of a garbage dump in India is 20 m above ground level, which most of the landfills have already crossed, shown in Figure 2.

Figure 2: Height of Landfill more than 20m [Howrah, 2023]

In India, most of the landfills have exhausted their capacity and are serving beyond their operational life (Sharholy et al., 2008). These landfills are containing large amount of legacy waste as shown in Figure 3. From the landfills some obnoxious gases are coming out as like methane, carbon dioxide, nitrogen, oxygen, ammonia, sulphides, hydrogen and various other gases. The landfills generate highly pollutant leachate which contains heavy metals, xenobiotic, inorganic and organic substances.

[a] [b]

Figure 3: Legacy Waste [(a) - Durgapur, 2024; (b)-Howrah, 2023]

The Government of India has notified the Solid Waste Management Rules (SWM Rules, 2016) for proper and effective management of municipal solid waste (MSW). Numbers of provisions have been made to manage old dumps of MSW. According to SWM Rules, 2016, Bio-mining of existing landfill is mandatory to manage and reduce the legacy waste. A landfill needs to be at least 15 years old before planning mining activities (Joseph et al. 2008). Figure 4 shows an ongoing Bio-mining project. The main products of bio-mining after segregation are:

(a) Over sized stones, debris, and coarse gravel (>50 mm)

(b) Combustible material (plastic, textile, wood etc.)

(c) Recyclable material (metal, glass etc.)

(d) Good Earth (< 6 mm)

Because of this high amount of generation of bio-mining products, management of this has become a severe issue globally. Combustible materials such as plastics, textiles, wood, and coconut husks, which have high calorific values, are often used as refuse-derived fuel (RDF) as an alternative to fossil fuels like coal. In cement factories and brick kilns, where coal is typically used as fuel, RDF can be a viable alternative due to its high calorific value. On the other hand, approximately 40-50% of bio-mined waste is good earth. If this material meets the required geotechnical and physicochemical properties for subgrade material, it can be used in road construction. This would free up valuable landfill space, making it available for future use.

Figure 4: Biomining Project [Durgapur Landfill Site, February; 2024]

When evaluating a project's viability, it is crucial to consider both environmental sustainability and economic feasibility. Environmental sustainability is assessed using Life Cycle Assessment (LCA), which examines the project's overall environmental impacts. For economic viability, a cost-benefit analysis is employed to compare the project's total costs with the expected benefits, ensuring the project is financially feasible. Together, these tools help confirm that a project is both environmentally responsible and economically viable.

1.2. Objective of the Proposed Work

The objective of the proposed study is to conduct a Life Cycle Analysis (LCA) and a Cost-Benefit Analysis of using good earth as subgrade material for roads and Refuse-Derived Fuel (RDF) as an alternative to coal in cement factories and brick kilns to check the economic viability and environmental sustainability of biomining project. To show the suitability of the work, biomining operations of Howrah and Durgapur landfill sites, West Bengal are considered as case studies.

To do that, it is necessary to characterize the legacy waste collected from landfills, check the geotechnical properties of good earth and analyse the heavy metals present, estimate the operation cost of biomining projects, and estimate direct and environmental costs associated with the proposed strategy after identifying the potential benefits.

1.3. Scope of the Proposed Work

a) Sampling of biomined product from different landfill sites.

b) Compositional analysis of legacy waste.

c) Physicochemical characterization of legacy waste.

d) Checking of the geotechnical properties of good earth as subgrade material in roads in accordance with the Indian Standard Code IS 2720: "Methods of Test for Soils."

Properties include:

- Water content
- Specific gravity
- Sieve analysis
- Atterberg limits
- Compaction
- Permeability
- Shear strength
- California bearing ratio (CBR)

e) Identification and quantification of total and leachable heavy metal in good earth.

f) Identification and quantification of soluble salt in good earth.

g) Development of LCA model to evaluate the environmental sustainability associated to biomining of legacy waste.

- Feasibility analysis of landfill mining projects by cost-benefit analysis method considering utilization of RDF as fuel in cement factory and brick kiln and good earth as subgrade material of road. To do that-Total cost was estimated considering all types of tangible and intangible costs related with biomining of landfill.
- Different types of benefits associated with the biomining of landfill were identified and quantified.

1.4. Thesis Overview

The thesis comprises of five chapters organized as follows:

Chapter 1: Introduction

Within this chapter, the rising tide of waste generation and the increasing complexity of waste management was examined. Additionally, it explores potential sustainable solutions to address the pressing issues of landfilling of solid waste. Additionally, this chapter outlines the specific objectives and scope of the present work.

Chapter 2: Literature Review

This chapter provides a comprehensive discussion on the background, current state, and other pertinent aspects of various topics related to the proposed study. Furthermore, Chapter 2 presents a synthesis of both national and international literature relevant to this work. A brief overview of LCA has been discussed here. Moreover, it briefly outlines different cost and benefit components and their estimation methods.

Chapter 3: Methodology

This chapter provides a concise discussion on data collection, including the collection area, testing apparatus, and testing procedure. It also covers the software relevant to Life Cycle Assessment (LCA), encompassing databases and data calculation tools. Additionally, the chapter features a schematic diagram of the LCA model, an overview of Cost-Benefit Analysis to evaluate the project's economic viability, and a detailed representation of the entire methodology.

Chapter 4: Result and Discussion

This chapter discusses the test results concerning geotechnical properties, comparing them with existing literature values and accepted limits. Additionally, it presents the values and graphs derived from the impact analysis conducted through Life Cycle Assessment (LCA). Additionally, meticulous attention has been given to the execution of Cost-Benefit Analysis.

Chapter 5: Conclusion and Recommendation

In this chapter, a conclusion has been drawn based on both environmental and economic evaluations. Furthermore, essential recommendations for the successful implementation of the proposed strategy are outlined. Additionally, the chapter addresses the major challenges associated with the proposal of utilizing bio-mined products from the waste management system, along with discussing the future scope of this study.

Chapter 2: Literature Review

2.1. General

This chapter provides a concise overview of present scenario of generation, management, and legislation concerning municipal solid waste. It also explores the landfill biomining process and its impacts on the environment and society, as evaluated through Life Cycle Assessment (LCA). Additionally, it summarizes relevant literature related to the research topic and discusses different costs, along with a review of methods for estimating these costs.

2.2. Present Scenario of Generation of Solid Waste

The growing world population is causing negative impacts on the planet. The current model of production and consumption generates a lot of waste that, in many cases, does not get reused or recycled. A significant portion of this waste, often in the form of packaging and product containers, is crafted for one-time use only.

Each year, the world produces a staggering 2.01 billion tonnes of municipal solid waste, with at least 33 percent of this colossal amount being handled inadequately from an environmental standpoint. Projections indicate that global waste will surge to 3.40 billion tonnes by 2050, marking a 70% increase (The World Bank, February 2022).

As indicated by The World Bank (2022), high-income countries are projected to experience a daily per capita waste rise of 19%, whereas low- and middle-income nations are anticipated to see an even more pronounced increase of 40% or beyond.

The East Asia and Pacific region currently account for the largest share of global waste generation, contributing 23 percent, while the Middle East and North Africa region produces the least, at 6 percent (The World Bank, 2022). Despite this, the regions experiencing the most rapid growth are Sub-Saharan Africa, South Asia, and the Middle East and North Africa. By 2050, these areas are expected to witness staggering increases in waste generation, with total projected to more than triple, double, and double again, respectively, as illustrated in Figure 5. Alarmingly, in these regions, over half of the waste is presently openly dumped. The trajectories of waste growth in these regions carry significant implications for the environment, public health, and economic prosperity, thus requiring urgent action (The World Bank, 2022).

In the past two decades, European nations have increasingly shifted their focus from disposing of municipal solid waste to prioritizing prevention and recycling. Waste policies and targets set at the European Union (EU) level now include minimum requirements for managing specific waste types. In 2015, the European Commission proposed ambitious new targets for municipal solid waste, aiming for 60% recycling and preparation for reuse by 2025, and 65% by 2030. Over the period from 2004 to 2014, total municipal solid waste generation in European Economic Area (EEA) countries decreased by 3% in absolute terms, with the average generation per person dropping by 7%. In 2014, Denmark and Switzerland recorded the highest municipal solid waste generation per person, while Romania, Poland, and Serbia reported the lowest figures (European Environment Agency, 2015).

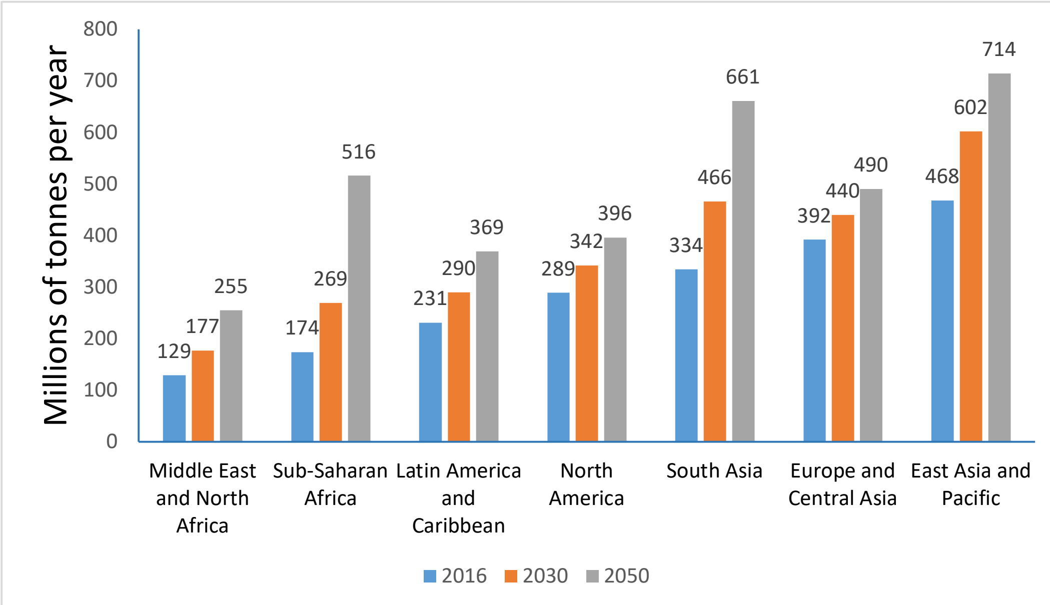


Figure 5: Projected solid waste generation, by Region (The World Bank, 2022).

India ranks among the top 10 countries globally in terms of municipal solid waste (MSW) generation. A report by The Energy and Resources Institute (TERI, 2022) indicates that India produces over 62 million tons (MT) of waste annually. However, only 43 MT of this total waste generated is collected, with 12 MT undergoing treatment before disposal, while the remaining 31 MT is simply discarded in waste yards. The insufficient infrastructure for waste collection, transportation, treatment, and disposal has emerged as a significant contributor to environmental degradation and public health issues in the country (The International Trade Administration; April, 2023).

According to a report in The Journal of Urban Management, the 62 million tons (MT) of waste generated annually in India comprises 7.9 MT of hazardous waste, 5.6 MT of plastic waste, 1.5 MT of E-waste, and 0.17 MT of biomedical waste (The Journal of Urban Management, December, 2021). These data are depicted in Figure 6 through a pie chart.

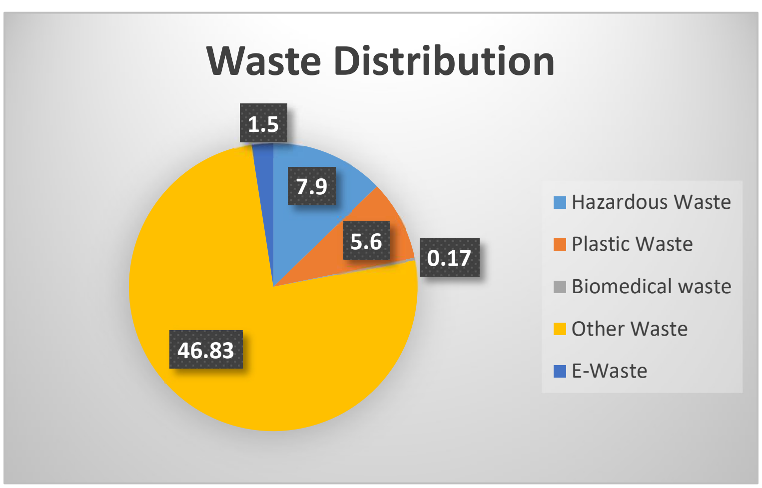


Figure 6: Waste Distribution in India [The Journal of Urban Management, December, 2021]

Indian Central Pollution Control Board (CPCB) has recently projected that annual waste generation in India will escalate to 165 MT by 2030 (The International Trade Administration; April, 2023). Per capita solid waste generation in India has been calculated for the six years spanning from 2015 to 2021. Figure 7 illustrates the trend in per capita waste generation over this period, showing a marginal decrease over the years (CPCB Annual Report, 2020-21).

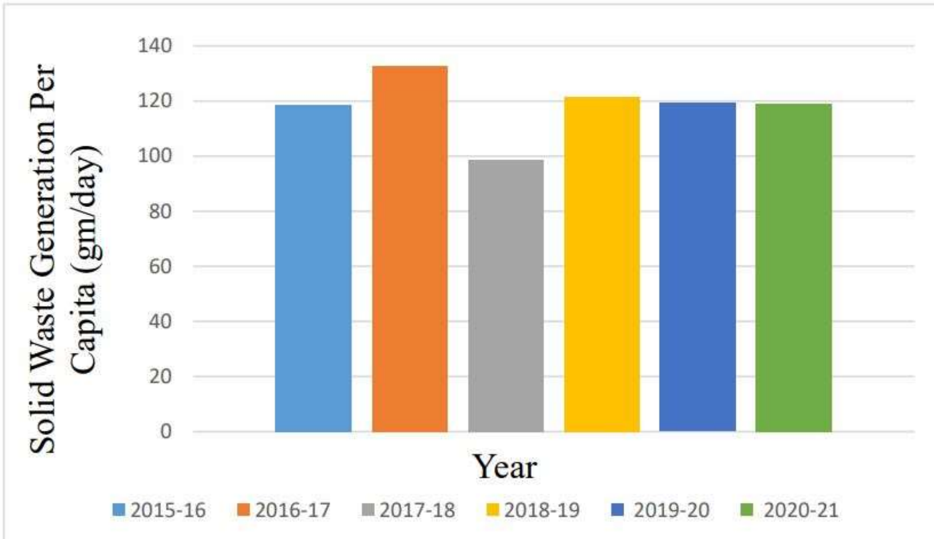


Figure 7: Solid waste generation per capita (CPCB Annual Report, 2020-21).

In India, the trend of the percentage of solid waste landfilled from 2015 to 2021 is shown in Figure 8. Specifically, solid waste landfilled has decreased from 54% to 18.4% in 2020-21 (CPCB Annual Report, 2020-21). The decline can be attributed to several key factors, including improved waste segregation, increased recycling efforts, growth in composting and waste-to-energy projects, more stringent regulations [Solid Waste Management Rules (SWM, 2016)], improved public awareness, and advancements in waste management technology.

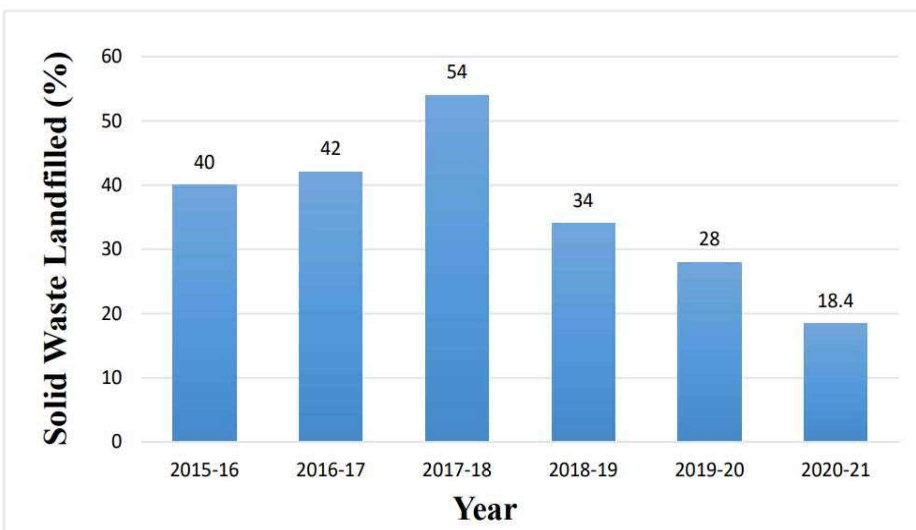


Figure 8: Solid waste landfilled (%) (CPCB Annual Report, 2020-21).

2.3. Integrated Solid Waste Management

Integrated Solid Waste Management (ISWM) is a comprehensive program designed to address waste prevention, recycling, composting, waste to energy and disposal. An ISWM system prioritizes methods that safeguard human health and the environment by minimizing waste generation and maximizing resource recovery. Key components of ISWM include waste prevention, recycling, composting and waste to energy, as well as the safe disposal of waste in properly engineered and managed landfills. By integrating these practices, ISWM aims to efficiently manage solid waste while minimizing environmental impact (United States Environmental Protection Agency, 2002).

The Integrated Solid Waste Management (ISWM) hierarchy is designed to evaluate the entire waste management process with the aim of ensuring sustainability from both environmental and economic perspectives. The Integrated solid waste management hierarchy is shown in Figure 9.

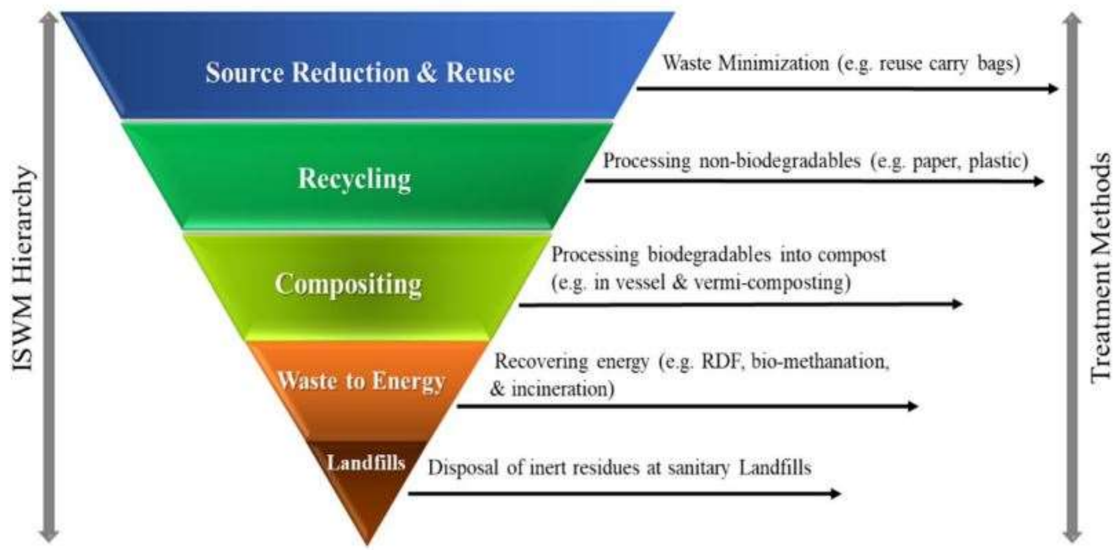


Figure 9: Integrated Solid Waste Management Hierarchy (Jasir Mushtaq et al., 2020)

The primary collection methods for solid waste are different for developed and developing countries:

Primary collection methods for developing countries are:

1. Door to Door
2. Community Bin
3. Private Bin

Primary collection methods for developed countries are:

1. Set-out Setback Collection
2. Set-out Collection
3. Curb Collection
4. Block Collection

The inadequate handling of waste, combined with unregulated dumping practices, can result in various detrimental consequences. These include contaminating water sources, attracting pests like rodents and insects, and escalating flood risks by obstructing drainage systems. Moreover, it can pose safety hazards such as explosions and fires. Additionally, improper solid waste management exacerbates greenhouse gas (GHG) emissions mainly CH_4 and CO_2, exacerbating climate change (Liveabout.com, Rick LeBlanc, 2019). The concept of integrated solid waste management is visually represented through a flow chart in the Figure 10.

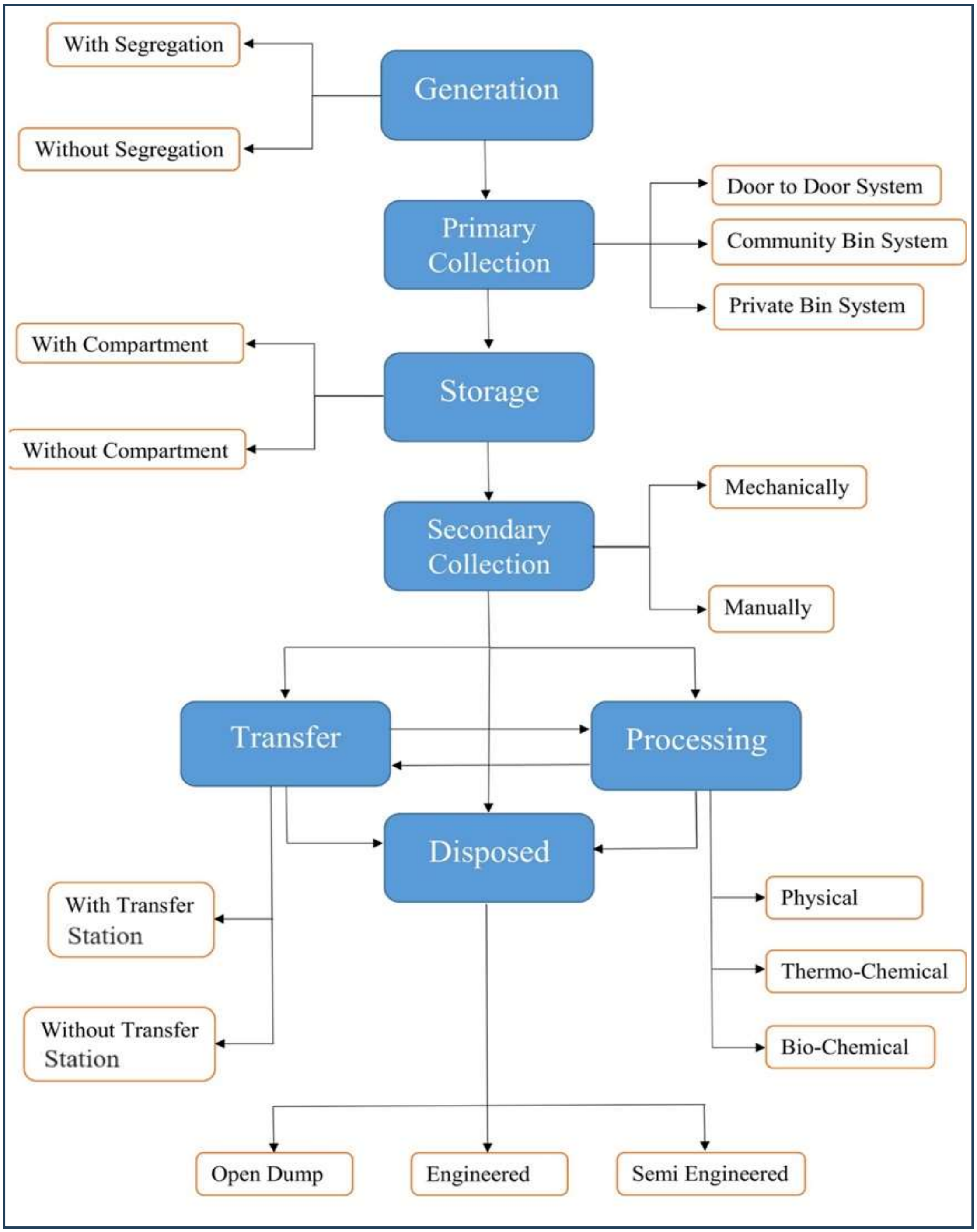


Figure 10: Flow Chart of ISWM

2.4. Different Types of Landfills

Modern landfills are carefully designed and managed places where solid waste is disposed of safely. They are strategically located, meticulously designed, and closely monitored to ensure adherence to federal regulations. Their primary aim is to safeguard the environment from any potential contaminants within the waste stream. Site selection avoids environmentally sensitive areas. Under the Resource Conservation and Recovery Act (RCRA), modern landfills are mandated to satisfy stringent criteria concerning their design, operation, and closure procedures (EPA, 2024).

Presently, there exist three primary landfill categories:

1. Municipal solid waste landfill
2. Industrial waste landfill
3. Hazardous waste landfill

Each type is designed to handle specific kinds of waste and implements different measures to minimize environmental impact. Additionally, there is a growing category known as green waste landfills, which specialize in the controlled disposal of organic materials.

Before analysing each landfill type individually, it's essential to provide an overview of the primary method of waste management. The three main methods of waste management are:

1. Open dumps
2. Engineered landfills
3. Incineration

Engineered landfills and incineration inhibit reuse, recycling, and natural decomposition. Open dumps allow for better decomposition compared to other methods and enable salvaging or recycling of discarded materials. However, open dumps also contribute to the spread of diseases, water and soil pollution due to migration of leachate and emission of GHGs, resulting illegal in many countries (Melissa Ha and Rachel Schleiger,2021).

2.4.1. Open Dumps

Open dumps represent the oldest and most widespread method of solid waste disposal. While thousands have been shut down in recent years, many are still in operation. Often, they are situated wherever land is accessible, with little consideration for safety, health hazards, or aesthetic concerns. Some sites allow the refuse to be ignited and left to burn, while others undergo periodic levelling and compaction (Sabahi et al. 2009).

Approximately 40 percent of the world's waste is deposited in open dumpsites, particularly in urban areas of middle and lower-income countries where proper waste collection systems are lacking. For instance, many African cities openly dump up to 90 percent of their waste, while in the region of Latin America and the Caribbean, the figure is around 45 percent (UNEP, 2021).

In India, the majority of waste, about 54 percent, is disposed of in open dumps (Bhargavi et al. 2020). Figure 11 provides a visual representation of open dumpsites.

Figure 11: Visual representation of Open Dumpsite (UNEP, 2021)

2.4.2. Engineered Landfills

An engineered landfill is essentially a pit lined at the bottom to prevent waste and other forms of trash from seeping into the ground. Waste is buried in layers, increasing stability and compactness. Engineered landfills serve to isolate waste from the environment, ensuring safety. Waste is considered safe only after undergoing complete biological, chemical, and physical degradation (Ayesha et al. 2022). The level of waste isolation in engineered landfills varies depending on the classification of economies. In high-income economies, the level of isolation is typically very high (Ziraba et al. 2016).

In India, about 23 percent of waste is disposed of in engineered landfill (Bhargavi et al. 2020).

2.4.3. Incineration

Waste incineration is the process of converting biomass into electricity. In this process, the organic fraction of municipal solid waste (MSW) is the primary feedstock, which is combusted with excess oxygen in a furnace or boiler under high pressure. The resulting hot combusted gas contains nitrogen, carbon dioxide, water, oxygen, and non-combustible residues. This hot flue gas then enters a heat exchanger, where it produces steam from water. The steam generated is used to drive a steam turbine through the Rankine cycle, thereby generating electricity (Bhargavi et al. 2020). However, biomass requires prior preparation and processing, such as pre-drying to reduce its high moisture content before it enters the combustion chamber for combustion with air. The incineration process typically requires temperatures ranging between 850 and 1100°C (Tan et al., 2015).

In Singapore, incineration reduces waste volume by up to 90 percent, effectively conserving landfill space and the heat produced during incineration is recovered to generate electricity, contributing to up to 3 percent of Singapore's electricity needs (Solid Waste Management in Singapore, 2019).

2.4.4. Municipal Solid Waste Landfill

A municipal solid waste landfill is a designated area where household waste, as well as other types of non-hazardous waste are disposed of. These landfills are engineered facilities that are designed to minimize environmental impact and protect public health. They typically involve compacting waste and covering it with layers of soil or other materials to reduce odours and minimize the risk of groundwater and surface water contamination due to migration of leachate. Proper management of municipal solid waste landfills is essential to minimize pollution and protect the surrounding environment. Municipal solid waste landfills are different types, like Bioreactor Landfills, Engineered Landfills, Sanitary Landfills etc.

Engineered landfills are structured to hold solid waste in a controlled manner, mitigating environmental impacts for an extended duration (Przydatek and Kanownik, 2019). Bioreactor landfills, equipped with effective liners, leachate extraction, and recirculation systems, prioritize microbial waste breakdown while minimizing environmental harm (Sackey et al., 2020).

2.4.5. Industrial Waste Landfill

Manufacturing processes generate a significant volume of waste, predominantly solid waste, are disposed directed to industrial landfills. Some different types of Industrial Waste Landfills are discussed below.

2.4.5.1. Construction and Demolition (C&D) Debris Landfill

A Construction and Demolition (C&D) Debris Landfill is a specialized industrial waste landfill, specifically for the disposal of construction and demolition materials. These materials encompass the debris produced during the building, renovation, and dismantling of structures like buildings, roads, and bridges (EPA, 2024).

2.4.5.2. Coal Combustion Residual (CRR) Landfill

An industrial waste landfill utilized for the management and disposal of coal combustion residuals (CCRs), commonly referred to as coal ash. The EPA has established specific requirements governing the disposal of coal combustion residuals (CCRs) in landfills (Federal Register, April 17, 2015).

2.4.6. Hazardous Waste Landfill

These landfills are used exclusively for the disposal of hazardous waste. Municipal solid wastes are not disposed into these landfills. As per Environmental protection agency (November, 2023), design standards for hazardous waste landfills require:

- Double leachate collection and removal systems
- Double liner
- Leak detection system
- Construction quality assurance program
- Run on, runoff, and wind dispersal controls

2.5. Biomining

2.5.1. Introduction

Biomining is rapidly becoming a crucial aspect of waste management. In biomining operations, various materials like metals, plastics, glass, combustibles, soil, and other fine substances are extracted from older landfill sites. The goal of this process is to extract reusable or recyclable materials from landfills, which can then be collected for future use. This practice serves a dual purpose: effectively managing waste and clearing open dumpsites. It involves segregation of the existing waste into different components and transforming the biodegradable portion into compost, methane gas, or biodiesel. Non-recyclable plastics are converted into refused-derived fuels, providing an alternative fuel source for industries. Furthermore, compostable waste undergoes separation through sieving and is then sold as soil enrichers/fertilizers or for landscaping applications (S. Mohan and Charles P. Joseph,2020).

Mining activities in a landfill are typically scheduled only after the landfill has reached a minimum age of 15 years (Joseph et al., 2008). The rising need for bio-mining concepts can be attributed to several major factors. These include the urgent need to reduce greenhouse gas emissions, the necessity to prevent contamination of surface water and groundwater caused by unlined open dumps, and the desire to minimize the footprint of landfills, thereby enhancing land value and reducing associated economic costs (S. Mohan and Charles P. Joseph,2020).

The first landfill mining process was started at Hiriya landfill, Israel in 1953. The primary objective was to obtain fertilizers for orchards (Parrodi et al., 2018). Over the past 30 years, more than 60 landfill mining projects have been undertaken worldwide (Zhou et al., 2015). By the late 1980s, numerous biominng projects, especially in the United States, were undertaken to remediate sources of groundwater pollution (Lee et al., 1990). The Hiriya Landfill is shown in Figure 12.

Figure 12: The Hiriya Landfill

2.5.2. Biomining In India

Waste management in India is regulated by the Union Ministry of Environment, Forests, and Climate Change (MoEFCC). In 2016, the ministry released the Solid Waste Management (SWM) Rules, which replaced the Municipal Solid Waste (Management and Handling) Rules of 2000, which had been in effect for 16 years. This national policy represents a crucial step by formally recognizing and integrating the informal sector, such as waste pickers, into the waste management framework for the first time (The Solid Waste Management Rules, 2016).

The Solid Waste Management Rules of 2016 in India mandate the investigation and analysis of all existing and operational dumpsites to assess their potential and feasibility for bioremediation, reclamation, and biomining. Subsequently, appropriate actions are to be taken to either initiate biomining processes or remediate the dumpsites as necessary (MoEFCC, 2016).

On average, approximately 70% of the solid waste produced in the South Asian region consists of biodegradable organic matter with a high moisture content (Government of Australia, AID Programme, 2012). The Central Pollution Control Board (CPCB), in collaboration with the National Environmental Engineering Research Institute (NEERI), conducted a survey of solid waste across 59 cities. The survey revealed that the predominant fraction (40 - 60%) of municipal solid waste is biodegradable (Gupta et al., 2015). This presents an opportunity to implement composting or energy recovery processes to manage this waste effectively.

In India, the first biomining experiment was conducted in Panchvati, Nashik City, Maharashtra, during 2002-2003. This biomining initiative successfully cleared an average depth of 4 to 7 meters of garbage spread across 28 acres within 120 days, at an estimated cost of about INR 6.4 million (Mohanand and Charles, 2018). The world's largest biomining project is at the Mulund dumping ground in Mumbai. This project aimed to reclaim 24 hectares of land and involves the biomining of approximately 7 million tonnes of solid waste (The Indian Express, 2018).

In India, an increasing trend in the percentage of solid waste processed has been observed over the past years. The percentage of solid waste treated has risen from 19% in 2015-16 to 49.96% in 2020-21, shown in Figure 13 (CPCB Annual Report, 2021).

Figure 13: Solid Waste Treated (%) (CPCB Annual Report, 2021).

2.5.3. Biomining Process

The primary aim of biomining is to efficiently extract materials and process them in a manner that allows for the separation of target materials from the excavated mass. These materials can then be further refined to meet the necessary grade for reuse or recycling purposes (S Mohan et al., 2020). A flow chart of biomining process is shown in Figure 14.

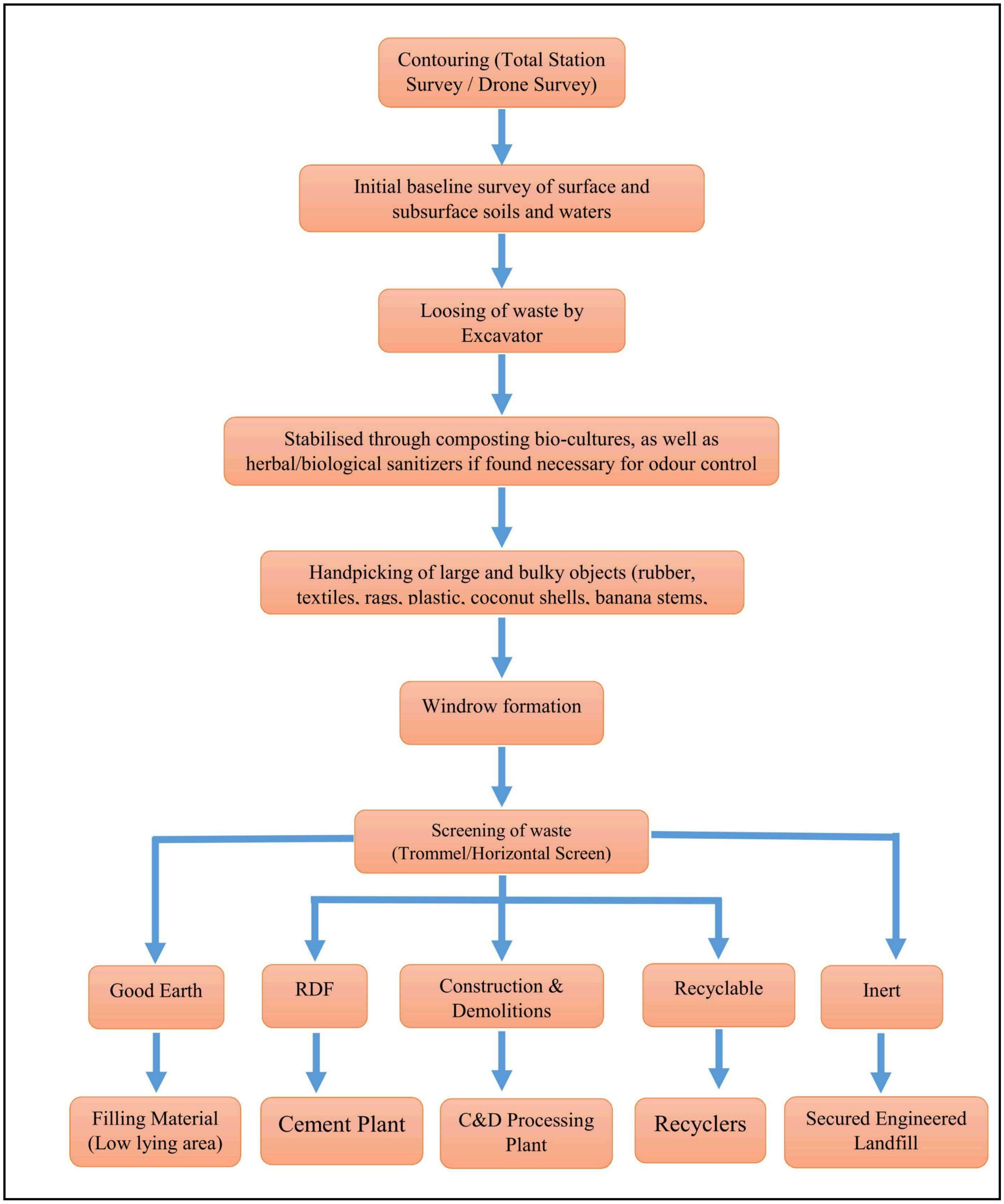


Figure 14: Flow Chart of Biomining Process (CPCB, February, 2019).

2.5.4. Composition of the Excavated Waste

Within landfill mining studies, waste characterisation is the most important. The majority of characterization studies primarily involve screening waste based on size and the next step typically involves the manual or mechanical separation of coarse particles into various categories, such as plastic, paper, textile, wood, metal, glass, and inert materials. According to Prechthai et al. (2008), the waste contained a significant concentration of fine fraction (19–39%) and plastic (35–51%). Similarly, Rong et al. (2017) also observed substantial concentrations of fine fraction, plastic, and stone, accounting for 52.4%, 13.9%, and 13.2%, respectively.

Physicochemical characteristics play a vital role in assessing the feasibility of landfill mining projects. For instance, determining the bulk density is a key parameter of recovery and recycling facility. Similarly, the moisture content of excavated waste is crucial for determining the valorisation route (whether thermal, recycling, or biological treatment), and it depends on various factors such as location, climatic conditions, age, leachate generation, and waste type (Ayush Singh and Munish K. Chandel, 2019). Composition of the excavated wastes of different countries is presented in Table 1.

Table 1: Composition of the excavated waste

	Europe	Thailand	China	Estonia	Finland	India	
	Hogland et al., 2004	Prechthai et al., 2008	Rong et al. 2017	Bhatnagar et al., 2017	Kaartinen et al., 2013	Kurian et al., 2003	Singh et al., 2019
Age (Years)	23-25	3-5	----	10	----	10	8-10
Plastic(%)	2.13	29.66	9.30	22.40	23.00	2.40	12.70
Paper/Cardboard (%)	2.27	3.33	1.80	5.10	7.50	----	0.05
Metal(%)	1.41	6.42	2.50	3.10	2.30	0.10	0.38
Glass(%)	0.93	6.51	7.20	4.60	----	0.40	1.19
Textile(%)	0.00	7.64	0.70	----	7.30	0.60	0.95
Wood(%)	1.96	7.97	----	4.70	7.10	0.50	3.04
Stone(%)	19.10	3.27	8.40	17.50	----	28.30	29.73
Others(%)	0.23	----	----	13.40	1.50	28	2.44
Fine fraction(%)	71.30	33.81	70.10	54.00	43.00	67.80	49.53

According to Table 1, the percentages of fine fraction and stone are higher in excavated wastes of every countries presented. The table also shows that Europe And China produce more fine fraction than India. It is possible because they use higher size sieve (Table 2) to segregate waste compare to India. From study of the literature found that the major concentration of biomined material is made up of fine fraction in India (Figure 15). According to Kurian et al., 2003 and Singh et al.,2019, the percentage of fine fraction is 67.80% and 49.53% respectively for India.

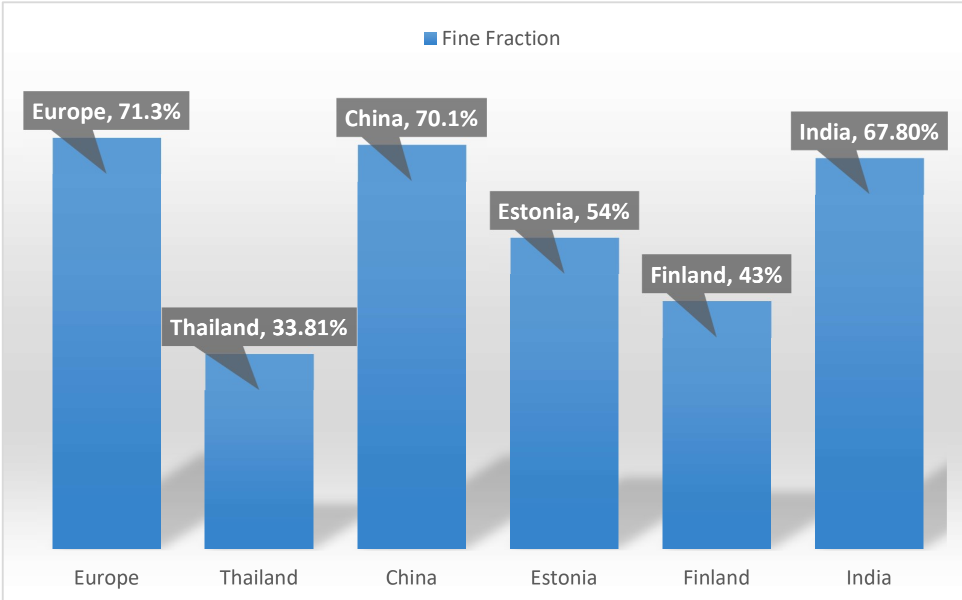


Figure 15: Percentage of Fine Fraction in Various Country

There is no proper size limit for defining the fine fraction and it is usually defined based on the size of screens adopted by different researchers (Table 2).

Table 2: Size of screens adopted by different researchers

Reference	Sieve Size (mm)
Hogland et al., 2004	18
Prechthai et al., 2008	25
Kaartinen et al., 2013	20
Bhatnagar et al., 2017	10
Rong et al., 2017	5
Kurian et al., 2003	20
Singh et al., 2019	4
Dutta et al., 2020	4.75

2.5.5. Biomining Products

In the earliest project of biomining cited in literature, the primary aim was to obtain compost materials intended for agricultural applications (Savage et al., 1993). In general, the organic fraction of municipal solid waste is composted, while the residual material from the pre-sorting operation is processed further to produce refuse derived fuel (RDF). Refuse derived fuel (RDF) has emerged as a valuable, energy-rich resource and it is one of the promising contenders to meet the demands of major fuel-consuming industries (Atun et al., 2022).

In India the fine fraction (less than 4.75 mm in size) is considered as Good Earth.The good earth can be used in the geotechnical field, as a backfill material or even as a construction material for brick manufacturing if its physicochemical parameters are within the allowable limits. The presence of high levels of organic matter, heavy metals, and soluble salts indicate that the Good Earth requires treatment before off-site re-use or that specific design measures are must before placing it as earth-fill in embankments, low-lying areas, and deep pits (Datta et al.,2020).

As per CPCB, the biomining products are:

- Refused Derived Fuel (RDF)
- Construction and Demolitions (C&D) waste
- Recyclable component
- Good Earth
- Inert materials

2.5.6. Machinery Used in Biomining Process

In the biomining process, waste excavation often involves the use of machinery like front-end loaders, backhoes, clamshells excavators, hydraulic excavators, or a combination of these (S Mohan et al., 2020). After excavation, trommel screens are commonly employed for screening purposes (Datta et al.,2020). In some cases, Powerscreens are used for high-capacity screening purposes. Some machineries used in biomining project are shown in Figure 16.

(a) (b)

(c)

Figure 16: [(a) - Hydraulic excavator (Howrah, October 2023); (b) - Trommel Screen (Howrah, October, 2023); (c) - Power screen (Durgapur, September, 2023)]

2.5.7. Existing Literature Related to the use of Biomining Products

Various research works have been undertaken to find the potential use of byproducts of biomining process. A few notable research works along with their findings related to use of biproducts of biomining process are presented below. The research works are classified in two groups. Some foreign research works along with their key findings are shown in Table 3.

Table 3: Foreign Research Works on Products is Getting from Biomining

Country	Key Findings	Suggested use of legacy waste	References
Finland	Mined from two Finnish municipal solid waste (MSW) landfills, in new landfill (1-to10-year-old) the FF (<20 mm) was on average 45 ± 7% of the content of landfill and in old landfill (24- to 40-year-old) 58 ± 11%. Sieving showed that 86.5 ± 5.7% of the FF was smaller than 11.2 mm and the fraction resembled soil. The total solids (TS) content was 46–82%, being lower in the bottom layers compared to the middle layers.	FF reuse as material or energy.	Tiina J. Mönkäre et al., 2015
Germany	Concept of enhanced landfill mining (ELFM) broadens conventional landfill mining (LFM) through a comprehensive processing of the various waste streams, using innovative technologies to recover as much resources and energy as possible while meeting ecological and social criteria. ELFM can be seen as an opportunity for industrial nations to secure raw material access and reduce import dependency by mining their own anthropogenic deposits.	Metals, high calorific fractions such as impure plastics, textiles and wood for the production of refuse derived fuels (RDF), and fine fractions such as recycling sand or gravel that can be used as construction material.	Karsten Kieckhäfer et al., 2016
China	Fine particles (70.1%), Plastics (13.9%), Stone (13.2%), Glass (8.2%). Fine particles are not suitable for agricultural purposes.	Resource recovery	Rong et al., 2017

Country	Key Findings	Suggested use of legacy waste	References
Sweden	5% metal and 65% was categorized as an indeterminate soil fraction.	Soil fraction is used as a covering material. Methane gas production	Hogland et al., 2004
Germany	Three main waste fluxes are obtained: Dense inert and dense fine fraction with a high content of minerals and a lightweight fraction with a high calorific value between 16 and 20 MJ/kg. An additional positive effect of wet mechanical treatment is the removal of the finest particles from the surface of the waste material, thus increasing the quality of the generated waste fluxes.	Fine material is redeposited on landfills, without any treatment.	Sebastian Wanka et al., 2016
Thailand	The soil fraction constituted 69% of the waste, with the remaining 31% primarily composed of plastics, indicating significant potential for recycling as refuse-derived fuel (RDF).	Used as RDF	Prechthai et al., 2008
Belgium	Soil-type material varied between (34-60) %, Inert (10-17) %, Combustible materials ranged from (21-50) %, Metal content ranging between (3-6) %	Used as construction material, Combustible material used as waste to energy.	Quaghebeur et al., 2012
Germany	With regard to contamination prediction, sulphate, pH and total organic carbon proved to be the most efficient indicator elements. Legal limit values have demonstrated effectiveness in managing substance flows such as chloride, sulphate, cadmium, lead, and zinc. However, they have proven ineffective in addressing biodegradability, PCB, benzo[a]pyrene, and cyanides.	Landfilling material.	Ingo Hölzle., 2018
Sweden	Soil-type materials (27.3%) Stones, asphalt etc. (36.1%) Wood (15.2%)	Metal extraction, waste to energy	Jani et al., 2016

Country	Key Findings	Suggested use of legacy waste	References
	Zinc, copper, barium and chromium were found in high concentrations.		
Japan	Most of the heavy metals are present as salts with low solubility, such as carbonates, sulphate and hydroxides, or they are adsorbed onto soil particles. Landfills in Japan mainly consist of incinerator ash. The temperatures in landfills often exceed 50 degree Celsius.	Use as landfilling material after separate of electrical and electronic waste.	Kazuo Kamura et al., 2019
China	New biomass fly ash-based binder (BB) containing biomass fly ash (BFA), carbide slag (CS), and phosphogypsum (PG) is designed to solidify the SLMs. Tests conducted on paste samples have determined that the ideal proportion of ternary BBs consists of 80% BFA, 15% CS, and 5% PG. The optimum ratio of the ternary BBs was determined by the compressive strength, which was 15.362 MPa at 28 days.	SLM from landfill mining as engineering backfill material after S/S (solidification / Stabilization) treatment was analysed and evaluated at multiple scales.	Zhifa Qin et al., 2023

Some Indian research works along with their key findings on byproducts of biomined waste are shown in Table 4.

Table 4: Indian Research Works on Products obtained from Biomining Process

Country	Key Findings	Suggested use of legacy waste	References
India (Mumbai)	Particle size above 80 mm was mostly plastic and textile, whereas <4 mm (Fine fraction) composed of soil-like material. Approximately 45% of waste was fine fraction. Metal content in the dumpsite was less than 1%. Heavy metals (cadmium, chromium, copper, nickel and lead) in the excavated waste	Combustible fraction is use for generating refuse-derived fuel [RDF].	Ayush Singh and Munish K. Chandel., 2019

	depicts increment with age except for zinc. Combustible fraction was 11–28%.		
India (Delhi, Hyderabad, Kadapa)	Examines the feasibility of using the soil-like material (SLM), less than 4.75 mm size recovered by the mining of old waste from four municipal solid waste dumps of India. This material constitutes 60−70% of the total excavated waste. The contamination levels of SLM for re-use as earth-fills were analysed on the basis of heavy metals, organic content, soluble salts, and release of dark coloured leachate. The presence of high levels of organic matter, heavy metals, and soluble salts indicate that the SLM requires treatment before off-site re-use.	Use as an earth-fill for embankments, low-lying areas, deep pits and as compost for horticulture, agricultural applications.	Manoj Datta et al., 2020
India (Hyderabad)	SLM is non-plastic with low specific gravity due to presence of organic material. The strength properties are found to be satisfactory, and permeability is similar to that of local soil. From the laboratory test results, it is found that the SLM is not hazardous. It is not similar to local soil. It is not inert.	Used in shallow earth-fills for raising low-lying areas for landscaping. It can be used as large area surface application for re-vegetation, soil conditioning and eco-forestry.	Mohammed Najamuddin et al., 2021
India (Varanasi)	Particle size less than 4.75 mm, which is almost 60% of the dry waste. The study includes sensitivity analysis of different parameters (confining pressure, relative compaction, loading frequency, and shear strain amplitude) on the dynamic shear modulus and damping ratio of the MSW fine fractions for which 44 CTTs (Cyclic triaxial test) were performed. The utilization of these MSW fine fractions in seismic-prone regions demand the dynamic characterization of the material	The material was compared with the similar kind of noncohesive soil, so that it can be used as a replacement of soil in various geotechnical applications (embankment/backfill materials).	Parul Rawat et al., 2021

	under dynamic loading conditions before its application in the field.		
India (Nagpur)	High organic fraction (77%), with plastics comprising (11.60%), (7.66%) paper and others making up the total content.	Inert materials are used in Civil Engineering works.	Mandpe et al., 2019
India (South India)	The SLM was in the range of 38-78 %. The nutrient level of SLM comprising 1.1% TN, 0.5% TP, and 0.8% TK readily supports the reuse potential as compost material, but uptake of heavy metal by vegetation should be seriously considered. The required concentration of TOC was found to be less than 0.4% in SLM.	SLM could be recommended for bulk reuse in smaller depths and larger open regions such as lightly loaded elements, including rural roads.	Deendayal Rathod et al., 2022
India (Kolkata)	Approximately 40% constituted soil-like material, while 30.3% non-combustible construction and demolition (C&D) waste, inert. About 7.3% was composed of combustible material, with the remainder being residual waste.	Used in low-lying areas for purposes such as filling basement/plinth structures and as bedding material for road construction.	Bir et al., 2022
India (Chennai)	Levels of certain heavy metals like Chromium (Cr), Copper (Cu), Mercury (Hg), Nickel (Ni), and Lead (Pb) exceed the limits set by the Indian Standard regulations. The soil fraction extracted from landfills ranges from 40% to 68%.	After checking the geotechnical properties used as cover material.	Kurian et al., 2003

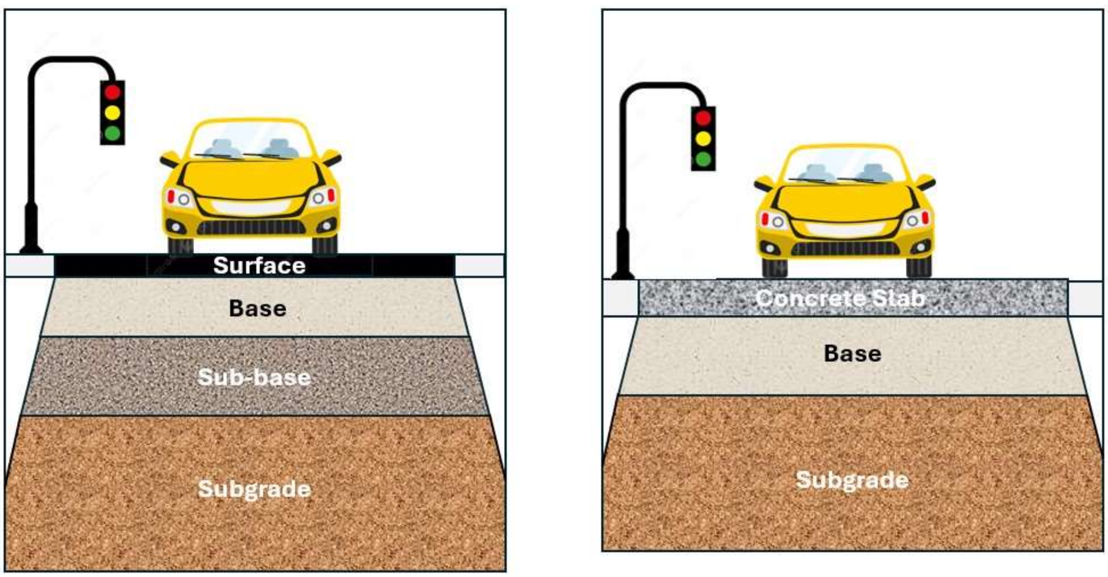
From the existing literatures of using products obtained from bio-mining process, following conclusions can be drawn-

- High calorific fractions such as impure plastics, textiles and wood can be used for the production of refuse derived fuels (RDF).
- Fine fractions such as recycled sand or gravel can be used as construction material.
- Fine fraction can be used as subgrade material in roads.
- Fine fraction can be used as large area surface application for re-vegetation, soil conditioning and eco-forestry.

2.6. Pavement Design of Roads

The surface of the roadway must be stable and non-yielding to support the heavy wheel loads of road traffic while minimizing rolling resistance (Kumar et al., 2017). Additionally, the road surface should be even along the longitudinal profile to ensure that vehicles can travel safely and comfortably at the design speed (Highway Research Board, 2003). The primary objective of a well-designed and constructed pavement is to maintain elastic deformation within permissible limits, allowing the pavement to withstand a large number of repeated load applications throughout its design life (Yoder & Witczak, 1975). Pavements are generally classified into two categories: flexible pavements and rigid pavements (Kumar et al., 2017).

- **Flexible Pavement**: This type of pavement, characterized by low flexural strength, transmits loads to the underlying layers through grain-to-grain transfer. According to IRC-37:2012, a typical flexible pavement comprises four layers: the surface course, base course, subbase course, and soil subgrade (Figure 17).
- **Rigid Pavement**: Rigid pavements have significant flexural strength and distribute wheel load stresses over a broader area through slab action. As defined by IRC-58:2012, rigid pavements consist of three layers: the cement concrete slab, base course, and soil subgrade (Figure 17).



Flexible Pavement **Rigid Pavement**

Figure 17: Components of Flexible & Rigid Pavement

2.6.1. Soil Subgrade

The soil subgrade is the natural soil layer that supports the pavement and bears the load transferred from the pavement structure. To ensure proper support, the subgrade soil must be compacted to a minimum depth of 50 cm at optimum moisture content and maximum dry density (Indian Road Congress, 2012).

2.6.2. Types of Subgrades

• IRC Classification

IRC:SP:72 - This is a standard practice guide by the Indian Roads Congress for the design of flexible pavements. It categorizes subgrade soils based on their California Bearing Ratio (CBR) values.

- **Class A:** High-quality subgrades with CBR values of 10% or more. Suitable for use with minimal or no treatment.
- **Class B:** Intermediate quality subgrades with CBR values ranging from 5% to 10%. May require some improvement or stabilization.
- **Class C:** Poor-quality subgrades with CBR values less than 5%. Generally it requires significant treatment or stabilization.

• MoRTH Classification

MoRTH, 2013 - These specifications include a more detailed classification of subgrade materials based on their physical and mechanical properties.

- **Granular Soils:** Coarse-grained soils with good drainage properties, such as gravel and coarse sand.
- **Cohesive Soils:** Fine-grained soils like clay and silt, which can have low permeability and higher compressibility.
- **Mixed Soils:** Soils that combine both granular and cohesive characteristics.

2.6.3. Function of Subgrade

As per Youn Su Jung et al., (2009), the soil subgrade performs several critical functions essential to pavement performance. It provides load support by transferring and distributing loads from the pavement structure to the underlying soil, which helps to prevent localized failures. Additionally, the subgrade ensures foundation stability by offering a stable base for the pavement, thereby minimizing differential settlement and maintaining structural integrity. Moreover, it plays a vital role in drainage by facilitating effective water management, allowing water to pass through or away from the pavement layers and thereby reducing moisture-related issues that could compromise the pavement's durability.

2.6.4. Design Properties of Subgrade

Key design properties of the subgrade include:

- **Soil Classification:** Soil is classified based on particle size distribution, plasticity, and compaction characteristics, which influence its load-bearing capacity (IRC:SP:72-2012).
- **Compaction:** Achieving the required dry density and moisture content through proper compaction is essential for ensuring subgrade stability and performance (IS 2720, 1980).
- **Shear Strength:** The subgrade's ability to resist shear forces is assessed using parameters like the California Bearing Ratio (CBR) (IRC:37-2012).
- **Drainage Characteristics:** Soil permeability affects water management and subgrade stability, which are critical for maintaining pavement performance (IS 2720, 1986).

2.7. Life Cycle Assessment

2.7.1. Introduction

Life cycle assessment (LCA) is one of the most common methodologies for measuring sustainability of a product. It involves a systematic analysis of the environmental impact throughout the entire life cycle of a product. According to ISO (14040: 2006), the term "product" includes both goods and services.

LCA includes everything from the acquisition of raw materials, through the production and utilization phases, to waste management practices (ISO, 14040: 2006). The waste management phase involves both disposal and recycling.

LCA generated significant interest during the 1990s. During that period, there was high expectations from LCA, but its results were frequently subjected to criticism. Comprehensive guidelines, like the ILCD Handbook (European Commission, 2011), and ISO standards (14040: 2006 & 14044: 2006), have been established to assist users in conducting LCAs effectively. Currently, there are over 50 models available to aid practitioners in their LCA projects, as highlighted by EPLCA (2013) (Hilty et al., 2014).

Several international initiatives are currently underway to facilitate consensus-building and provide recommendations. These include the Life Cycle Initiative led by the United Nations Environment Program (UNEP) and the Society of Environmental Toxicology and Chemistry (SETAC; UNEP, 2002), the European Platform for LCA initiated by the European Commission (2008), and the developing International Reference Life Cycle Data System (ILCD) (Goran Finnveden et al., 2009).

2.7.2. LCA Models

In Life Cycle Assessment (LCA), several different models are commonly used to assess the environmental impacts of products or processes. These models include:

2.7.2.1. Cradle-to-gate

A cradle-to-gate Life Cycle Assessment (LCA) provides a comprehensive analysis of a product's environmental impact from the initial acquisition of raw materials (the cradle) to the point when it is completed and leaves the factory (the gate). This approach focuses exclusively on the manufacturing phase of a product's life cycle, excluding considerations of its use and disposal (https://ecochain.com/blog/life-cycle-assessment-lca-guide/).

2.7.2.2. Cradle-to-cradle

Cradle-to-gate LCA focuses primarily on analysing a product's environmental impacts throughout its manufacturing phase. In contrast, cradle-to-cradle represents a broader design philosophy that views products as integral parts of a continuous cycle, inspired by natural ecosystems.

2.7.2.3. Gate-to-gate

Gate-to-gate considers the inputs and outputs of a particular operation, typically from one "gate" (the entry point or start of the process) to another "gate" (the exit point or end of the process). It focuses on resource use, emissions, and waste generation, offering insights for improving efficiency and reducing environmental impact in production or manufacturing processes.

2.7.2.4. Well-To-Wheel

Well-to-wheel is used in Life Cycle Assessment (LCA) to evaluate the environmental impacts associated with transport fuels and vehicles. This approach includes two main stages: "well-to-tank," which covers the extraction, processing, and transportation of fuels to filling stations, and "tank-to-wheels," which assesses emissions and energy use during vehicle operation (https://ecochain.com/blog/life-cycle-assessment-lca-guide/).

2.7.3. LCA Phases

According to ISO 14040 and ISO 14044: 2006, LCA has four different phases (Figure 18). The phases are described below.

2.7.3.1. Goal and scope

The ISO LCA Standard mandates that a series of parameters, often termed as study design parameters (SPDs), be expressed both quantitatively and qualitatively. The two primary SPDs for an LCA are the Goal and Scope, which must be clearly articulated. It's advisable for a study to employ the specific keywords outlined in the Standard when documenting these particulars, thereby minimizing confusion and ensuring that the study is interpreted for its intended purpose (Matthews et al., 2014).

2.7.3.2. Life Cycle Inventory

In every LCA, there exists an inventory, which comprises the data collected by practitioners. This inventory encompasses emissions, energy requirements, and material flows for each process involved. These represent the flows into and out of the system under study by practitioners. The data within the inventory are adjusted based on the functional unit that practitioners are examining.

2.7.3.3. Life Cycle Impact Assessment

During the Life Cycle Impact Assessment (LCIA), the environmental impacts are calculated. Practitioners select categories of impacts, and based on the flow of emissions, energy, and materials from the inventory, they assess the impacts on these chosen categories. There are different types of impacts:

- Depletion of abiotic resources
- Global warming
- Ozone layer depletion
- Acidification
- Air, water and soil pollution
- Eco-toxicity
- Human toxicity

- Resource depletion
- Eutrophication etc.

2.7.3.4. Interpretation

Ultimately, the results are analysed within the context of the study's established goal and scope. This step ensures that the findings are interpreted within the intended context of the study.

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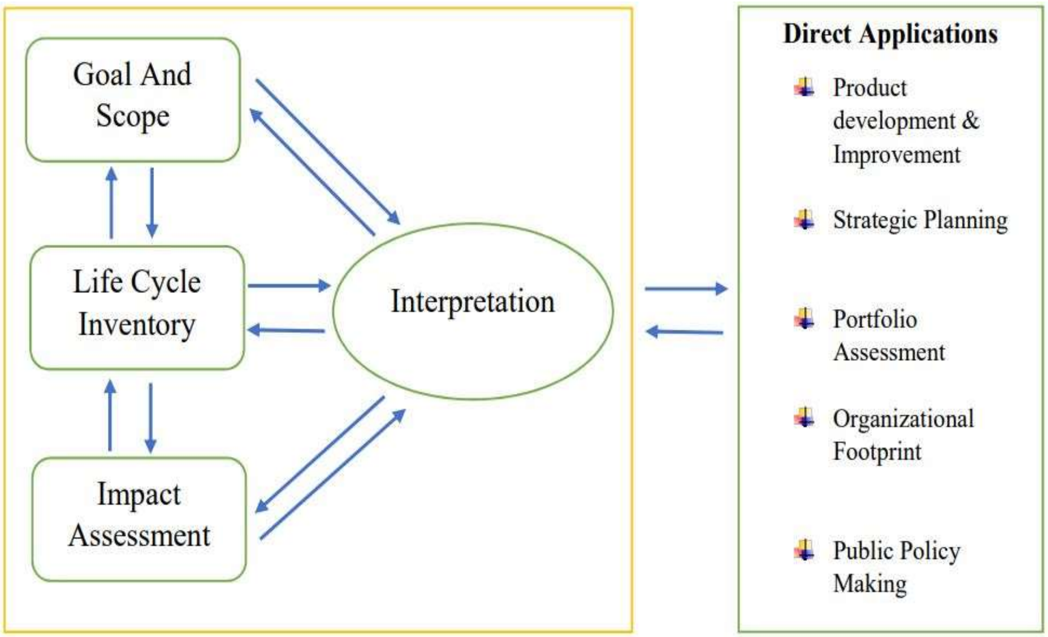


Figure 18: LCA Phases and Applications (ISO 14040, 2006)

2.7.4. LCA Databases

Databases are fundamental for conducting Life Cycle Assessment (LCA), serving as the primary source of secondary data. They contain scientific average data detailing the environmental impact of a wide range of materials and processes used in our daily lives and national economies.

Secondary data for specific processes is consolidated within datasets, sourced from scientific or industrial research. These databases can contain varying quantities of datasets, ranging from a few to several thousand. Access to these databases varies, with some freely available and others requiring paid subscriptions. Many databases are designed to meet the specific needs of individual nations, often resulting from collaborations among governmental agencies, research institutions, and national universities, as shown in Table 5. The most used databases are:

2.7.4.1. Ecoinvent

Ecoinvent is recognized as the largest, most consistent, and transparent database within the life cycle assessment (LCA) field. Featuring over 18,000 unique datasets, it comprehensively covers a diverse range of products, services, and processes. Compatible with nearly all LCA methods, including the EF 3.0 method. Ecoinvent is used on popular LCA software platforms such as Helix, Mobius, Simapro, GaBi and openLCA.

Table 5: LCA databases developed by various nations

COUNTRY NAME	DATABASES
Europe	ELCD
USA	USLCI
Sweden	SPINE@CPM
Australia	AusLCI
Korea	Korea LCI database
Japan	IDEA v.2

2.7.4.2. GaBi

The GaBi database comprises around 15,000 datasets and is characterized as "industry-born," reflecting its development with substantial input from stakeholders and feedback from industry and third-party sources. GaBi is owned by Sphera and serves dual functions as both LCA software and an LCI database, providing comprehensive tools for life cycle assessment. This database is integrated into openLCA and GaBi software.

2.7.4.3. Product Environmental Footprint

The Product Environmental Footprint (PEF) standard, along with its accompanying database, was initiated by the European Commission. The PEF standard aims to establish a harmonized framework across the European Union to ensure comparability between life cycle assessment (LCA) results. PEF datasets are compatible with the PEF method exclusively and are implemented in various LCA software platforms such as Ecochain and Mobius. The predecessor database to PEF, known as the Environmental Life Cycle Database (ELCD) version 3.2, was discontinued in 2018. However, it remains accessible through Mobius.

2.7.4.4. Nationale Milieudatabase (NMD)

The NMD (Nationale Milieudatabase) encompasses a broad spectrum of building materials and construction-related services within the Dutch context. Its datasets adhere to the EN 15804+A2 standard, which is the LCA standard for construction products. Now, versions 3.3 and 3.5 of the NMD are accessible through Ecochain, Mobius, and Helix.

2.7.5. Procedure Related to LCA

According to ISO 14040 and ISO 14044:2006, the procedures for conducting a Life Cycle Analysis (LCA) study include initiation, data collection, data quality checks, modeling and analysis, reporting, and external assurance. These steps are discussed through a flow chart below (Figure 19).

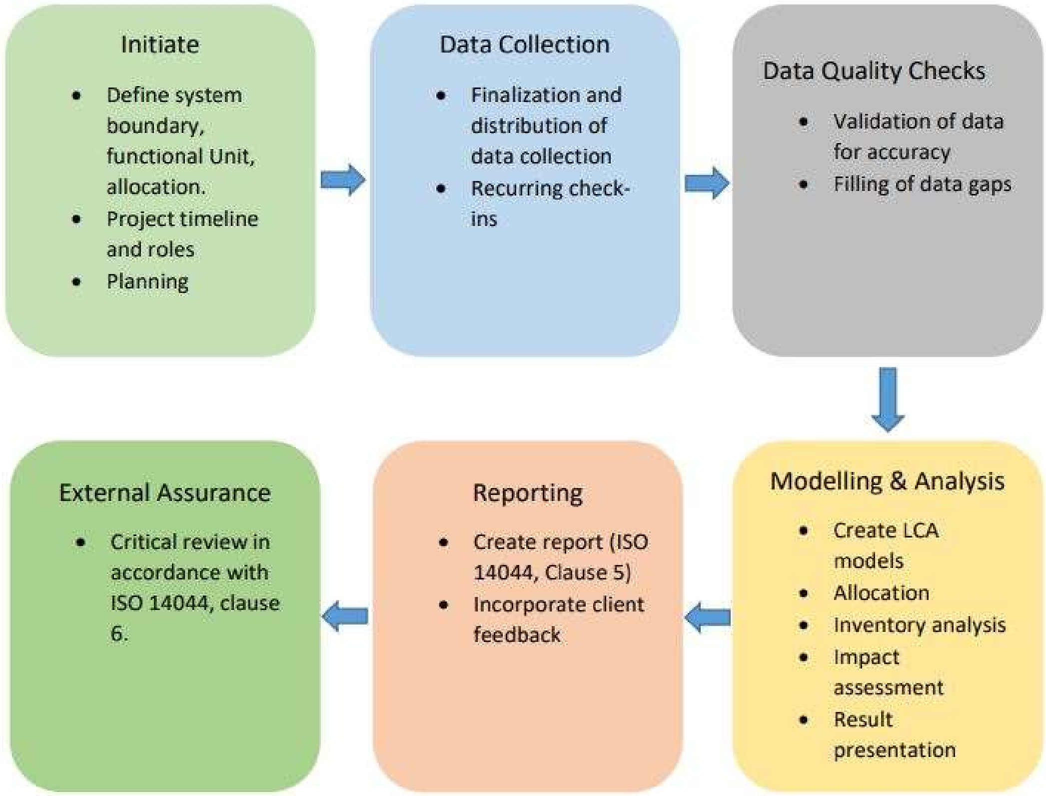


Figure 19: Procedure related to LCA

2.7.6. Life Cycle Impact Assessment Methods

Life Cycle Impact Assessment (LCIA) methods are essential for quantifying and calculating environmental impacts within a Life Cycle Assessment (LCA). As part of the LCA process, raw data regarding emissions, waste, and material production are collected and transformed into numerical results. Quantifying the diverse impacts on the environment and measuring their effects is complex due to interconnected nature of ecosystems. LCIA methods address this complexity by categorizing impacts generated by processes into areas like water use, climate change, or toxicity. Some common LCIA methods are discussed below.

2.7.6.1. ReCiPe 2016

In 2008, ReCiPe, a method for conducting life cycle impact assessments (LCIA), was originated through collaboration among RIVM (National Institute for Public Health and the Environment), Radboud University Nijmegen, Leiden University, and PRé Sustainability. The ReCiPe 2016 method is a new version of ReCiPe 2008 (RIVM Report, 2016-0104a).

The main goal of the ReCiPe method is to condense the extensive life cycle inventory results into a limited number of indicator scores. In ReCiPe, indicators are two types: midpoint and endpoint.

- Midpoint indicators =18
- Endpoint indicators =3

Midpoint indicators focus on single environmental problems, like climate change, acidification etc. There are 18 midpoint indicators.

Endpoint indicators demonstrate the environmental impact at three higher aggregation levels, namely human health, resource scarcity, biodiversity.

2.7.6.2. CML IA Baseline

Centrum voor Milieukunde Leiden (CML) IA baseline method was developed by the Institute of Environmental Sciences (CML) at Leiden University in the Netherlands. This method provides a framework for evaluating the environmental impacts associated with various human activities, processes, or products throughout their life cycles. It encloses a range of impact categories such as

- Climate change
- Acidification
- Eutrophication
- Photochemical oxidation
- Ozone depletion
- Human toxicity
- Resource depletion
- Ecotoxicity
- Land use

2.7.6.3. Pfister et al, 2010

At ETH Zurich, Stephan Pfister is a Professor in the Ecological Systems Design group. His methodological advancements in two key areas: Life Cycle Assessment (LCA) and Multi-Regional Input-Output Analysis (MRIO). This method demonstrates the environmental impact on Ecosystem quality, Human health, Resources.

2.7.6.4. IPCC GWP 100a

The Intergovernmental Panel on Climate Change (IPCC) provides guidelines and factors for calculating the Global Warming Potential (GWP) of various greenhouse gases. The "100a" in "GWP 100a" indicates the timeframe considered, which is 100 years. This is a standard timeframe used for comparing the warming potential of different greenhouse gases.

GWP is a measure of how much heat a greenhouse gas traps in the atmosphere over a specific time period compared to carbon dioxide (CO_2), which is assigned a GWP of 1. Gases with higher GWPs contribute more to global warming per unit mass than CO_2 over the given timeframe.

2.7.7. Existing Literature Related to Life Cycle Assessment of Biomining Process of Landfill

Some research has already been conducted on the Life Cycle Assessment (LCA) of biomining, and ongoing research in this area continues to expand. Table 6 presents a few notable research studies and their findings.

Table 6: Literature related to Life Cycle Assessment of Biomining Process of Landfill

Country	Key Findings	Conclusions	References
Europe (Latvia)	The excavation of waste significantly contributes to increased negative effects on both "Ecosystems" and "Human Health" categories. This is largely attributed to the release of gases during the extraction process.	Sorting waste at the landfill site reduces environmental impact by 28% more compared to sorting at a centralized plant.	Julija Gusca et al., 2015
United States (Denton)	Reusing mined plastics and papers has been shown to save 1.8 million MJ and 2300 MJ of energy, respectively, for every 1 ton of product	The LCA results indicate that mining 1 ton of MSW with material recovery can reduce approximately 0.1 million kilograms of equivalent CO_2 compared to the no-mining condition of the landfill. This reduction is equivalent to removing about 21 thousand cars from the road per year.	Umme Zakira, 2017
Denmark	A pilot-scale waste refinery designed for enzymatic treatment of municipal solid waste (MSW). This refinery separates the initial waste into two main fractions: a liquid component containing liquefied organic materials and paper, and a solid fraction comprising non-degradable materials.	If metal recycling rates are below 50% and the liquid waste doesn't produce enough methane (less than 70%), the benefits of the waste refinery are lost. This includes savings from biogas that helps fight global warming and acidification.	Davide Tonini et al., 2018
Sri Lanka	Refuse Derived Fuel (RDF) as an alternative fuel for coal in the cement industry and thermal power plants.	The utilization of RDF has the potential to eliminate more than 1.6 million tonnes of CO_2 equivalent of Global Warming Potential (GWP).	Danthurebandara Maheshi et al., 2015

Country	Key Findings	Conclusions	References
Tehran	This study aimed to assess the environmental performance of enhanced landfill mining method (ELFM) through the application of life cycle assessment (LCA) using SimaPro (v 8.5) for a 55-hectare closed dumpsite of the municipality of Tehran in Kahrizak for reclamation of land for further landfilling.	The study indicated that adopting ELFM could lead to considerable environmental benefits in comparison to the existing condition of landfill (the do-nothing scenario). The ELFM project could reduce the global warming impact by 1,759,790-ton CO_2 eq, which is equal to 134% decrease compared with the do-nothing scenario. Among all the processes assessed, recycling and thermal treatment of legacy waste reduced environmental effects significantly.	Sabour et al., 2020
China	Mechanical recycling of high-quality plastic waste combined with chemical recycling of low-quality plastic waste was the most carbon-feasible solution.	If all sorted plastic waste undergoes incineration with power generation, the climate-change impact of mining is calculated at 134.10 kg CO_2-eq per ton of aged refuse will surge by 100.47% by 2050.	Mengqi Han et al., 2023
India	The selection of energy sources, transportation methods, and fuel types for waste management activities influenced the effectiveness of different scenarios in terms of Global Warming Potential (GWP). Using recovered metals in manufacturing, incinerating plastics, and processing textile components enhanced environmental performance. Additionally, composting and applying recovered soil to land helped offset environmental impacts in GWP, Human Toxicity (HT), and Freshwater Eutrophication and Waste	Emissions from excavation and on-site sorting were responsible for 55.1% of freshwater toxicity, 25.5% of human toxicity, 16.2% of climate toxicity, change, and 10.8% of terrestrial acidification	Cheela et al., 2022

Country	Key Findings	Conclusions	References
	(FEW), although it did lead to some increase in Toxic Emissions (TE).		

2.8. Cost Analysis

Cost analysis involves a comprehensive examination of expenses associated with a particular project, endeavour, or activity. Therefore, it's crucial to calculate the expenses and advantages of a project in advance. This proactive step not only helps in forecasting expenditures but also allows for the discovery of opportunities to save money and generate income. By conducting this analysis beforehand on, individuals and entities can make informed decisions, optimizing their financial strategies for the best possible outcomes.

Cost can be classified based on various factors. Classifications by two of those factors relevant to this study have been discussed here.

2.8.1. Classification by Nature

Based on the nature of the expenditure, cost can be classified into broadly three categories, namely Material Cost, Labour Cost and Expenses (Vedantu, 2023). Expenses can be further classified into more divisions.

2.8.1.1. Material Cost

The expenditure on the raw materials to use for production of goods is classified as Material Cost. Material cost is a significant component of overall costs for businesses across various industries, and efficient management of it is crucial for optimizing profitability and competitiveness.

2.8.1.2. Labour Cost

Labour Cost is the expenditure on the salary and wages of the permanent and temporary workers.

2.8.1.3. Expenses

All the other expenditures associated with the production and selling of the goods are classified as Expenses. This consist of expenditures on land, construction, equipment, transportation, electricity, operation and maintenance etc.

The classification of cost based on nature is shown in Figure 20.

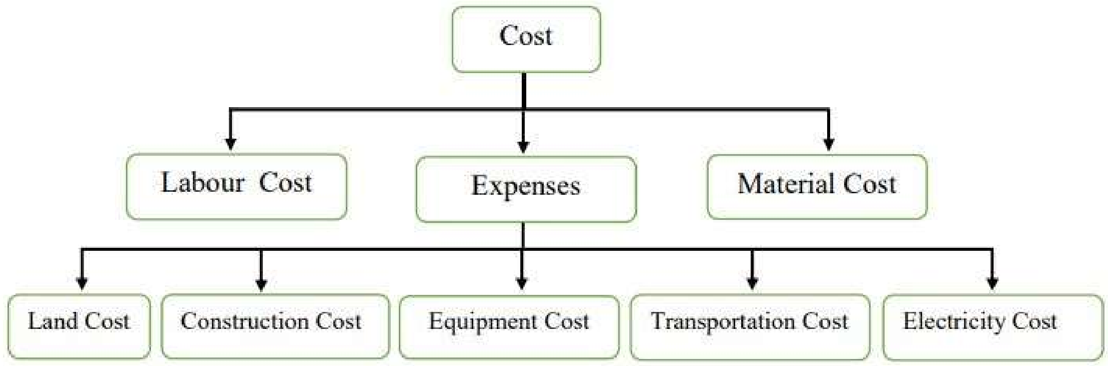


Figure 20: Cost Classification by Nature

2.8.2. Classification by Traceability

Cost can be classified into two major categories based on the degree of traceability, namely Direct Cost and Indirect Cost [Vedantu, 2023]. Figure 21 represents the classification of cost based on the traceability.

a.) Direct Cost

The expenditures which can be directly tied to cost of a good or service and can be put in one specific cost centre, is known as Direct Cost. These can be traced to the cost objective.

b.) Indirect Cost

The expenditures which are not directly tied to cost of a good or service and cannot be put in one specific cost centre, is known as Indirect Cost. These cannot be traced to the cost objective. For economic evaluation in this study, Indirect Costs are further classified into Environmental Cost and Social Cost.

• Environmental Cost

The costs which are incurred to prevent, reduce or repair damages to the environment arising from any activities, are known as Environmental Cost (Terna Driving Energy, 2023).

• Social Cost

As implied by its name, social costs encompass expenses borne by society collectively. These are the sum of private costs and other external costs imposed on society by production or consumption of a good or service [FRBSF, 2002].

Non-market goods have no prices, but economic values can be estimated with several techniques. In addition to the Contingent valuation method (CVM), other common and widely accepted methods are travel cost, and hedonic pricing [Ekstrand and Draper, 2000]. Still CVM is the most used technique to evaluate economic values of various types of ecosystem and environmental services [Nautiyal and Goel, 2021], as it is based on stated preferences for goods, rather than observed behaviour of consumers.

According to Markandya and Ortiz (2011), contingent valuation is a stated preference method in which respondents are asked to state their preferences in hypothetical or contingent markets. In this survey-based method, respondents are asked to state their Willingness to Pay (WTP) or Willingness to Accept (WTA). WTP is the maximum amount of money that respondents are ready to pay in exchange of a service where they gain a positive change. On the contrary, WTA is a minimum amount of money which people are ready to accept as a consequence of a negative change [Hasan-Basri et al., 2015].

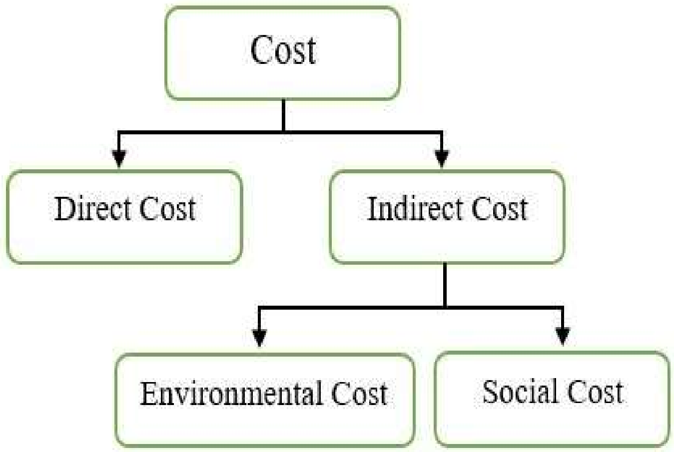


Figure 21: Cost Classification by Traceability

2.8.3. Different Methods to Calculate Cost and Benefit

Some of the typical methods to calculate cost and benefit are

- Cost-Benefit Analysis
- Life Cycle Cost Analysis

2.8.3.1. Cost-Benefit Analysis

A cost-benefit analysis (CBA) is a systematic approach to evaluating the costs and benefits of a project or investment. It is a useful tool for making decisions about whether or not to proceed with a project, and for choosing between different projects.

The CBA process involves the following steps:

a.) Define the Project or Investment

The first step in CBA analysis is to define requirements and establish basic objectives of what the structure or project must achieve. These requirements are generally developed from an analysis of the needs.

b.) Identify all of the Costs and Benefits

This includes both tangible and intangible costs and benefits.

• **Tangible costs and benefits:** Tangible costs and benefits can be easily quantified, such as the cost of materials and labour, or the increase in revenue.

• **Intangible costs and benefits:** These are more difficult to quantify, such as the improvement in employee morale or the reduction in environmental impact.

c.) Estimate the Value of each Cost and Benefit

This can be done using a variety of methods, such as market research, expert opinion, or discounted cash flow analysis.

d.) Comparison of the Costs and Benefits

This can be done by calculating

- The net present value (NPV)
- The internal rate of return (IRR)
- The benefit-cost ratio.

e.) Decision Making

Based on the results of the CBA, it can be decided whether or not to proceed with the project, and which project to choose if there are multiple options.

CBA is a valuable tool for making informed decisions about projects and investments. However, it is important to note that it is not a perfect tool. The accuracy of the results depends on the accuracy of the estimates, and there is always some uncertainty involved in any projection.

2.8.3.2. Life Cycle Cost Analysis

Life cycle cost analysis (LCCA) is a tool to determine the most cost-effective option among different competing alternatives over the life span of the project. In this technique, initial costs, all expected costs of significance, disposal value and any other quantifiable benefits to be derived are taken into account. It is used especially to select the best option when multiple options are available to satisfy the same performance requirements but differ in terms of operating costs and initial costs, which must compare for selecting the method for maximization of net savings.

2.8.3.2.1. Purpose

The purpose of this analysis is to estimate the overall cost of project options and then select the approach that can ensure the facility provides the overall lowest cost without compromising the function and its quality. The analysis should be performed early so that there will be chances of refining the approach to ensure the reduction in life cycle total cost. The most challenging assignment of this analysis or any economic evaluation technique is to ascertain the economic effects of alternate approaches of the project and quantify these effects in monetary terms. However, the LCCA is useful for evaluation of the economic impact of the options available in the industry (Thakur and Vaidya, 2022).

2.8.3.2.2. Steps involved in LCCA

The approach to a typical LCCA analysis is composed of a few key steps which are itemized below (Macedo et al., 1978; Brown and Yanuck, 1985).

2.8.3.2.3. Establish Objectives

The first step in LCCA analysis is to define requirements and establish basic objectives of what the structure or project must achieve. These requirements are generally developed from an analysis of the needs of the client or the owner. Also, any special constraints must be identified at this time.

2.8.3.2.4. Define Alternatives

A set of alternatives that satisfy the requirements and achieve the basic objectives are selected. It is necessary to identify all practical approaches for further analysis. The steps involved in choosing alternatives for further examination can be outlined as follows:

- Identify practical and feasible alternatives.
- Obtain performance requirements for each option.
- Screen alternatives, eliminating those that do not meet defined performance requirements and constraints.
- The remaining alternatives are selected for further study.

2.8.3.2.5. Select Life Cycle

This involves deciding upon a finite planning horizon or life cycle applicable to all the alternatives. Determining a specific timeframe for a life cycle sets the period during which future costs (such as operating and maintenance expenses) are projected.

2.8.3.2.6. Estimate Costs

All the costs and revenues which are directly relevant to the comparison of alternatives are identified. First, the initial costs for each alternative are calculated. There are three types of recurring costs: normal operation and maintenance costs incurred on a daily, weekly or monthly basis, the annual costs for utilities and fuels and the recurring costs of repairs, alterations and replacement of structural elements or systems. Figure 22 presents different types of costs of a typical project. Other than these, some more different types of cost may be involved depending upon the type of the project. Estimates of their occurrence and periodicity depend on the estimates of the live cycles derived in the previous step. Also, adjustments are made for price escalation.

2.8.3.2.7. Compute Present Values or Annual Equivalents

As the various expenditures estimated above take place at different times during the life cycle of the structure, the costs are adjusted to a common time period by converting to present values or annual equivalents. This is done by multiplying these costs by the appropriate discount factors in order to take time value of money into account.

Figure 22: Different types of cost considered in LCCA (CFI Team, 2022)

2.8.3.2.8. Test sensitivity of results in LCCA

The results from present value or annual equivalent computations for each alternative establish their ranking. The lowest alternative is the preferred one based on a total life cycle cost approach. However, finally a sensitivity analysis is carried out to assess the influence of the various input parameters on the life cycle cost. Once these sensitivity tests are completed, the resulting lowest life cycle cost alternative is recommended for implementation.

2.8.4. Existing Literature Related to Cost Analysis of Biomining Process of Landfill

Although initial research on the cost analysis of biomining is ongoing, the field continues to evolve with further investigations. Table 7 summarizes several important studies and their results.

Table 7: Literature Related to Cost Analysis of Biomining Process of Landfill

Country	Key Findings	Conclusions	References
China	The rental of excavation and hauling equipment, waste processing, and material transportation were the top three costs in landfill mining, making up 88.2% of the total expense. The average cost per ton of stored waste was 12.70 USD.	The NPV of the Yingchun landfill mining project could range from 1.92 million USD to 16.63 million USD, depending on land reuse, energy recovery, and financial support from avoiding post-closure care.	Zhou et al., 2014

Country	Key Findings	Conclusions	References
Belgium	The NPV value varies with the net electrical efficiency of the thermal treatment system, the calorific value of RDF, the selling prices of various products, and the investment and operational costs associated with different valorisation processes.	The total variation in NPV can be explained by 27-30% due to changes in the net electrical efficiency of the thermal treatment process. However, improvements in electrical efficiency may lead to higher investment costs, which could negatively impact NPV by 26-30%.	Danthurebandara et al., 2015
Sri Lanka	Two scenarios are examined: Scenario 1 replaces coal with refuse-derived fuel in cement production, and Scenario 2 involves thermally treating the fuel to produce electricity. Both are environmentally beneficial but not economically viable.	Economic viability can be achieved by adjusting waste transport distances and electricity prices.	Maheshi et al., 2015
Germany	Six alternative landfill mining processes are defined. They vary in their complexity and the degree of innovation of the used technologies.	The economic performance of landfill mining processes is significantly influenced by the costs of thermal treatment (including waste incineration and refuse-derived fuel incineration) and the value of recovered land or airspace.	Kieckhäfer et al., 2016
Tehran	This study aimed to assess the economic performance of enhanced landfill mining method (ELFM) applying comprehensive cost-benefit analysis for a 55-hectare closed dumpsite of the municipality of Tehran in Kahrizak for reclamation of land for further landfilling. Monte Carlo simulation was adopted to address the related uncertainties during estimation of costs. In addition, the indicator of net	The study indicated that adopting ELFM could lead to considerable benefit of 370 million $.	Sabour et al., 2020

Country	Key Findings	Conclusions	References
	present value (NPV) was adopted to understand the economic feasibility of the project.		
India (Ahmedabad)	From the study it is noted that about 30 % to 60 % of the conventional fine aggregates can be replaced with LMSF in subbase courses depending on the traffic conditions	By using the newly developed granular sub-base (GSB) (Grade-II) with 60% landfill mined soil like fraction (LMSF) replacement for low-volume roads, material costs can be reduced by 50.36%, while the GSB (Grade-VI) with 50% LMSF for high-volume roads can reduce costs by up to 41.88%.	Reddy et al., 2024

From the existing literatures related to cost analysis of biomining process of landfill, following conclusions can be drawn

- Landfill biomining with material recovery is a profitable practice.
- In landfill biomining, the NPV depends on factors such as land reuse, energy recovery, electricity prices, and thermal treatment costs. Transportation costs for waste are a crucial factor in cost analysis.
- Utilizing quality earth in road construction can lower costs and enhance the benefits of landfill biomining projects.

2.9. Critical Literature Review

- Every year, billion tonnes of solid waste is collected worldwide. The global waste generation has increased from 635 MT in 1965 to 1999 MT in 2015 and might reach up to 3539 MT by 2050. The current trends show continuous rise in waste production with unsustainable treatments, landfilling being the most dominating one (Chen et al. 2020).
- As indicated by The World Bank (2018), high-income countries are projected to experience a daily per capita waste rise of 19%, whereas low and middle-income nations are anticipated to see an even more pronounced increase of 40% or beyond.
- India ranks among the top 10 countries globally in terms of municipal solid waste (MSW) generation. A report by TERI (The Energy and Resources Institute) indicates that India produces over 62 million tons (MT) of waste annually. However, only 43 MT of this total waste generated is collected, with 12 MT undergoing treatment before disposal, while the remaining 31 MT is simply discarded in waste yards.
- Maharashtra (22,632.71 tonnes per day), Uttar Pradesh (14,710 TPD) and West Bengal (13,709 TPD) generate the highest solid waste in the country (Zeenews.india.com. Oct 28, 2022). If cities continue to dump the waste at present rate without treatment, it will need 1240 hectares of land per year in India (Solid Waste Management Rules, 2016).
- In 2015, the European Commission proposed ambitious new targets for municipal waste, aiming for 60% recycling and preparation for reuse by 2025, and 65% by 2030. In 2014, Denmark and Switzerland recorded the highest municipal waste generation per person, while Romania, Poland, and Serbia reported the lowest figures (European Environment Agency, 2015).
- In India, % of solid waste landfilled has decreased from 54% to 18.4% in 2020-21 and the percentage of solid waste treated has risen from 19% in 2015-16 to 49.96% in 2020-21 (CPCB Annual Report, 2020-21).
- According to the literature, specifically the studies by Hogland et al. (2004), Rong et al. (2017), Kurian et al. (2003), and Singh et al. (2019), the highest percentage amounts found in legacy wastes are good earth and Refuse-Derived Fuel (RDF).
- In developed countries, the fine fraction obtained from biomining process is used for production of refuse derived fuel (RDF) or filling material (Hogland et al., 2004; Prechthai et al., 2008; Jani et al., 2016; Karsten et al., 2016). But in India, fine fractions are mainly used as filling material in low lying areas or deep pits (Manoj Datta et al., 2020; Mohammed Najamuddin et al., 2021; Deendayal Rathod et al., 2022).
- The physicochemical characteristics of byproduct of biomining process are necessary for checking the feasibility of landfill mining project (Ayush Singh and Munish K. Chandel., 2019). In India the fine fraction from biomining (less than 4.75 mm in size) is considered as Good Earth.
- The presence of high levels of organic matter, heavy metals, and soluble salts indicate that the Good Earth requires treatment before off-site re-use or that specific design measures are must before placing it as earth-fill in embankments, low-lying areas, and deep pits (Datta et al., 2020).
- There are several advantages of using Good Earth from bio-mining. The large amount of Good Earth can be used as backfill material or even as a construction material for brick manufacturing which helps to clear the landfill area for future use.

- A number of environmental risks are associated with bio-mining projects. LCA is a very helpful tool for calculating the environmental impacts. Environmental impacts can be managed well if considered in advance of the operations and appropriate mitigation measures have been designed by the executing agency.
- According to Zhou et al. (2014), excavation, hauling, waste processing, and material transportation account for 88.2% of landfill mining costs, underscoring the need for meticulous financial planning and cost management.
- Net present value (NPV) variations are closely tied to factors such as RDF calorific value, product prices, valorisation costs, waste transport distances, and electricity prices. Adjusting these factors could enhance economic feasibility, highlighting the need for strategic adjustments in waste management (Maheshi et al., 2015; Danthurebandara et al., 2015).

2.10. Green Area of Research

- Landfill mining is practiced both in India and globally; however, there is limited existing literature on its environmental sustainability and economic viability.

- While most research focuses on the use of Refuse-Derived Fuel (RDF) in cement manufacturing, there is limited exploration of RDF pellets in brick kilns. Additionally, the environmental impacts of RDF preparation and transportation are often overlooked.

- Existing literature primarily addresses the feasibility of good earth as filling or embankment material, with only a few studies considering its use as subbase material in roads. There is a lack of research on using good earth as subgrade material in road construction.

- Although many studies examine the geotechnical and physicochemical properties of good earth, very few consider the cost-effectiveness of utilising good earth.

- Previous research on assessment of feasibility of biomining process typically focuses on direct costs, neglecting indirect costs such as land space generation and carbon emission reduction (CER) credit.

- Previous studies often prioritize primary objectives, with cost analysis being a secondary consideration, leading to numerous assumptions during the analyses.

Therefore, there is a significant need for more comprehensive environmental and economic analysis of biomining projects. Such analysis would guide policymakers in developing effective methodologies for utilizing RDF as an alternative to fossil fuels in cement factory and brick kilns, as well as for using good earth as subgrade material in roads. This would also facilitate the broader implementation of landfill biomining projects on a larger scale while considering circular economy and environmental sustainability.

Chapter 3: Methodology

3.1. General

The study aimed to assess the viability of landfill biomining process from both environmental and economic perspectives. A brief description of the methodology employed to achieve this objective is provided, along with a schematic representation. Three scenarios were compared to conduct a detailed life cycle assessment. Also, the methodology for conducting a cost-benefit analysis is presented, including the assumptions and considerations made within this study.

3.2. Study Area

Howrah and Durgapur, located in the eastern part of India, exhibit distinct physical features influenced by their geographic settings (Figure 23). Howrah, positioned on the western bank of the Hooghly River, features a predominantly flat terrain with gentle undulations and is impacted by the river's hydrology. The city benefits from its proximity to the Hooghly, which affects its water resources and drainage. Vegetation in Howrah includes a mix of urban green spaces and parks, contributing to its environmental quality. In contrast, Durgapur is situated on the alluvial plains of the Damodar River, presenting a relatively flat landscape with low-lying areas that are susceptible to seasonal flooding. The city's water resources are closely tied to the Damodar River, which influences its hydrological patterns. Durgapur's urban fabric includes both developed industrial zones and pockets of natural vegetation, reflecting a blend of urban and green environments.

Howrah is positioned on the western bank of the Hooghly River, an arm of the Ganges River, with latitude and longitude coordinates approximately 22º 35′N and 88º 21′E respectively. Covering an area of 1467 sq. km and inhabited by over 4.8 million people, Howrah experiences a humid climate during summer and pleasant conditions in winter, with temperatures ranging between 10°C to 40°C. The city receives an average annual rainfall of 1400-1700 mm (Howrah Municipal Corporation). The shortest distance from Howrah landfill site (Bhagar) to Howrah railway station is 6 km (https://www.maps.google.com/).

Durgapur city is located on the left bank of the Damodar River, approximately 160 km from Kolkata. Its geographic coordinates extend from 87°13′ E to 87°22′ E longitude and 23°28′ N to 23°36′ N latitude. Covering an area of about 154.2 sq. km, Durgapur has a population density of 3891 per sq. km. The temperature in Durgapur varies from as low as 6°C in winter to as high as 42°C in summer. The shortest distance from the Durgapur landfill site (Sankarpur dumping ground) to Durgapur railway station is 9.9 km (https://www.maps.google.com/). The data regarding Howrah and Durgapur landfill site is shown in Table 8.

Table 8: Howrah and Durgapur Landfill Site Data

Site Name	Age (Years)	Area (m^2)	Avg. Height (m)	Volume of waste (ton/m^3)
Howrah (Zone 1)	65	38130	11.186	287902.47
Howrah (Zone 3)	30	7240	5.258	38067.91
Durgapur	40	21240	10.514	76153.72

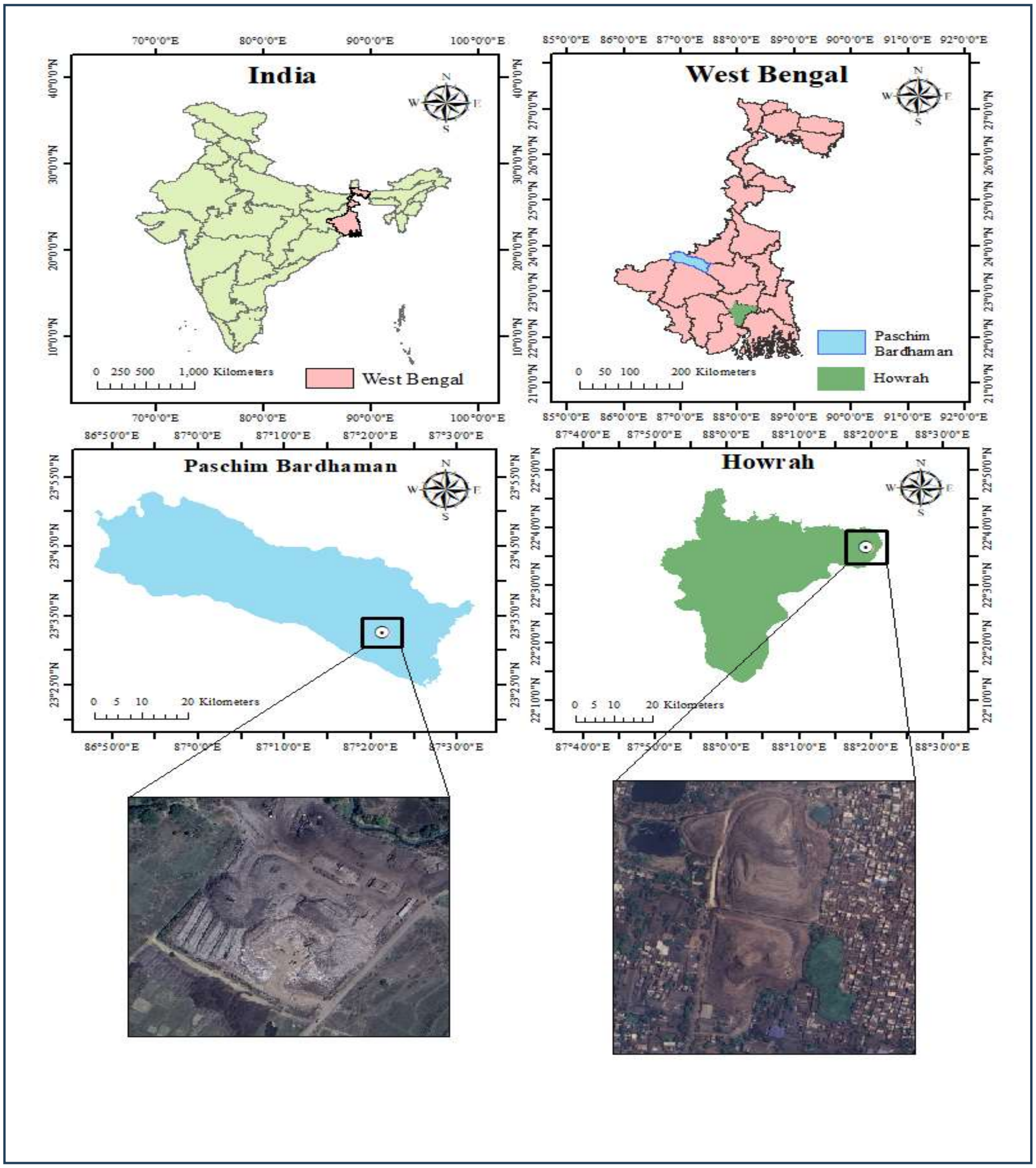


Figure 23: Study Area of Durgapur and Howrah (ArcGIS 10.8)

3.3. Overview of the Strategy Followed in the Project

The demonstration projects in this study included several initiatives to show practical applications and test ideas in its specific focus. These projects were conducted in various locations and involved different durations and scales. Each project is designed to demonstrate specific methods or technologies related to the study's objective. The strategy followed in the project involves:

i. Segregation of municipal landfill waste using a trommel or power screen to collect good earth, RDF (Refuse Derived Fuel), and inert material.

ii. Transporting the good earth to Jadavpur University for a thorough analysis of its physicochemical characteristics, geotechnical properties.

iii. Testing of total and leachable heavy metals and leachable salts.

iv. Concurrently, assessment of RDF's calorific value to evaluate its suitability as a fuel source.

v. Additionally, manual segregation at the landfill site for detailed composition analysis.

vi. Following these assessments, a life cycle analysis (LCA) to evaluate environmental impacts.

vii. Alongside a cost-benefit analysis for feasibility assessment of the project.

Figure 24 illustrates a schematic diagram outlining the proposed strategy for this study.

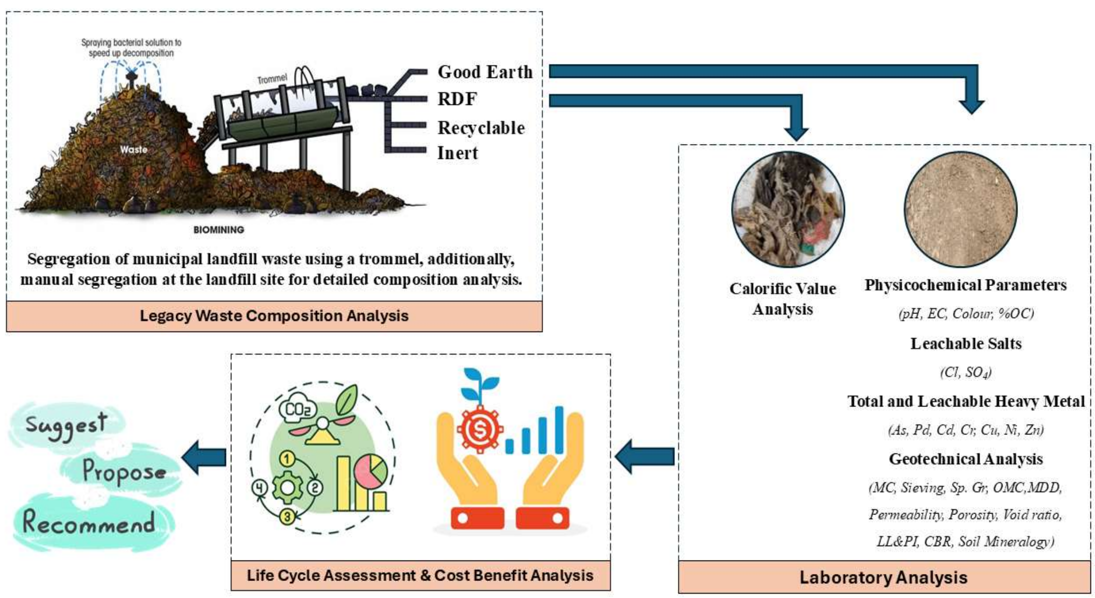


Figure 24: Schematic Diagram Outlining the Proposed Strategy

3.4. Sample Collection

At the Howrah landfill site, the area is divided into three distinct zones. Samples are excavated from Zone 1 and Zone 3, specifically from depths below 1.5 to 2 meters beneath the surface after removing top liner. From each of these zones, three different locations are chosen for sample collection. Subsequently, six individual samples, three from each zone, are combined and thoroughly mixed using the quartering method to ensure homogeneity. During this process, any oversize particles and large debris are removed to facilitate further analysis. Then samples are screened through various Indian Standard (IS) sieves like 26.5, 8 and 4.75mm (CPCB, 2019). This sampling was conducted in October 2023.

Similarly, at the Durgapur landfill site, sampling occurred in September 2023. The solid waste samples are manually excavated from depths ranging between 1.5 to 2 meters below the top surface. From this site, individual samples were gathered from five distinct locations. To ensure uniformity, the collected waste was meticulously mixed and subjected to the quartering method. Following the mixing process, the waste underwent segregation utilizing various Indian Standard (IS) sieves, including those with sizes of 26.5, 8, and 4.75mm. The sampling was carried out in.

The waste samples that measured below 8 mm in size were carefully sealed in bags to preserve their integrity and prevent contamination. These sealed samples were then transported to Jadavpur University.

In Jadavpur University, upon arrival, all samples undergo a drying process under the sun for a duration of five days. This step ensures that the samples are thoroughly dried, removing any moisture that may affect subsequent analysis. Following the drying process, the samples are carefully sealed in bags. These sealed bags are then stored in a cool and dry environment to preserve the samples' quality until they are used for future analysis.

3.5. Composition Analysis

In both sites, composition analysis is conducted directly onsite shown in Figure 25. The process begins with physical sorting to separate different components based on visual characteristics. Subsequently, the sorted waste is screened using Indian Standard (IS) sieves of varying sizes, including 45mm, 26.5mm, 8mm, and 4.75mm. This sieving process further segregates the waste into distinct size fractions. Finally, the segregated waste fractions are weighed using a spring weight machine. This comprehensive method allows for immediate assessment of waste characteristics.

Figure 25: Composition Analysis (Durgapur site, 2023)

3.6. Testing Methodology of Physicochemical Properties of Good Earth

Physicochemical properties of soil are important for a wide range of applications in environmental management and engineering. Parameters such as porosity, void ratio, soil pH, electrical conductivity (EC), colour, organic carbon and organic matter content are meticulously analysed using specialized methods. This information aids engineers in evaluating the soil's compaction behaviour, its ability to withstand load pressures, and its overall stability under varying environmental conditions.

3.6.1. Sample Preparation

Large particles are first separated from the good earth sample. The separated small particles are then oven-dried overnight at 65-70˚C. After drying, they are ground into coarse granules using a wooden roller, thoroughly mixed, and passed through a 2 mm sieve. Finally, the prepared sample is stored in labelled zipper-mouth polyethylene bags.

3.6.2. pH Test

The good earth sample is mixed with double-distilled water in 1:5 ratio to ensure a homogeneous solution for pH testing, in accordance with the Fertiliser Association of India standard (FAI, 2007). The pH meter is calibrated using standard buffer solutions. Once calibrated, the pH electrode is immersed into the sample solution, allowing sufficient time for the reading to stabilize. All the experiments were performed in triplicate.

3.6.3. Electrical Conductivity Test

To prepare for conductivity measurement, a 1:5 dilution of the sieved sample with distilled water is mixed thoroughly for one hour to ensure homogeneity. After stabilization, conductivity is measured using a calibrated conductivity meter at 25°C (APHA Standard Method, 1975). Results are taken in microsiemens per centimeter (µS/cm). All the experiments were performed in triplicate.

3.6.4. Colour Test

According to American Public Health Association (APHA Standard Method, 1976), guidelines, the good earth sample is diluted with double distilled water in 1:10 ratio. After thorough mixing and allowing time for settlement, the mixed solution is filtered to remove particulates and separate the soil extract. The color characteristics of samples is determined using spectrophotometry at a specific wavelength of 450 nm and expressed in Platinum-Cobalt Units (PCU). All experiments were carried out three times.

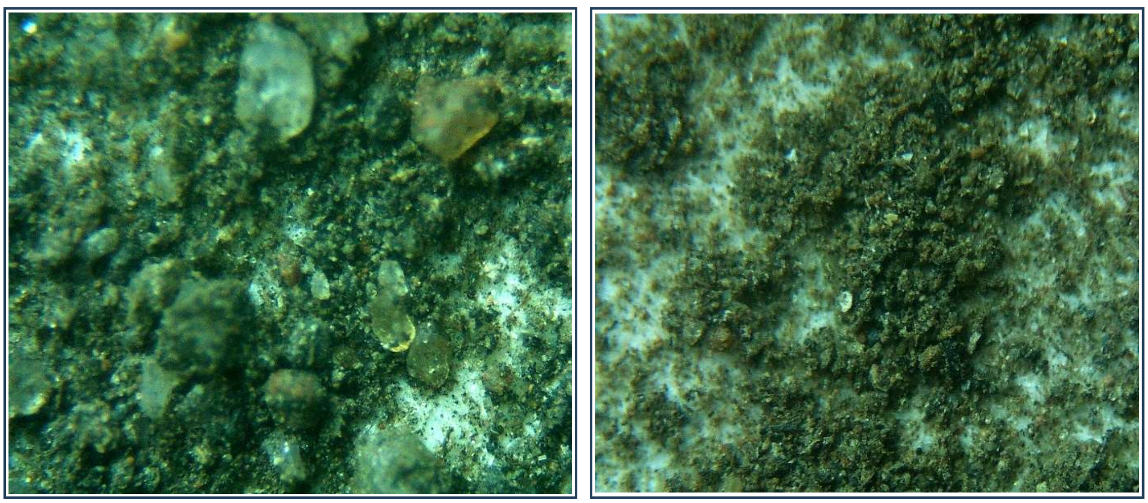
3.6.5. Organic Carbon and Organic Matter Content

The organic carbon content in soil is determined using the Walkley and Black method (Suraj Poudel, 2020). In this method, organic matter present in the soil is oxidized using a mixture of potassium dichromate and concentrated sulfuric acid, utilizing the heat generated from the dilution of sulfuric acid. The oxidation reaction breaks down organic matter into carbon dioxide (CO_2). Excess potassium dichromate was back-titrated with ammonium ferrous sulfate to determine the amount used in the reaction. All the experiments were performed in triplicate.

The percent of organic matter in soil was calculated by multiplying the percent of organic carbon, obtained through the Walkley and Black method, by a conversion factor of 1.724.

3.7. Testing Methodology of Geotechnical Properties of Good Earth

Geotechnical property testing of soil is crucial for various engineering applications, ranging from road construction to building foundations. These tests yield crucial information about soil performance under varying conditions, enabling engineers to make well-founded choices regarding design, construction techniques, and potential hazards. By assessing parameters such as particle size distribution, plasticity, compaction characteristics, shear strength, permeability, and California bearing ratio (CBR), geotechnical testing ensures that soils meet specified criteria for stability, load-bearing capacity, and long-term performance. The good earth sample taken from the landfill site consists of soil particles smaller than 8 mm. However, for geotechnical property testing, the samples need to be less than 4.75 mm. Therefore, the good earth sample is sieved using an IS 4.75 mm sieve. The particles passing through the 4.75 mm sieve are then examined under a high-resolution optical microscope (Dewinter) with 100X magnification, as shown in the Figure 26. The testing methodologies are described below.



(a) **(b)**

Figure 26: Microscopic View of Good Earth Particles (**a**- Durgapur site, **b**- Howrah site)

3.7.1. Water Content Determination Test [IS: 2720, (Part 2) 1973]:

Water content is calculated as the ratio of the mass of water to the mass of solids in each substance. In the oven drying method, soil samples are exposed to temperatures between 60°C to 65°C for approximately 24 hours. For soils containing organic matter, a lower drying temperature of 60°C is recommended to prevent oxidation of the organic components. Once cooled in a desiccator, the final weight is measured. The water content is then calculated using the weight changes and expressed as a percentage.

Calculation

- M_1 = empty mass of can with lid.
- M_2 = mass of can with lid and wet soil.
- M_3 = mass of can with lid and dry soil.

Water Content is given by $w = \left\{\frac{(M_2 - M_3)}{(M_3 - M_1)}\right\} \times 100$

3.7.2. Sieve Analysis Test [IS: 2720, (Part 4) 1985]:

Good earth is composed of various particles of different shapes and sizes. In this study, the good earth particles are categorized into distinct size ranges to analyze the relative proportions of each size category based on their dry weight.

Two main methods, sieving and sedimentation, are employed for grain size analysis to cover the wide spectrum of particle sizes. Sieving is utilized for particles ranging from gravel to sand sizes, which are separated into different size fractions using a series of sieves with standardized openings. However, sieving cannot effectively separate silt and clay-sized particles, for which sedimentation techniques (such as using a hydrometer) are employed.

From the grain size distribution curve generated by these methods, specific particle sizes such as D_{10}, D_{30}, and D_{60} can be determined. D_{10}, D_{30}, and D_{60} represent the particle diameters at which 10%, 30%, and 60% of the soil sample's mass is smaller, respectively. Among these, D_{10} represents the effective particle size of the good earth, providing crucial information about its grain size distribution.

Calculation

- Coefficient of Uniformity Cu:

$$C_u = \left(\frac{D_{60}}{D_{10}}\right)$$

- Coefficient of Curvature Cc:

$$C_c = \left\{\frac{(D_{30})^2}{(D_{60} * D_{10})}\right\}$$

3.7.3. Specific Gravity Test [IS: 2720, (Part 3) 1980]:

The specific gravity (G_S) of good earth refers to the ratio of the mass density of solids to mass density of water. Specific gravity is usually reported at 20°C. Since the sample contains significant amounts of silt and clay particles, it was soaked overnight in density bottles as part of the testing process. This procedure was conducted using three separate density bottles for accuracy and consistency in the measurements, shown in Figure 27.

Figure 27: Density Bottle (Jadavpur University, 2024)

The specific gravity is given by

$$G_s = \left[\frac{(m_2 - m_1)}{\{(m_2 - m_1) - (m_3 - m_4)\}}\right]$$

- m_1 = mass of empty bottle
- m_2 = mass of bottle and dry soil
- m_3 = mass of bottle, soil and water
- m_4 = mass of bottle filled with water only

3.7.4. Atterberg limits test [IS: 2720, (Part 6) 1972]:

3.7.4.1. Liquid Limit (LL):

In the liquid limit test procedure, a soil sample is mixed thoroughly with distilled water to form a consistent paste. This paste is then placed into a Casagrande apparatus, and an ASTM tool is used to create a standard groove along the symmetrical axis of the sample. The number of blows required for the groove to close is recorded during multiple water content determinations, typically ranging from 10 to 40 blows. These measurements are used to plot a graph of water content against the logarithm of the number of blows yields a flow curve, from which the liquid limit is determined as the water content corresponding to 25 blows.

3.7.4.2. Plastic Limit (PL):

It is the water content (w) at which a thread of soil just begins to crack and crumble when rolled to a diameter of 3mm.

Calculation

- Plasticity index (PI): The plasticity index (PI) is defined as:

$$PI = (LL - PL)$$

- Liquidity index (LI): This index is defined as:

$$LI = \frac{(w - PL)}{(LL - PL)}$$

3.7.5. Proctor Compaction Test [IS: 2720, (Part 7) 1980]:

In the Proctor compaction test (Figure 28) , the soil sample undergoes standard compaction within each mould. Initially, 2 kg of good earth is taken and mixed with 4% of water relative to the total weight of the sample. The process involves dividing the sample into three distinct layers, each receiving 25 blows from a 2.6 kg rammer dropped from a height of 310 mm. After compacting each layer, the mould containing the compacted sample is weighed to determine its mass accurately. A small sample of soil is then extracted from the middle portion of the compacted mould and placed in a designated container for moisture testing.

Following this initial test, an additional 4% water by weight is mixed into the soil sample, and the compaction process is repeated. This iterative process continues until reduces the weight of the entire assembly. The aim is to find the optimal amount of mixing water that results in the maximum weight of soil per unit volume.

Next, the data collected from these tests are used to plot a graph of dry density against water content. The maximum dry density (MDD) and OMC values are then calculated directly from this graph.

(a) **(b)**

Figure 28: **(a)-** Proctor mould with compacted sample, **(b)-** Sample for oven drying (Jadavpur University, 2024)

3.7.6.Void Ratio and Porosity of the Sample

A systematic approach is taken to determine the porosity of the good earth sample using the equation involving dry density (γ_d), specific gravity (G), unit weight of water (γ_w) and void ratio (e). The void ratio (e) is calculated using the equation:

$$\gamma_d = \left(\frac{G * \gamma_w}{1 + e}\right)$$

Once the void ratio (e) is determined, use the relationship between porosity (η) and void ratio (e):

$$\eta = \left(\frac{e}{1 + e}\right)$$

From the above eqation, the value of porosity (η) is determined.

3.7.7. Permeability Test [IS: 2720, (Part 17) 1986]:

Considering the particle size and composition of the samples, the falling head permeability test was performed. In Falling Head Permeameter test, the good earth sample is compacted in the permeameter mould and the standpipe is filled almost to the top with water. As the soil is not already saturated, it is left for approximately 24 hours to ensure complete saturation. When the water level in the standpipe begins to fall steadily, the clamp is released, and a stopwatch is started. The time taken for the water level to decrease over a specified distance is recorded. This process is repeated for five independent readings. The average coefficient of permeability (K) is calculated from these readings. The permeameter test apparatus is shown in Figure 29.

The coefficient of permeability is determined by $K = 2.303\frac{aL}{At}\log\frac{H_0}{H_1}$

- a= area of cross section of stand pipe
- A= area of cross-section
- H_0 and H_1= water head at time t_0 and t_1 respectively
- L= Length of the soil sample

Figure 29: Falling Head Permeameter test apparatus (Jadavpur University, 2024)

3.7.8. Shear Strength Test [IS: 2720, (Part 13) 1986]:

The shear resistance of soil is the result of friction and the interlocking of particles and possibly cementation or bonding at the particle contacts. The shear strength parameters of soils are defined as cohesion and the friction angle.

The shear strength of soil depends on the effective stress, drainage conditions, density of the particles, rate of strain, and direction of the strain. Thus, the shearing strength is affected by the consistency of the materials, mineralogy, and grain size distribution, shape of the particles, initial void ratio and features such as layers, joints, fissures and cementation.

The shear strength parameters of a granular soil are directly correlated to the maximum particle size, the coefficient of uniformity, the density, the applied normal stress, and the gravel and fines content of the sample. It can be said that the shear strength parameters are a result of the frictional forces of the particles, as they slide and interlock during shearing. Soil containing particles with high angularity tend to resist displacement and hence possess higher shearing strength compared to those with less angular particles.

A representative soil specimen with dimensions typically 60 mm × 60 mm square, and a thickness of about 26 mm is prepared, depending on the particle size of the soil.

The shear strength parameters, cohesion (c) and friction angle (φ) are calculated, using the following formulas:

- **Cohesion (c)**: $C = \frac{\tau_{max}}{\sigma_n}$

- **Friction Angle (φ)**: $\emptyset = tan^{-1}\left(\frac{\tau_{max}}{\sigma_n}\right)$

3.7.9. California Bearing Test (CBR) [IS: 2720, (Part 16) 1987]:

5 kg of good earth was measured and mixed with 20% water according to the OMC (Optimum Moisture Content) value. Attaching the extension collar and base plate to the mould, the spacer disc was placed on top of the base plate and a filter paper was laid over the spacer disc the soil mixture was compacted in the mould in three layers, using a 2.6 kg rammer to apply 56 blows per layer. Removing the collar and trimming the excess soil, the mold was turned upside down to remove the base plate and spacer disc. The mould was weighed with the compacted soil to calculate the bulk density and dry density. Next, a filter paper was placed on top of the compacted soil and a perforated base plate was clamped over it.

For the soaked test, the same steps were followed as described previously. Afterward, annular weights were placed on the sample to create a surcharge equivalent to the weight of the base material and pavement expected in actual construction, with a minimum of 5 kg required. The mould was immersed in a water tank for 4 days (Figure 30-a). After the soaking period, the mould was removed from the tank.

Next, the mould assembly was placed, along with the surcharge weights, onto the penetration test machine (Figure 30-b). The penetration piston was positioned at the center of the specimen and the stress-strain dial gauge was set to zero. The piston was applied at a penetration rate of approximately 1.25 mm/min. The load readings at penetrations of 0.5, 1, 1.5, 2, 2.5, 3, 4, 5, 7.5, 10, and 12.5 mm were recorded. The maximum load and the corresponding penetration depth were noted. After completing the test, the mould was removed from the loading equipment. 20 to 40 grams of soil were extracted from the center of the mould to determine the moisture content.

(a) **(b)**

Figure 30: (a)- Mould in a water tank during soaked CBR, ***(b)-*** CBR Penetration test machine (Jadavpur University, 2024)

3.8. Heavy Metal Analysis

The concentration of heavy metals in good earth was analysed using the X-ray fluorescence spectroscopy (XRF) press pellet technique to evaluate its potential as a subgrade material for road construction. The total metal content was quantified using wavelength dispersive X-ray fluorescence spectroscopy (WD-XRF, S8 Tiger, Bruker, Germany, as depicted in Figure 31), following the established protocol by Majumdar et al. in 2024.

Figure 31: X-ray Fluorescence Spectrometry (XRF) Facility, IISER Kolkata

3.9. Leachable Heavy Metals

Single batch leaching tests following SS-EN 12457-2, 2003 were carried out to determine the leachable components of good earth material. Water extract in 1:10 dilution ratio was prepared using deionized water as mentioned by Somani et al., 2020. The water extract was digested using HNO_3 following Prechthai et al. (2008) and metals were subsequently analysed by an ICP-OES spectrometer (PerkinElmer-Optima 2100 DV).

3.10. Soluble Salts

Sulphates and chlorides were determined by turbidimetric method and argentometric titration method in accordance with American Public Health Association (APHA), 2012.

3.10.1. Preparation of Soil Extracts

The soil sample, after being air-dried, is sieved through a 1mm sieve. A 5g portion of the soil sample is then mixed with 25ml of double-distilled water and this mixture is left to shake overnight. After shaking, the mixture is filtered through Whatman filter paper No. 42 to separate the solid particles from the liquid extract. Next, the filtered sample is stirred with a solution containing a 1:10 ratio of charcoal to extract for 15 minutes. Finally, the mixture is refiltered to obtain a clear extract shown in Figure 32, which is then ready for further analysis.

Figure 32: Soil Extracts (Jadavpur University, 2024)

3.11. Major Oxides

The concentrations of major oxides in soil samples were analysed using X-ray fluorescence spectroscopy (WD-XRF, S8 Tiger, Bruker, Germany) with the press pellet technique. The sample preparation and testing procedures were identical to those used for heavy metal analysis.

3.12. RDF Calorific Value Test

To determine the calorific value of Refuse-Derived Fuel (RDF) from the Howrah and Durgapur landfills, the ASTM E711-87(1996) standard is followed. First, RDF samples are collected from both landfill sites. These samples are then cut using a sizer to achieve a uniform particle size, which is crucial for accurate testing. Next, 1 gram of sized RDF is taken and form it into small pellets using a pelletizer. The calorific value of these RDF pellets is then determined using a bomb calorimeter (Instrumentation India), which burns the pellets in a controlled environment to measure their energy content (Figure 33) . This procedure is repeated three times for each sample. The energy values are then converted to a dry basis using the following equation:

$$Energy\ (dry\ basis) = Energy\ (as\ \ discarded) \times \left(\frac{100}{100 - \%\ moisture}\right)$$

Figure 33: Bomb Calorimeter (Instrumentation India)

3.13. Life Cycle Assessment

The Life Cycle Assessment (LCA) methodology comprises four essential phases: goal and scope definition, life cycle inventory (LCI) analysis, impact assessment, and interpretation, as outlined in ISO 14040 and ISO 14044 standards. This study adhered to these international standards for conducting Life Cycle Assessments. Below is a breakdown of each phase and its relevance to the study:

3.13.1. LCA Model

The LCA model has been developed in Open LCA using Ecoinvent (version 1.02) database. Default normalization factors were used based on Ecoinvent-97 data. Data inventory was developed into the system from Ecoinvent 3.0 default database and environmental footprint database along with field investigation and questionnaire surveys. ReCiPe is a midpoint-oriented life cycle impact assessment methodology which facilitates the characterization of environmental stressors that have potential effects methodology which facilitates the characterization of environmental stressors that have potential effects, including (i) Fine particulate matter formation, (ii) Fossil resource scarcity, (iii) Freshwater ecotoxicity, (iv) Freshwater eutrophication, (v) Global warming, (vi) Human carcinogenic toxicity, (vii) Human non-carcinogenic toxicity, (viii) Ionizing radiation, (ix) Land use, (x) Marine ecotoxicity, (xi) Marine eutrophication, (xii) Mineral resource scarcity, (xiii) Ozone formation-Human health (xiv) Ozone formation-Terrestrial ecosystems, (xv) Stratospheric ozone depletion, (xvi) Terrestrial acidification, (xvii) Terrestrial ecotoxicity, (xviii) Water consumption. Additionally, the IPCC GWP 100a is utilized to express the sensitivity analysis of the model.

3.13.2. Goal and Scope

The goal of this LCA study is to evaluate the environmental impacts of landfill mining (LFM) comparing with existing condition of landfill (Do nothing scenario). In this study three scenarios were considered as:

- RDF sent to cement factory or brick kiln
- Good earth used as subgrade material in roads
- Combination of the first two scenarios

Functional unit of the LCA is 1 ton of municipal solid waste. The study covers activities from excavating 1 ton of landfilled waste to processing it into Refuse-Derived Fuel (RDF) and good earth, as well as disposing of unrecovered materials.

3.13.3. Life Cycle Inventory (LCI)

The system boundary, as defined by ISO 14040, represents the interface between a product system and its environment or other product systems. For this study, processes such as landfill construction and waste collection are excluded from the scope and was not considered within the inventory. The inventory specifically covers all ingredients found in legacy waste and the fuel needed for the trommel during the biomining process. This also includes coal used in cement factories and natural soil used as subgrade of road. Some data are collected through questionnaire surveys conducted among landfill personnel, field survey and from previous studies conducted in the same study area or similar projects. All additional required data are sourced from the Ecoinvent database. A flow chart of the study is shown in Figure 34.

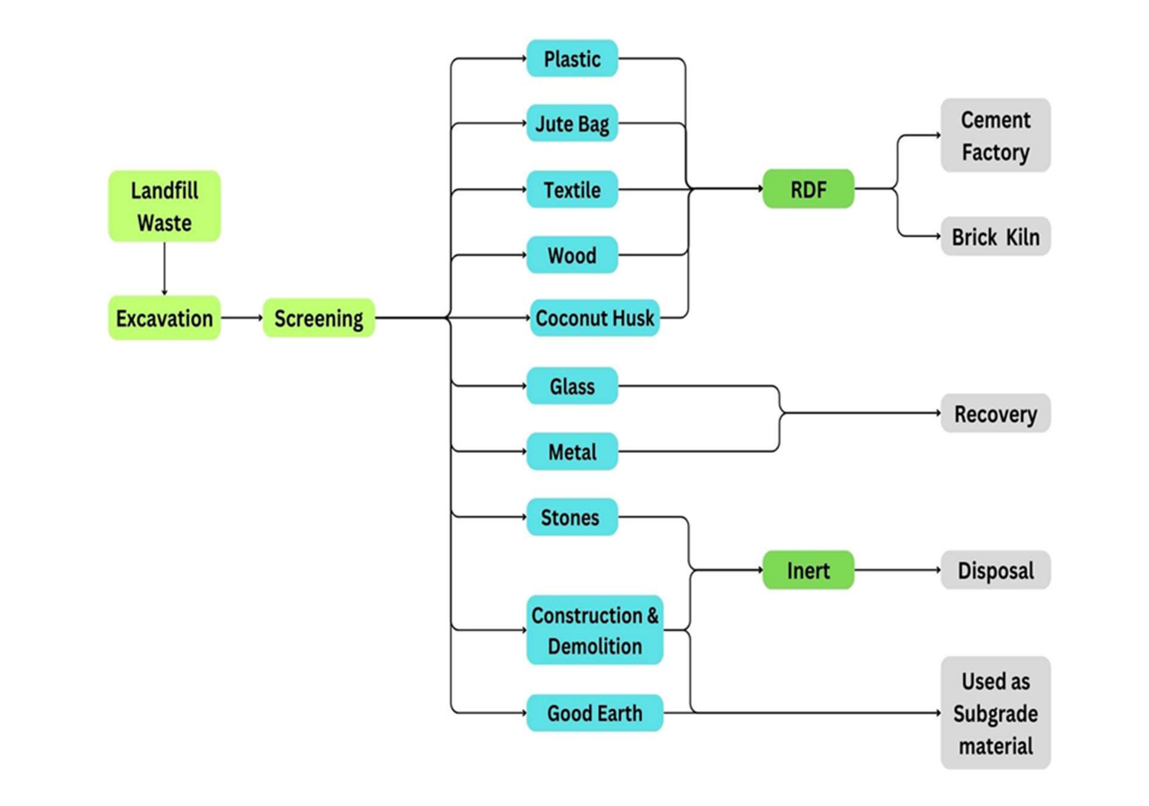


Figure 34: Biomining Products and their uses

3.13.4. Life Cycle Impact Assessment

The environmental impacts of the project's life cycle are calculated using modelled inventory data. Also, these impacts are quantified using indicators such as ReCiPe midpoint 2016 and IPCC GWP (Global Warming Potential) 100a in OpenLCA V2.1.

3.13.5. Scenario Considerations

Four scenarios were modelled to evaluate the feasibility of biomining, considering the environmental impact of mining 1 ton of MSW from each of two old landfills. Throughout all scenarios, the consistent parameter was the management of 1 ton of MSW waste, encompassing all emissions and activities associated with it. To assess the advantages of biomining over leaving the landfill undisturbed, the biomining scenarios were compared with a baseline scenario where biomined products are used for insitu filling and cover material, referred to as the 'do-nothing' scenario. The other scenarios involved sending RDF to a cement factory or brick kiln (scenario 1) and utilizing good earth for subgrade material in roads (scenario 2). The environmental impact of transportation of RDF or good earth was not included in any of the scenarios. Furthermore, a combined scenario of scenario 1 and scenario 2 was analysed. Figure 35 illustrates all the scenarios.

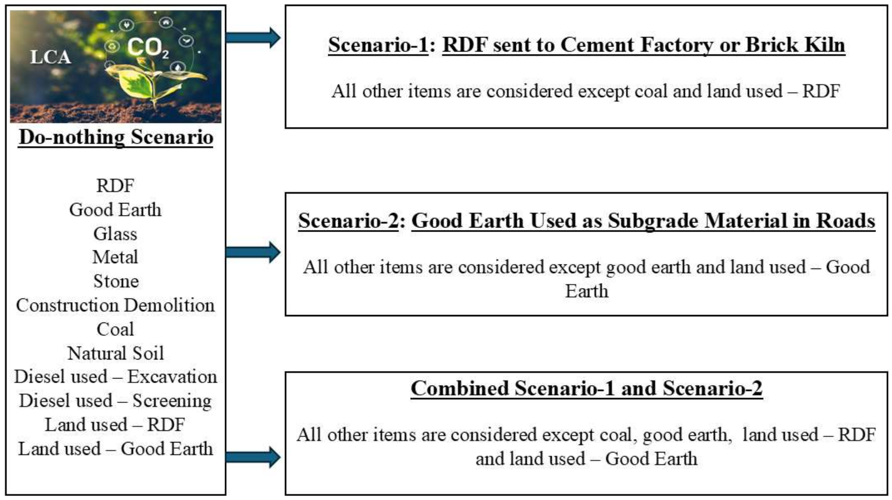


Figure 35: Illustration of All Possible Scenarios

3.13.5.1. Do-nothing Scenario

The baseline scenario evaluates the landfill's present effects after biomining operations. This means the landfill continues to affect its surroundings as it currently does. The cement factory and brick kiln still use coal as its main fuel source, which adds to its environmental impact. Moreover, natural soil remains in use as a subgrade material in roads, which may have an impact on the quantity and quality of local soil resources. These factors collectively define the existing conditions and their ongoing implications in the absence of biomining initiatives.

3.13.5.2. Scenario-1: RDF sent to Cement Factory or Brick Kiln

In this scenario of life cycle assessment (LCA) involving refuse-derived fuel (RDF) sent to cement factories and brick kilns, several environmental and economic aspects come into play. RDF, derived from non-recyclable waste materials, serves as an alternative fuel source in these industries, aiming to reduce the demand on traditional fossil fuels like coal.

The effect of natural soil used as subgrade material in roads is considered here. Furthermore, this scenario considers emissions from diesel-powered machinery like trommels, and excavators used in biomining process. Because RDF is used as fuel in brick kilns and cement factories, the environmental effects typically associated with coal combustion are excluded from this evaluation.

3.13.5.3. Scenario-2: Good Earth Used as Subgrade Material in Roads

Good earth is used as subgrade material instead of traditional natural soil, several environmental considerations arise. The effect of coal used as fuel in cement factory and brick kiln is considered here. The impact of RDF is also considered, even if it isn't used as fuel in brick kilns or cement factories. Also, this scenario considers emissions from diesel-powered machinery like trommels, and excavators used in biomining process as like scenario 1. The effect of normal soil is not considered because good earth is put in its place.

3.13.5.4. Combined Scenario-1 and Scenario-2

This scenario evaluates the environmental impacts of both Scenario-1 and Scenario-2, specifically analysing the effects of RDF as a partial replacement of coal in cement industry or brick kiln and good earth as subgrade material in road construction projects. It does not account for the impacts of coal or traditional soil but considers the use of diesel in machinery during the biomining process.

3.13.6. Sensitivity Analysis and Uncertainty Analysis in LCA

Sensitivity and uncertainty analyses are crucial in a Life Cycle Assessment (LCA) of a landfill mining project because they provide insight into the reliability and precision of the results. Sensitivity analysis reveals which variables have the greatest impact on the outcomes, allowing for a better understanding of key drivers and informing more targeted decision-making. Meanwhile, uncertainty analysis assesses the range of possible outcomes by considering variability in data and assumptions, which helps quantify the confidence in the results. Together, these analyses make sure that the LCA results are clear, useful and helping manage risks and guiding future improvements in the project.

3.13.6.1. Sensitivity Analysis

A sensitivity analysis of the Do-Nothing scenario, the effects of varying Refuse Derived Fuel (RDF) and Good Earth ingredients on the Global Warming Potential (GWP), as measured by the IPCC GWP 100a, are examined adjusting RDF ingredients by ±15% from baseline levels and recalculating the GWP. Similarly, ±15% adjustments in Good Earth ingredients are analysed to determine their impact on GWP. This analysis identifies the relative influence of each ingredient on GWP, identify which factor has a more significant effect.

3.13.6.2. Uncertainty Analysis

In the Monte Carlo uncertainty analysis, four scenarios are evaluated using the ReCiPe Midpoint 2016 method as an indicator. This process involves running 1000 simulations to account for variability and uncertainty in the input parameters for each scenario.

3.14. CO_2 Generation Due to Transportation of RDF

To assess the CO_2 generation associated with the transportation of Refuse-derived Fuel (RDF), a methodology was developed focusing on comprehensive data collection and calculation procedures. At first, the transportation routes for RDF from its processing site at the Howrah and Durgapur landfills to designated end-users were estimated by using geographic information system (GIS) tools.

Next, fuel consumption per 100km for a specific truck having gross weight of 25–31 tons was calculated. This value is multiplied by the round-trip distance to determine total fuel use. By incorporating data on CO_2 generation per Liter of diesel, the total CO_2 emissions for a round trip is calculated. Finally, dividing this total by the amount of waste transported per trip yields the CO_2 generated per ton of waste.

Overall, this methodology enabled a systematic evaluation of CO_2 generation attributable to RDF transportation, providing essential data for assessing the environmental footprint associated with this aspect of landfill biomining operations.

3.15. Landfill Gas Emission Calculation

The study examines landfill gas generation in Howrah and Durgapur landfill sites. Population data from the 1991, 2001, and 2011 censuses was collected to assess demographic patterns. From Howrah's historical development, a logistic growth model is applied to project population changes, while Durgapur, being a growing city, utilized a geometric increase model. Then waste generation per capita is considered, and total annual waste generation is calculated accordingly.

Next, The LandGEM model version 3.1 is applied, incorporating parameters such as waste generation per year, methane generation rate per year, and landfill geographical region, to calculate emissions of gases including total landfill gas, methane, carbon dioxide, and non-methane organic compounds.

3.15.1. Logistic Growth Model

In logistic growth, population expansion slows down as the carrying capacity of the environment is reached, resulting in an S-shaped curve. The equations involved in this model are discussed below.

The population after any time from the start (P) is given as

$$P = \frac{P_s}{1 + m log_e^{-1}(nt)}$$

The saturation population (P_s):

$$P_s = \frac{2P_0P_1P_2 - P_1^2(P_0 + P_2)}{P_0P_2 - P_1^2}$$

- P_0 = Population at the beginning of census record
- P_1 = Population after time t_1 years
- P_2 = Population after time t_2 years
- m & n = Constants

$$m = \frac{P_s - P_0}{P_0}$$

$$n = 2.3\frac{1}{t}\log_{10}\left[\frac{P_0(P_s - P_1)}{P_1(P_s - P_0)}\right]$$

3.15.2. Geometric Increase Model

The geometric increase model is suitable for cities with unlimited potential for future expansion and where a constant rate of growth is expected.

Population after ‘n’ decades:

$$P_n = P_0\left(1+\frac{k}{100}\right)^n$$

Average percentage growth rate per decade:

$$k = \sqrt[m]{k_1 k_2 k_3 \ldots\ldots k_m}$$

- P_0 = Initial Population
- n = Number of decades

3.16. Cost Benefit Analysis

The cost-benefit analysis for the waste biomining project involves several steps to assess its economic viability. Firstly, the amount of waste processed annually by the trommel was calculated based on its capacity and operational hours per day. From this data the amount of coal and traditional soil replaced was calculated. To evaluate the economic efficiency of replacing coal with Refuse-Derived Fuel (RDF) and traditional soil with "Good Earth", the costs and benefits were quantified.

Cost includes the land acquisition costs, machinery costs encompassing the purchase and installation of equipment like trommels, and ongoing operational expenses such as fuel costs for waste transportation, labour expenses, and expenditures for maintenance and repairs. Additionally, working capital requirements are factored in to ensure smooth project operation. Once all costs are quantified, the cost-benefit ratio, which compares total benefits to total costs, was computed to determine the project's economic efficiency. Furthermore, the Net Present Value (NPV) was calculated to assess the project's profitability over its lifecycle, considering the time value of money.

• Cost-Benefit Ratio

$$Cost - Benefit\ Ratio = \frac{Total\ Benefits}{Total\ Costs}$$

- **Cost-Benefit Ratio > 1:** Benefits are greater than costs, suggesting the investment could be a good choice.
- **Cost-Benefit Ratio < 1:** Costs are greater than benefits, indicating the investment might not be worthwhile.
- **Cost-Benefit Ratio = 1:** Benefits and costs are equal, meaning the investment breaks even.

• Net Present Value (NPV)

$$NPV = \frac{Total\ Benefits}{(1+r)^t} - Total\ Costs$$

- r = Discount rate
- t = Time period

Chapter 4: Results and Discussion

4.1. Introduction

Landfill biomining offers a solution for both cleaning up landfills and recovering resources from waste. This study analysed its potential through geotechnical property assessments, heavy metal evaluation, life cycle assessment (LCA), and cost-benefit analysis at two different sites: Howrah landfill and Durgapur landfill.

The extraction and utilization of resources from landfills not only mitigate environmental hazards but also present opportunities for sustainable resource management. This section presents the detailed results obtained from the assessments and discusses their implications for environmental sustainability and economic viability, supporting the adoption of landfill biomining as a sustainable solution within broader environmental management practices.

4.2. Composition analysis

In analysing the composition of legacy waste at landfill sites in Howrah and Durgapur, distinct differences were observed, highlighted variations in waste characteristics between the two cities. The composition analysis is shown in Table 9.

Table 9: Composition Analysis of Howrah and Durgapur Landfill Site

Waste Item	Howrah Landfill Site (%)	Durgapur Landfill Site (%)
Plastic	15.38	19.56
Good Earth	51.78	39.56
Jute Bag	5.05	6.81
Textile	1.56	3.31
Wood	1.66	1.82
Glass	2.47	2.27
Stones	8.65	11.36
Construction & Demolition	5.46	7.81
Coconut Husk	6.28	4.41
Metal	0.52	1.68
Undefined	1.224	1.41

In Howrah, the waste stream is notably higher in "Good Earth" content, accounting for 51.78% of the landfill material, compared to 39.56% in Durgapur. This suggests that Howrah's waste has a greater proportion of organic or biodegradable material, which could be indicative of different residential or commercial waste generation patterns.

Conversely, Durgapur's waste stream has a higher percentage of plastics (19.56%) compared to Howrah's waste (15.38%) and stones (11.36% versus Howrah's 8.65%), reflecting a greater presence of non-biodegradable and inert materials. This difference might be attributed to variations in local consumption habits, industrial activities, or construction practices.

Additionally, Durgapur's landfill contains a higher percentage of metals (1.68% compared to 0.52% in Howrah), which could point to differences in the types of goods consumed or the efficiency of recycling programs in the area.

The presence of jute bags, textiles, and construction and demolition debris are also slightly higher in Durgapur, which may indicate variations in packaging materials and construction activities between the cities. For instance, the greater presence of textiles and jute bags could reflect regional preferences or industrial activities.

This composition analysis of legacy waste reveals that Durgapur's landfill contains a higher percentage of materials suitable for producing Refuse-Derived Fuel (RDF) compared to Howrah. Specifically, Durgapur landfill contains 359.1 kg of RDF per ton of waste, while Howrah landfill has 299.11 kg per ton. As a result, the Durgapur landfill site can replace more coal with RDF compared to Howrah. This is advantageous from an energy perspective, as utilizing RDF reduces dependence on fossil fuels and promotes waste-to-energy solutions

4.3. Physicochemical Properties of Good Earth

The evaluation of physicochemical properties of Good earth from Howrah and Durgapur landfill sites is crucial to determine its suitability as subgrade material for road construction. This study summarizes the test results with existing literature and the standards set by the Ministry of Road Transport and Highways (MoRTH, 2013), India in Table 10.

Table 10: Physicochemical Properties of Good Earth

Literature & Test Result	pH	Electric Conductivity (dS/m)	Colour (PCU)	Organic carbon	Organic matter content (%)
Manoj Datta et al., 2020	7.1-8.0	0.8-6.5	330-925	2.90-8.12	5.0-14.0
Najamuddin et. al., 2021	-	-	325-580	3.48-10.44	6.0-18.0
Devahi et al., 2022	7.2-8.0	0.6-2.45	380-819	3.77-11.37	6.5-19.6
Howrah Site	7.18	3.1	241.125	2.25	3.88
Durgapur Site	7.32	3.36	233.05	2.11	3.64
Background Soil	6.8	3.7	30	0.81	0.81
MoRTH, 2013	6.0-8.5	-	-	-	< 3%

4.3.1. pH

The pH values for both Howrah and Durgapur sites fall within the acceptable range (6.0-8.5) specified by MoRTH and are consistent with literature values. This suggests that the soils have a neutral to slightly alkaline nature, which is favourable for soil stability and compatibility with other construction materials. Proper pH levels help in minimizing adverse chemical reactions and ensuring the longevity of the road infrastructure.

- **Howrah Site:** 7.18
- **Durgapur Site:** 7.32

4.3.2. Electric Conductivity (EC)

The electric conductivity values for both Howrah and Durgapur sites are within the broader range reported in the literature but are on the higher side. Elevated EC can indicate high salinity, which may adversely affect the compaction of the material and its interaction with other road construction materials. Although MoRTH does not provide specific limits for EC, high salinity can lead to issues with stability and compaction efficiency (Ying et al., 2021), potentially requiring additional management or treatment to mitigate these effects.

- **Howrah Site:** 3.1 dS/m
- **Durgapur Site:** 3.36 dS/m

4.3.3. Colour (PCU)

The colour values of good earth from Howrah and Durgapur landfill sites are lower than those reported in the literature. While colour is not a regulated parameter by MoRTH, it can provide insights into the organic content and soil composition. The colour of good earth can also influence the appearance of local surface water bodies, which should be monitored to ensure that good earth does not adversely affect water colour. Lower colour values may indicate reduced levels of organic matter, which is generally favourable for subgrade material and contributes to better soil performance and stability under load.

- **Howrah Site:** 241.125

- **Durgapur Site:** 233.05

4.3.4. Percentage of Organic Carbon & Organic Matter

The percentage of organic carbon in soils tested for use as subgrade material in road construction was 2.25% at the Howrah landfill site and 2.11% at the Durgapur landfill site. These values reflect moderate organic content in both locations.

The organic matter content at both Howrah and Durgapur sites exceeds the MoRTH limit (<3%). High organic matter can negatively impact soil strength and stability, leading to potential settlement and deformation issues under load. For effective use as road subgrade material, it is essential to either reduce the organic matter content through treatment or stabilization techniques or blend the material with other stabilizing agents to ensure it meets the required performance standards.

All the physicochemical values of good earth are within the acceptable range. But the organic matter content exceeds the MoRTH limit. To address this, 20% construction and demolition (C&D) waste is mixed with good earth to reduce the organic matter content and bring it within MoRTH specifications.

4.4. Geotechnical Property of Good Earth

This section analyses and interprets the geotechnical test results for good earth samples from landfill sites in Durgapur and Howrah, focusing on their suitability as subgrade material for road construction. It examines key properties such as load-bearing capacity, stability, and overall performance. By comparing these results with standard engineering criteria, the discussion will highlight significant findings, assess the strengths and weaknesses of the materials, and explore their implications for road construction. Additionally, recommendations will be provided for addressing any challenges related to using these good earth samples in road subgrade applications.

In this study, the test results are evaluated against the existing literature and the standards set by the Ministry of Road Transport and Highways (MoRTH, 2013), India, which are detailed in the accompanying Table 11.

Table 11: Comparision Result of Geotechnical Properties of Good Earth

Literature & Test Result	Water Content (%)	Specific Gravity	Atterberg Limit		Void Ratio	Porosity (%)	MDD (g/cc)	OMC (%)	Shear Strength	
			LL (%)	PL (%)					C (kPa)	Φ (Degree)
Datta et al., 2020	8-10	2.10 - 2.75	-	-	0.255 - 0.272	20.36 - 21.42	-	-	7.6-24	34-38
Rawat et al., 2021	-	2.32	33.34	N.P.	-	-	1.51	18.4	57.11	30.61
Najamuddin et. al., 2021	-	2.20 - 2.30	-	N.P.	0.485	32.67	1.35-1.68	16-28	24	36
Devahi et al., 2022	-	2.11 - 2.67	26	N.P.	0.221 - 0.507	18.07 - 33.65	1.21	16	32.67	38-44.2
Qin et al., 2023	-	2.51	29.54	18.51	-	-	1.72	18.93	74.35	36.59
Reddy et al., 2024	20.2 - 21.5	2.28 - 2.41	35.3 - 36.2	Not defined	-	-	1.6 - 1.64	17.5 - 19.5	-	-
Howrah Site	19.21	2.279	28.65	N.P.	0.4155	29.35	1.621	19.94	30.2	39.58
Durgapur Site	14.06	2.185	27.68	N.P.	0.551	35.52	1.627	18.75	26.5	41.00
Background Soil Data	7.24	2.34	36.82	18.37	0.391	28.10	1.894	13.05	52.46	33.29
MoRTH, 2013	8-20	-	< 45	< 25	-	-	1.6-2.0	10-20	< 30	15-35

- **C** – Cohesion
- **Φ** – Angle of Internal friction
- **L.L.** – Liquid Limit
- **P.L.** – Plastic Limit
- **N.P.** – Non plastic

4.4.1. Detailed Analysis of Geotechnical Properties

In this analysis, the soil properties from the Howrah and Durgapur landfill sites will be evaluated by comparing them with background soil data and literature values, as well as the MoRTH (Ministry of Road Transport and Highways) standards. The parameters considered include water content, grain size, specific gravity, Atterberg limits, maximum dry density (MDD), optimum moisture content (OMC), shear strength and California bearing ratio (CBR).

4.4.1.1. Water Content (%)

At the Howrah site, the water content is 19.21%, whereas at the Durgapur site, it is 14.06%. The higher moisture level at Howrah is typical for landfill soils, probably due to ongoing biological activity and leachate accumulation from decomposing organic materials. In contrast, while the moisture content at Durgapur is within the MoRTH range, it is still higher than typical background soil data. This suggests that although Durgapur's landfill soil is less saturated than Howrah's, it remains elevated due to similar probable factors, including leachate and organic material.

4.4.1.2. Sieve Analysis

The sieve analysis of good earth from the Durgapur and Howrah landfill sites provides crucial information about their particle size distribution, which is essential for assessing their suitability for road construction.

For the Durgapur Landfill site, the sieve analysis shows the following distribution:

- **Coarse Sand:** 0.7%
- **Medium Sand:** 43.7%
- **Fine Sand:** 49.6%
- **Fine Fraction (Silt and Clay):** 6%
- **Coefficient of Uniformity (Cu):** 3.2
- **Coefficient of Curvature (Cc):** 1.089

The significant presence of fine sand (49.6%) in Durgapur's sample indicates that nearly half of the good earth consists of smaller particles. Fine sand tends to compact less effectively compared to coarser sands, which can affect the soil's stability and drainage properties. The 6% fine fraction (silt and clay) further suggests a minor presence of materials that could potentially impact drainage and compaction, though the effect might be less pronounced compared to a soil with higher fine content. The particle size distribution of Durgapur landfill site is shown in Figure 36.

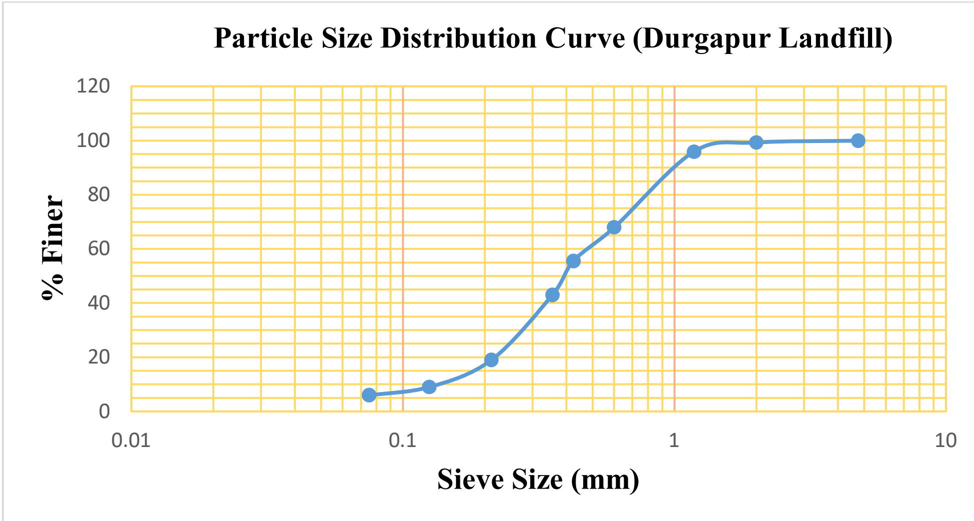


Figure 36: Particle Size Distribution Curve (Durgapur)

For the Durgapur Landfill site, the sieve analysis shows the following distribution:

- **Coarse Sand:** 0.8%
- **Medium Sand:** 57.2%
- **Fine Sand:** 37.6%
- **Fine Fraction (Silt and Clay):** 4.4%
- **Coefficient of Uniformity (Cu):** 3.056
- **Coefficient of Curvature (Cc):** 1.237

The Howrah sample contains 49.6% medium sand, this can affect soil stability and drainage, as fine sand compacts less effectively than coarser sand. The 4.4% fine fraction (silt and clay) suggests a minor impact on drainage and compaction. Figure 37 shows the particle size distribution of Howrah Landfill site.

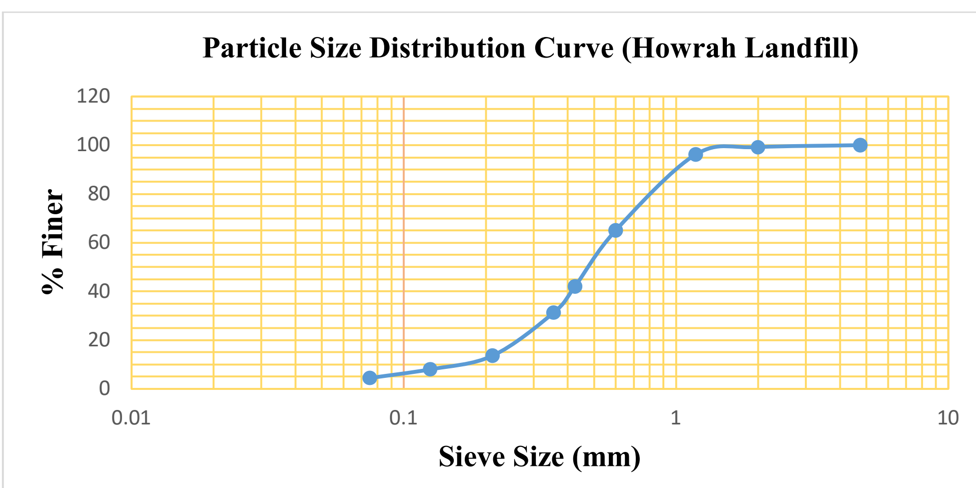


Figure 37: Particle Size Distribution Curve (Howrah)

The Uniformity Coefficient (Cu) measures the range of particle sizes in soil, with Durgapur at 3.2 and Howrah at 3.056, indicating both soils have a moderate range. This suggests they are suitable for road subgrade applications when properly compacted. The Coefficient of Gradation (Cc) assesses the distribution of particle sizes, with Durgapur scoring 1.0889 and Howrah 1.237. Both values fall within the ideal range of 1 to 3, suggesting that the soils are well-graded. However, due to their Cu values, they are considered poorly graded. Howrah's slightly better Cc value implies a more favourable particle size distribution, which can enhance compaction and stability compared to Durgapur.

4.4.1.3. Specific Gravity

Howrah Site: 2.279
Durgapur Site: 2.185
Background Soil Data: 2.34

At the Howrah site, the specific gravity of 2.279 is lower than the background soil's value of 2.34, reflecting the impact of lighter materials such as plastics and decomposed organic matter typically found in landfills. In comparison, the Durgapur site exhibits an even lower specific gravity of 2.185, suggesting a greater proportion of lightweight materials or a higher degree of decomposition. This lower specific gravity at Durgapur is indicative of a higher presence of less dense waste materials compared to Howrah.

4.4.1.4. Atterberg Limits

• Liquid Limit (LL):

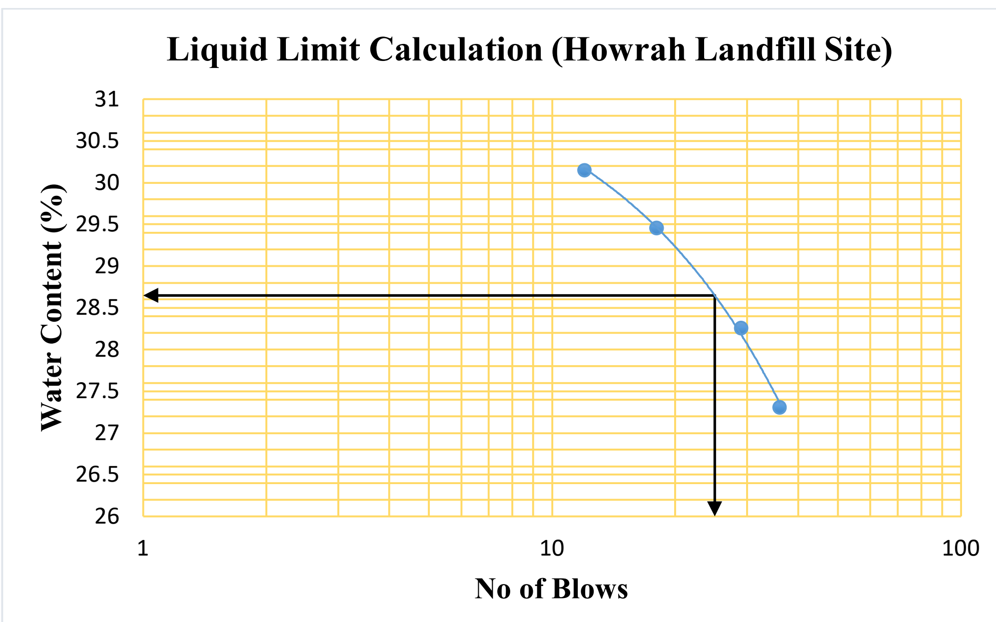


***Figure 38*:** Liquid Limit - Howrah Landfill Site

From Figure 38 the equation of the curve is

$$y = -0.1168x + 31.57$$

Based on the equation, when the number of blows (X) is 25 and the corresponding moisture content (Y) is 28.65%. The liquid limit of good earth from the Howrah landfill site is to be 28.65%.

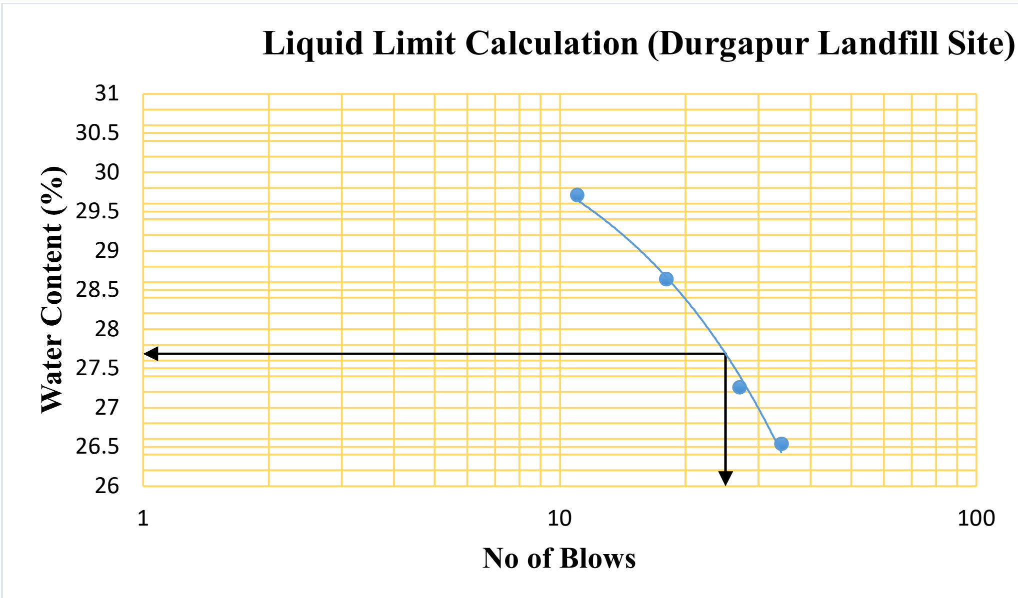


Figure 39: Liquid Limit - Durgapur Landfill Site

From Figure 39 the equation of the curve is

$$y = -0.1399x + 31.185$$

According to the equation the liquid limit of good earth from Durgapur landfill site is 27.68%.

• **Plastic Limit (PL):** The plastic limit (PL) at both sites indicates that the soil is non-plastic, meaning that it does not exhibit plasticity behaviour.

At both the Howrah and Durgapur sites, the Liquid Limit (LL) values are 28.65% and 27.68%, respectively, both well within the MoRTH standard of less than 45%. Additionally, the Plastic Limit (PL) for both samples is classified as non-plastic. The relatively high LL values, compared to background soil, can be attributed to the presence of fine materials and decomposed organic waste. These factors enhance the good earth's water absorption capacity, thereby affecting its plasticity.

4.4.1.5. Proctor Analysis Value

The Proctor analysis values for good earth at the Howrah landfill site and Durgapur landfill site are presented in Table 12 & Table 13 respectively.

• **Howrah Landfill Site:**

Table 12: Howrah Landfill Proctor Values

Percentage water increased	4	8	12	16	20	24	28
Wt. of Mould + compacted Soil	6034	6112	6196	6285	6391	6410	6402

Wt. of compacted Soil	1481.5	1559.5	1643.5	1732.5	1848.2	1857.5	1850
Bulk Density	1.56	1.64	1.73	1.82	1.94	1.95	1.95
Can No.	26	90	612	6	16	10	322
Wt. of empty can (W1)	26.51	14.45	11.5	13.5	20	21	15.5
Wt. of can + Wt. of wet soil (W2)	45.224	38.24	34.54	42.418	52.169	56.542	47.22
Wt. of Can + Dry soil (W3)	44.425	36.32	31.98	38.452	46.822	49.442	40.22
w=[(W2-W3)/(W3-W1)] × 100	4.46	8.78	12.50	15.89	19.94	24.96	28.33
Dry Density= (Bulk Density)/(1+w)	1.492	1.508	1.537	1.573	1.621	1.564	1.516

From the above table a graph is plotted between water content and dry density (Figure 40).

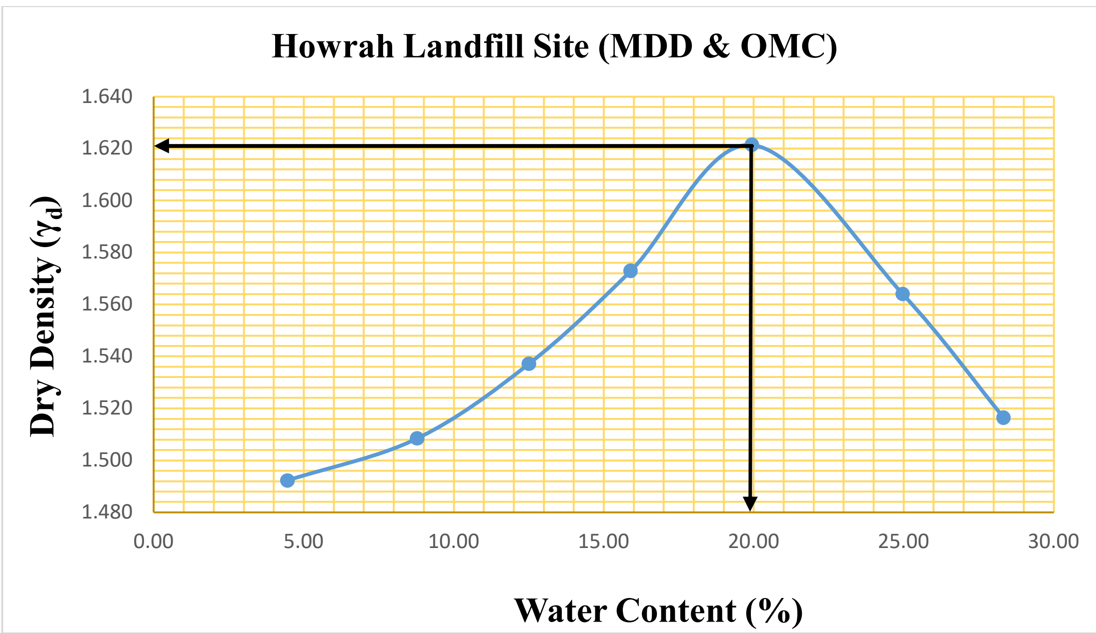


Figure 40: Water Content verses Dry Density (Howrah Landfill Site)

• Maximum Dry Density (MDD):

The Howrah site MDD of 1.621 g/cc falls within the MoRTH standard range of 1.6 - 2.0 g/cc. Comparing to the Background Soil Data, the Howrah site's MDD is lower (1.621 g/cc vs. 1.894 g/cc), indicating the Howrah soil might have a lower compaction capability or could contain more finer particles or organic matter affecting its density.

• Optimum Moisture Content (OMC):

The Howrah site OMC of 19.94% is within the MoRTH standard range of 10 - 20%. It is higher compared to the Background Soil Data OMC of 13.05%. This higher moisture content could suggest that the Howrah soil retains more water, possibly due to higher organic content or other factors related to its landfill origin.

• Durgapur Landfill Site:

Table 13: Durgapur Landfill Proctor Values

Percentage water increased	4	8	12	16	20	24	28
Wt. of Mould + compacted Soil	6054	6137	6221	6310	6394	6421	6428
Wt. of compacted Soil	1501.5	1584.5	1668.5	1757.5	1841.5	1868.5	1875.5
Bulk Density	1.58	1.67	1.76	1.85	1.94	1.97	1.97
Can No.	602	4	73	32	52	40	42
Wt. of empty can (W1)	11.5	13.4	17.1	13.5	20.8	15.5	15.5
Wt. of can + Wt. of wet soil (W2)	40.76	34.02	41.68	43.95	45.81	40.445	51.575
Wt. of Can + Dry soil (W3)	39.623	32.551	39.015	39.811	41.802	35.521	43.721
w=[(W2-W3)/(W3-W1)] × 100	4.04	7.67	12.16	15.73	19.08	24.59	27.83
Dry Density= (Bulk Density)/(1+w)	1.518	1.548	1.565	1.598	1.627	1.578	1.544

Figure 41 shows the relationship between water content & dry density at the Durgapur landfill.

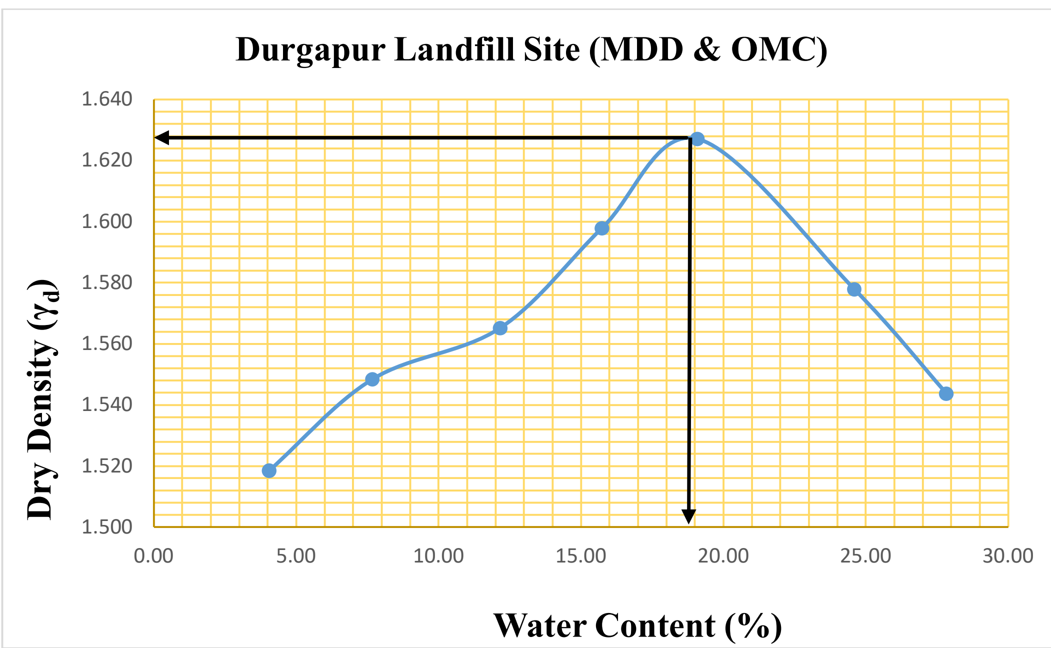


Figure 41: Water Content verses Dry Density (Durgapur Landfill Site)

• Maximum Dry Density (MDD):

The MDD of 1.627 g/cc for the good earth sample is closer to the lower end of the MoRTH standard range of 1.6 - 2.0 g/cc. This indicates that the soil has a somewhat better compaction capability or potentially lower moisture content compared to the Howrah landfill site good earth. The difference in MDD could be attributed to varying waste compositions or more efficient compaction processes employed at Durgapur landfill site.

• Optimum Moisture Content (OMC):

The OMC of 18.75% for this sample falls within the MoRTH standard range of 10 - 20%, but it is still higher than the background soil's OMC of 13.05%. This suggests that while the moisture content is somewhat more controlled or lower compared to the Howrah landfill site, it remains elevated, likely due to similar factors related to landfill conditions.

Overall, the Good Earth samples from the Howrah and Durgapur landfill sites meet MoRTH standards. However, their higher optimum moisture content (OMC) compared to the background soil, and their maximum dry density (MDD) being closer to the lower end of the acceptable range, indicate some concerns. These factors suggest that while the soil is generally suitable for use as subgrade material, additional measures may be needed to manage the higher moisture content and ensure that compaction and stability meet the required engineering specifications.

4.4.1.6. Void Ratio and Porosity

The void ratio and porosity values of good earth from Howrah and Durgapur sites provide important insights into their suitability as road subgrade material. At Howrah, a void ratio of 0.4155 and porosity of 29.35% and at Durgapur, a void ratio of 0.551 and porosity of 35.52% indicate relatively low void spaces, suggesting a moderate capacity for compaction and potentially better strength and load-bearing capacity when the good earth is properly compacted. This lower void ratio generally correlates with enhanced soil strength, which is beneficial for supporting loads on roads. Devahi et al., 2022 and Najamuddin et al., 2021 also reported void ratio and porosity is this range as presented in Table 11.

4.4.1.7. Permeability

In the Falling Head Permeameter test, the calculated average coefficient of permeability (K) values are as follows:

- **Durgapur:** K= 0.0225 cm/s
- **Howrah:** K= 0.0324 cm/s

In road construction, the coefficient of permeability is a crucial factor in assessing the suitability of subgrade materials. The tested good earths from Durgapur and Howrah show varying permeability values that affect their performance. The Durgapur sample, with a permeability of 0.0225 cm/s, has relatively low permeability compared to the Howrah sample. In contrast, Howrah good earth, with a higher permeability of 0.0324 cm/s, facilitates better drainage, which helps mitigate water-related issues and enhances road stability. However, both types of good earth may require appropriate design modifications or treatment to optimize their effectiveness in supporting the road structure.

4.4.1.8. Shear Strength

• **Howrah Landfill Site:**

The direct shear test was conducted three times for each sample using surcharge weights of 4.5 kg, 9 kg, and 13.5 kg. The resulting normal stress values were 0.0613125, 0.122625, and 0.1839375 N/mm², respectively, and the corresponding shear stress values were 0.0794, 0.1344, and 0.1807 N/mm² for the Howrah landfill site. A graph of normal stress versus shear stress is plotted, as shown in Figure 42.

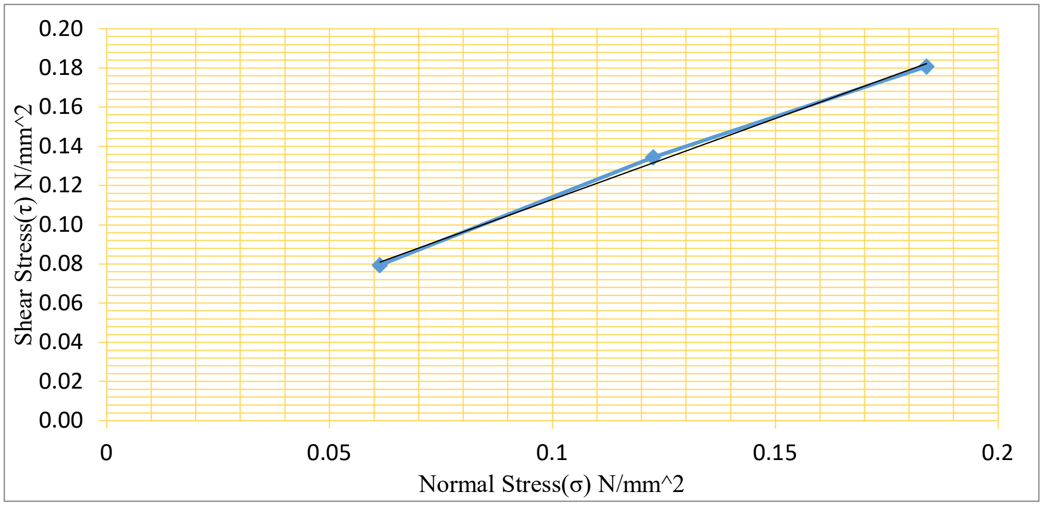


Figure 42: Normal Stress vs. Shear Stress at the Howrah Landfill Site

The equation derived from the graph is:

$$y = 0.8261x + 0.0302$$

From this equation, the cohesion (C) value is calculated to be 30.2 kPa, and the angle of internal friction is 39.58˚. The cohesion value of 30.2 kPa is just above the MoRTH limit, while the angle of internal friction of 39.58° is higher. The increased shear strength may be due to the presence of fine materials and partial compaction, which provide additional resistance. However, the higher water content and organic materials can reduce the shear strength over time.

• **Durgapur Landfill Site:**

The resulting normal stress values were 0.0613125, 0.122625, and 0.1839375 N/mm², respectively, and the corresponding shear stress values were 0.0783, 0.1358, and 0.1848 N/mm² for the Durgapur landfill site. A graph of normal stress versus shear stress is plotted, as shown in Figure 43.

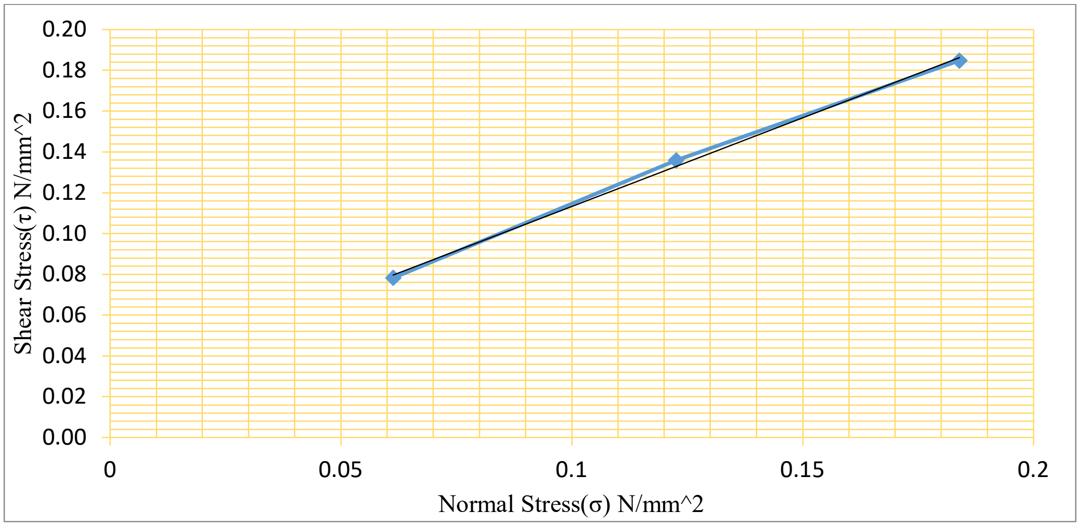


Figure 43: Normal Stress vs. Shear Stress at the Durgapur Landfill Site

The equation derived from the graph is:

$$y = 0.8685x + 0.0265$$

With a cohesion of 26.5 kPa and an angle of internal friction of 41°, this site shows relatively lower shear strength. This could be due to better compaction practices or a different waste composition that provides higher frictional resistance compared to Howrah. However, the contribution from cohesion is also significant and direct. Since Howrah has a higher cohesion, it means that even if the friction angle contribution is less, the total shear strength can still be higher if the normal stress (σ) is not excessively high.

4.4.1.9. California Bearing Ratio (CBR)

The California Bearing Ratio (CBR) measures the load required to achieve 2.5 mm or 5 mm of penetration in a material compared to a standard load for crushed rock or stones. In this study, CBR values are assessed under both unsoaked and soaked conditions (for 96 hours).

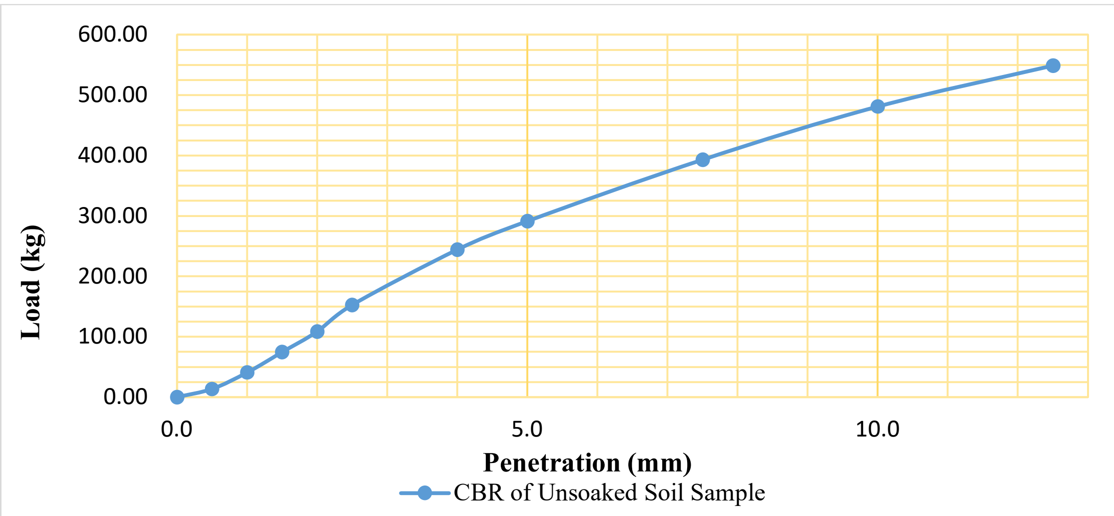
Howrah Landfill Site:

The CBR values for the Howrah good earth sample under soaked and unsoaked conditions are presented in Table 14, with the associated penetration (mm) versus load (kg-f) graph shown in Figure 44.

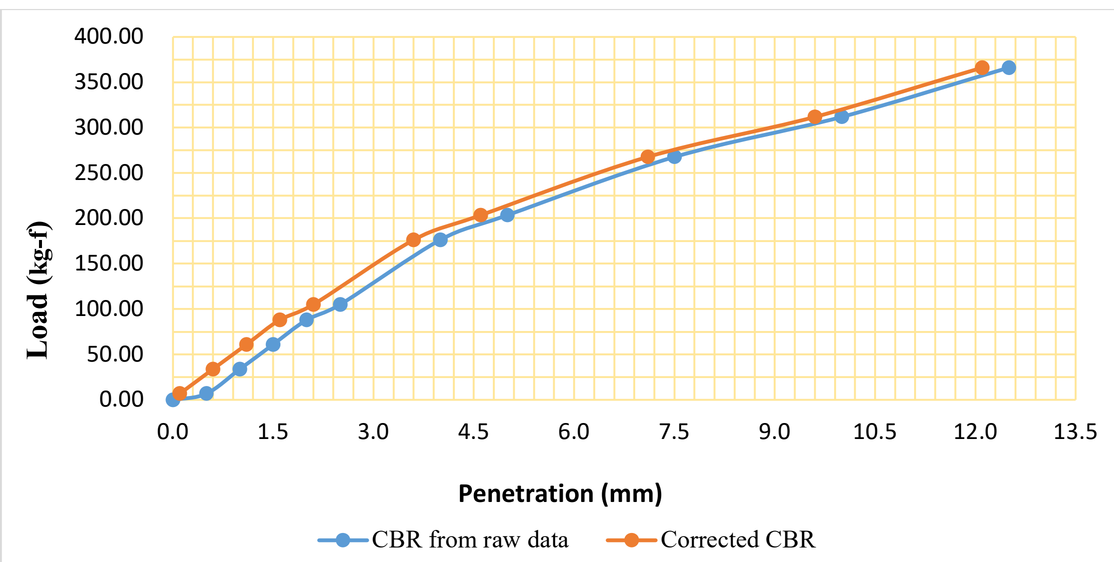
Table 14: CBR Value of Howrah Landfill Site

Conditions	Penetration Value	CBR (%)
Unsoaked CBR	2.5	11.13
	5.0	14.18
Soaked CBR	2.5	7.67
	5.0	9.89

Conditions	Penetration Value	CBR (%)
Soaked CBR with Concavity Correction	2.5	9.05
	5.0	10.40
Reddy et al., 2024 (Unsoaked)	-	9.34-11.82
Reddy et al., 2024 (Soaked)	-	6.8-11.78
MoRTH Standard	-	>7



(a)



(b)

Figure 44: **[(a)-** Unsoaked CBR; **(b)-** Soaked and Corrected CBR] (Howrah Landfill Site)

The results from testing the Howrah good earth sample provide valuable insights into its load-bearing capabilities under various conditions. Both soaked and unsoaked conditions show high CBR values at 5 mm penetration, prompting a repetition of the test, which confirmed consistently high results at this penetration depth. The unsoaked CBR values are notably higher, while the soaked values are significantly lower, reflecting a reduction in soil strength due to moisture saturation. Concavity correction addresses this non-linear behavior by adjusting the measurements to better reflect the soil's true strength and performance in field conditions (IS: 2720 Part 16, 1987). After applying concavity correction, the soaked CBR values improve slightly, with corrected values of 9.05% and 10.40% for 2.5 mm and 5.0 mm penetration, respectively, suggesting a more accurate representation of the good earth's performance under saturated conditions.

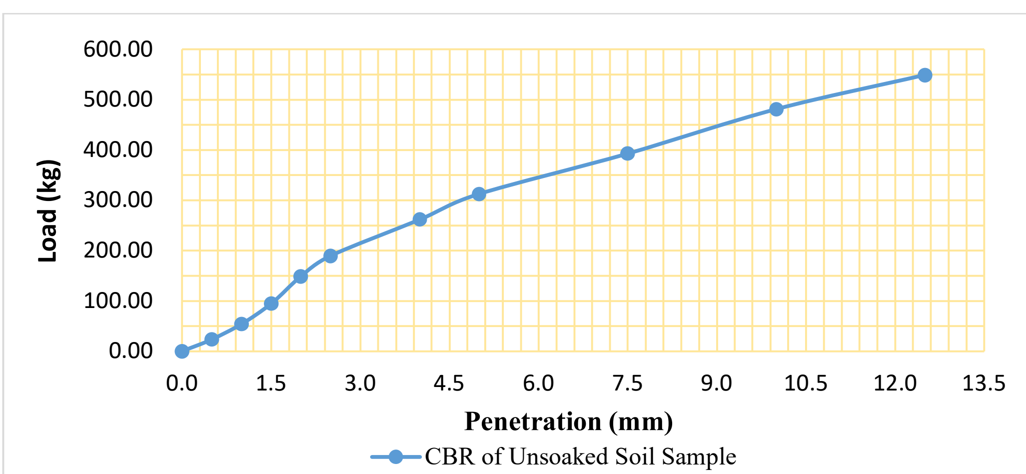
Durgapur Landfill Site:

The CBR values for the Durgapur sample under both soaked and unsoaked conditions are presented in Table 15 and graph shown in Figure 45.

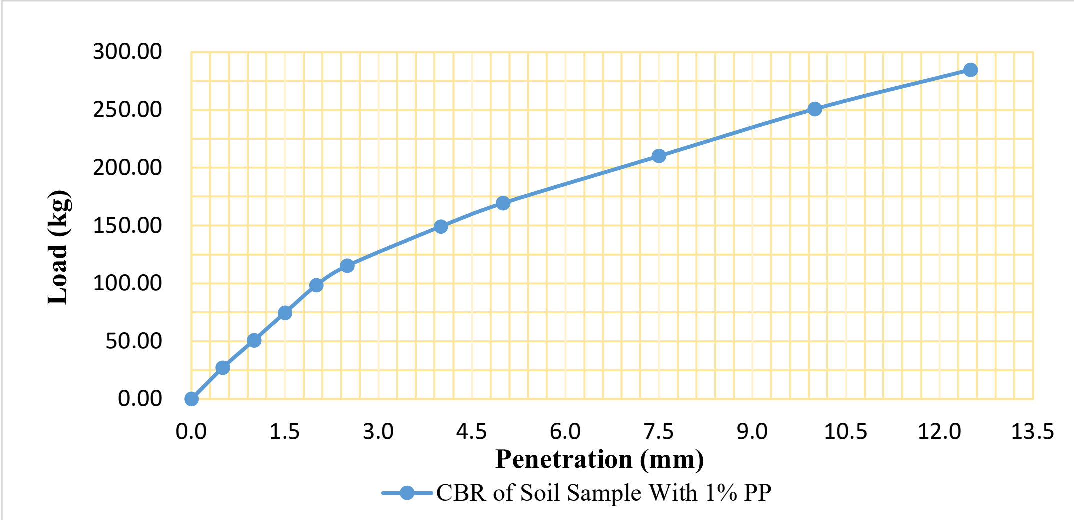
Table 15: CBR Value of Durgapur Landfill Site

Conditions	Penetration Value	CBR (%)
Unsoaked CBR	2.5	13.85
	5.0	15.22
Soaked CBR	2.5	8.41
	5.0	8.25
Reddy et al., 2024 (Unsoaked)	-	9.34-11.82
Reddy et al., 2024 (Soaked)	-	6.8-11.78
MoRTH Standard	-	>7

The data shows that at 5 mm penetration, the Durgapur good earth sample exhibits a high CBR value only under unsoaked conditions. Therefore, there is no need to repeat the test under soaked conditions.



(a)



(b)

Figure 45: **[(a)-** Unsoaked CBR; **(b)-** Soaked CBR] (Durgapur Landfill Site)

According to the Ministry of Road Transport and Highways (MoRTH, 2013) guidelines, a CBR value greater than 7% is considered acceptable for subgrade soils. Both Howrah and Durgapur soils meet this criterion, indicating they are suitable for use. Specifically, Howrah's unsoaked CBR value is 14.18%, while Durgapur's is slightly higher at 15.22%, suggesting that Durgapur's soil offers marginally better load-bearing capacity in dry conditions. In soaked conditions, however, Howrah's soil outperforms Durgapur's, with a soaked CBR of 10.4% compared to 8.41%. This demonstrates that Howrah's soil retains better strength when wet, making it more suitable for areas prone to moisture. Durgapur's soil, although stronger in dry conditions, might require additional stabilization to maintain performance in wet environments. Thus, Howrah's soil is preferable for moisture-prone regions, whereas Durgapur's soil is suited for drier areas or may need treatment to enhance its performance under wet conditions. Similar results are reported by Reddy et al., 2024.

4.4.1.10. Summary

A comparison of soil properties between the Howrah and Durgapur landfill sites, along with background soil data, reveals significant differences shaped by factors such as waste composition, moisture content, and landfill management practices. At the Howrah landfill, elevated moisture content due to substantial leachate and ongoing decomposition results in a lower specific gravity and moderate Atterberg limits, characteristic of landfill environments (Tchobanoglous et al., 1993). The high moisture content reduces the Maximum Dry Density (MDD) and increases the Optimum Moisture Content (OMC). Despite these conditions, Howrah exhibits higher shear strength parameters, with greater cohesion and internal friction, though the overall stability is still affected by the high moisture content. In contrast, the Durgapur landfill has lower moisture content compared to Howrah, although it remains higher than background soils. This reduced moisture contributes to a specific gravity similar to Howrah, influenced by the lightweight nature of the waste materials (Kumar et al., 2009). The MDD at Durgapur is closer to the range specified by the Ministry of Road Transport and Highways (MoRTH), indicating improved compaction or reduced moisture levels, and the

OMC aligns with MoRTH standards but remains higher than natural soils (MoRTH, 2013). The shear strength at Durgapur is lower compared to Howrah, which could be attributed to variations in waste management or compaction practices (Cheng et al., 2007).

4.5. Heavy metal analysis

The concentration of heavy metals in Good Earth is evaluated using the X-ray fluorescence spectroscopy (XRF) press pellet technique. The findings, which are crucial for ensuring environmental safety and material performance, are listed in detail in Table 16. along with the values obtained in literature and Flemish regulatory standards (VLAREBO limits, 2007).

Table 16: Heavy Metal Concentrations (mg/kg)

Literature & Test Result	As	Pb	Cd	Cr	Cu	Ni	Zn
Hogland et al., (2018) (Torma landfill)	-	141	0.5	260	321	34	1046
Hölzle et al., 2019 (Germany)	8	130	0.9	29	62	29	350
Datta et al., 2020. (Okhla landfill)	5.7−7.8	27−333	0.28−1.2	89−230	140−501	39−53	153−326
Reddy et al., 2024	0.013	0.167	0.003	-	0.831	15.58	-
Howrah Landfill	11	520.1	1.5	267.5	639.3	90.6	1680.9
Durgapur Landfill	13.8	111.8	1.2	125.3	261.4	49.7	511.1
Background Soil	3.6	17.6	1.1	72	32.5	25	105
VLAREBO limit, 2007	250	1250	10	880	375	250	1250
USEPA Standards, 1994	41	300	39	-	1500	420	2800

- VLAREBO limit for soil used in or as construction material

The heavy metal concentration of the good earth from both landfill sites presents notable challenge due to elevated concentrations. As compared to both sites the heavy metal concentrations are more in Howrah landfill sites. The age of Howrah landfill site is more so, the degradation of waste over the years can also result in the more release and accumulation of heavy metals in the soil.

The good earth from Howrah and Durgapur landfill site shows significantly elevated levels of cadmium, copper, nickel, and zinc compared to background soil values. These elevated concentrations pose considerable risks; for instance, high levels of cadmium and zinc can lead to potential leaching into the environment, which could contaminate surrounding soil and groundwater. Such contamination might compromise not only environmental health but also the structural stability of the roadbed. Elevated nickel levels may affect the compaction and load-bearing capacity of the subgrade material, potentially impacting road durability (Browning et al., 2003).

When comparing heavy metal concentrations in good earth with previous studies, Flemish regulatory standards (VLAREBO limit, 2007), and USEPA standards (1994) for reusing it as subgrade material, most results align with reported values. However, zinc, copper and lead levels at the Howrah landfill site are notably higher than most of the values found in the literature. Both sites, while showing increased metal levels, remains within acceptable limits for construction but still requires careful monitoring to mitigate any potential long-term risks. Proper assessment and management strategies are crucial to ensure that the good earth used in road construction does not lead to adverse environmental impacts or affect road performance. It's also crucial to perform leachable heavy metal tests to verify that the soil does not pollute water resources (Central Pollution Control Board [CPCB], 2008).

4.6. Leachable Heavy Metals

The results of the leachable heavy metal tests are crucial for ensuring that the subgrade material meets environmental and safety standards. Table 17 below presents the concentrations of various heavy metals detected in the leachate from the samples.

Table 17: Leachable Heavy Metals (mg/l)

Literature & Test Result	As	Pb	Cd	Cr	Cu	Ni	Zn	Hg
Dutta et al., 2020. (Okhla landfill)	0.013-0.014	0.0270-0.0336	0.0069-0.0070	0.188-0.201	0.121-0.155	0.110-0.130	0.118-0.242	-
Hölzle et al., 2019 (Germany)	0.001–0.05	0.01–0.50	0.001–0.050	0.01–0.10	0.01–0.30	0.02–0.40	0.05–1.50	-
Howrah Landfill	0.534	0.017	0.048	0.061	0.828	0.214	8.406	0.005
Durgapur Landfill	0.555	-0.002	0.002	0.006	0.058	0.009	1.186	0.012
Background Soil	0.426	0.001	0	0.311	0.019	0.072	0.234	0.001
CPCB, 2008	0.05	0.1	0.01	0.05	0.2	0.2	1.0	0.0005
LAGA., 2012	0.05	0.1	0.005	0.1	0.2	0.1	0.4	0.0005

For the materials under consideration, the leachability of heavy metals is a significant factor in determining their suitability. For instance, the data provided reveals that materials from landfills such as Howrah and Durgapur show slightly high concentrations of metals like Zinc and Lead. High levels of these metals in leachate can pose environmental risks, such as soil and water contamination.

Standards from environmental agencies, such as CPCB (2008) and LAGA (2012), set thresholds for leachable heavy metals to ensure materials do not adversely affect the environment. The CPCB limit for Lead, for instance, is 0.05 mg/kg, which is significantly lower than the levels observed in both Howrah and Durgapur landfills. This suggests that these materials could exceed permissible limits for leachable Lead, raising concerns about potential environmental impacts.

The presence of heavy metals in leachate could lead to contamination of groundwater and surrounding soil, impacting plant and animal life and posing health risks to nearby communities (Kumar et al., 2017). Therefore, it is essential to conduct leachability tests and compare the results against regulatory standards before using these materials in road construction. If the leachable metal concentrations exceed permissible limits, appropriate treatment or stabilization measures should be implemented to mitigate environmental risks (USEPA, 2018).

4.7. Soluble salts

Subgrade materials are susceptible to various chemical influences, among which the presence of soluble salts, such as chlorides and sulphates, plays a significant role. The concentrations of these salts found in the good earth from the Durgapur and Howrah landfill sites are presented in detail in the following Table 18.

Table 18: Soluble Salts

Literature & Test Result	Chlorides (mg/l)	Sulphates (mg/l)
Kaartinen et al., 2013	85−120	710−1500
Hölzle et al., 2019 (Germany)	1.4	54
Datta et al., 2020. (Okhla landfill)	295−585	378−680
Howrah Landfill	40.86	90.18
Durgapur Landfill	172.88	56.58
Background Soil	22	28
LAGA., 2012	150	600

- German Technical Bulletin- sealing of the surface (LAGA - Länderarbeitsgemeinschaft Abfall., 2012)

Soils with higher chloride content exhibited a decrease in compaction efficiency, resulting in reduced maximum dry density (MDD) and increased optimum moisture content (OMC) compared to control samples (Tiwari & Reddy, 2007). At the Durgapur landfill site, the chloride concentration of 172.88 mg/l exceeds the recommended limit of 150 mg/l, which contributes to the lower maximum dry density (MDD) observed in samples from this site compared to background soil.

On the other hand, the sulphide levels at the site fall within the acceptable range outlined by the German Technical Bulletin (LAGA, 2012) and are lower than values reported in other literature (Datta et al., 2020). Although sulphates generally lead to reduced strength and stability, with expansive behavior causing increased volume change and instability (Dames & Langer, 2008), the low sulphate concentrations observed at both sites suggest minimal expansive effects and stability concerns in the soil.

The variation in soluble salt concentrations between the Durgapur and Howrah landfill sites can be attributed to several factors, including differences in waste composition, local environmental conditions, and landfill management practices (Dutta et al., 2020; Hölzle et al., 2019). The types of waste and their decomposition rates affect the levels of soluble salts, while local rainfall and groundwater conditions influence their distribution in the soil. Additionally, varying management strategies and soil properties at each site contribute to the observed differences. Understanding these factors is essential for effective soil management and construction practices.

4.8. Major Oxides

The major oxides in soil primarily influence its mineral composition and geochemical properties. These oxides affect soil fertility, stability, and behaviour. The concentrations of major oxides in good earth from both sites are shown in Table 19.

Table 19: Major Oxides

Site Name	Na_2O (%)	MgO (%)	K_2O (%)	CaO (%)	Fe_2O_3 (%)	Al_2O_3 (%)	SiO_2 (%)	P_2O_5 (%)	MnO (%)
Durgapur Landfill	0.65	1.2	2.41	7.82	5.66	9.36	43.46	0.9021	0.13
Howrah Landfill	0.62	1.66	2.1	7.76	7.1	11.28	42.51	0.9132	0.12
Background soil	1.24	1.01	2.24	0.91	5.04	13.24	51.37	0.210	0.05

The chemical analysis of soils from the Durgapur and Howrah landfill sites reveals several differences that impact their suitability as subgrade materials for road construction compared to background soils. Both landfill sites exhibit higher levels of Calcium Oxide (CaO) compared to background soil, which can enhance soil stabilization and reduce plasticity, potentially improving their performance as subgrade materials (Khan et al., 2012; Gupta et al., 2019). However, the landfill soils also have lower Silicon Dioxide (SiO_2) and Aluminum Oxide (Al_2O_3) content compared to natural soils, which may affect their structural integrity and load-bearing capacity (Chowdhury & Rahman, 2016; Bindu et al., 2021). Specifically, Durgapur Landfill soil shows a more favorable composition with slightly lower Magnesium Oxide (MgO) and better CaO levels, suggesting it may be better suited for subgrade applications than Howrah Landfill soil (Saha et al., 2018; Jha et al., 2020). The differences in Sodium Oxide (Na_2O), Potassium Oxide (K_2O), and other oxides are less critical but still contribute to the overall chemical profile influencing soil behavior (Bhattacharya & Prasad, 2014; Sharma & Arora, 2017). Thus, while both landfill soils have some beneficial properties for road subgrade use, their lower SiO_2 and Al_2O_3 levels compared to background soil indicate potential limitations in their structural performance.

In summary, the major oxides in soil subgrade materials significantly impact their engineering properties, including stability, strength, and compaction characteristics. Understanding these effects is essential for designing and constructing durable infrastructure that performs well under load and environmental conditions.

4.9. Calorific Value of RDF

The calorific value of the RDF pellets is measured using a bomb calorimeter on a discarded basis. Additionally, the calorific value of the RDF is calculated on a dry basis. The moisture content of the RDF from the Howrah and Durgapur landfill sites is 11% and 12%, respectively. The results, along with relevant literature, are summarized and discussed in Table 20.

Table 20: Comparative Analysis of Energy Content of RDF

Site Name & Literature	Basis	Test-1 (Kcal/kg)	Test-2 (Kcal/kg)	Test-3 (Kcal/kg)	Avg. Calorific Value	
					(Kcal/kg)	(MJ/kg)
Howrah	As discarded	4293.77	4005.66	4265.51	4188.31	17.52
	Dry	4824.46	4500.74	4792.71	4705.97	19.69
Durgapur	As discarded	4397.71	4419.73	4182.64	4333.36	18.13
	Dry	4886.34	4910.81	4647.38	4814.84	20.15
Andhra Pradesh (Cheela et al., 2021)	As discarded	4899.62	4899.62	4899.62	4899.62	20.50
China (Zhou et al., 2014)	As discarded	10707.46	10707.46	10707.46	10707.46	44.80

The calorific value of RDF at the Durgapur site is higher than that at the Howrah landfill site. This is due to the higher proportion of plastic in the RDF composition at Durgapur compared to the amounts of textile, coconut husk, and rubber, which increases its calorific value. According to Zhou et al. (2014), RDF in China has a notably higher calorific value compared to India. This is attributed to the greater presence of clean plastic bags in China, with fewer contaminants or additional materials mixed in.

According to the SWM Rules 2016, RDF samples derived from solid waste are recommended for use as fuel in incineration units if their calorific value exceeds 6.3 MJ/kg. The calorific values of RDF samples from Howrah and Durgapur landfill sites exceed this threshold. Therefore, this RDF can be utilized as an alternative fuel in cement factories and brick kilns.

4.10. Life Cycle Assessment

This section presents the results of the environmental impact assessment for each scenario evaluated at both Durgapur and Howrah landfill sites. The LCA model is designed to evaluate the environmental impacts of biomining processes across multiple impact categories using the ReCiPe Midpoint 2016 method. This includes assessments of ozone depletion, global warming, acidification, eutrophication, carcinogenic and non-carcinogenic effects, eco-toxicity, and fossil fuel depletion. Emissions are quantified using the model's default normalization factors, which help to gauge the relative significance of each impact category. All results are based on the biomining of 1 ton of legacy waste.

4.10.1. Environmental impact analysis

The composition analysis reveals significant differences in the legacy waste ingredients between the two sites. The Howrah landfill site contains a larger proportion of Good Earth materials, while the Durgapur site is primarily composed of Refuse-Derived Fuel (RDF) materials. As a result, the environmental impact results vary between the sites.

4.10.1.1. Durgapur Landfill Site

At the Durgapur site, the biomining process is conducted on 1 ton of legacy waste. In this process, Refuse-Derived Fuel (RDF) with a calorific value of 16.736 MJ and weighing 359.1 kg replaced 227.65 kg of coal, which has a calorific value of 26.4 MJ.

Do-Nothing scenario: All components of the waste are considered, including the burning effects of coal in cement industries and the impact of natural soil as subgrade materials of road.

Scenario 1: RDF is diverted to a cement factory or brick kiln, thereby excluding the partial effect of coal burning. The effect of natural soil as subgrade materials of road and good earth are considered.

Scenario 2: 395.6 kg of natural soil is replaced by the same amount of Good Earth, used as subgrade material for road construction. This scenario considers both the burning effects of coal and the presence of RDF in the landfill.

Combined scenario: Both the natural soil (395.6 kg) as subgrade materials and the effects of burning 227.65 kg of coal in cement factories are excluded from consideration.

These scenarios enable a thorough evaluation of the environmental impacts associated with various waste management strategies, highlighting their implications for energy consumption and emissions. By considering the effects of different waste processing approaches, including the replacement of RDF with coal, the diversion of RDF to cement factories or brick kilns, and the substitution of traditional soil with Good Earth as subgrade material for road construction, a comprehensive understanding of each strategy's environmental footprint as achieved is shown in Table 21.

Table 21: Environmental Effects of Durgapur Landfill Sites

Impact category	Reference unit	Do Nothing Scenario a - IN	RDF sent to Cement Factory or Brick Kiln - IN	Good Earth sent for subgrade material - IN	Combined Scenario 1 & Scenario 2
Fine particulate matter formation	kg $PM_{2.5}$ eq	3.2020	1.4461	2.7727	1.0058
Fossil resource scarcity	kg oil eq	538.9086	376.1020	490.6139	319.0353
Freshwater ecotoxicity	kg 1,4-DCB	72.8700	39.9960	38.8807	6.8819
Freshwater eutrophication	kg P eq	0.2830	0.0712	0.2592	0.0515
Global warming	kg CO_2 eq	2137.4681	1344.5029	1801.7167	984.8353
Human carcinogenic toxicity	kg 1,4-DCB	75.6839	46.8614	68.0236	38.2134
Human non-carcinogenic toxicity	kg 1,4-DCB	1952.9039	927.2128	1181.6511	177.8858
Ionizing radiation	kBq Co-60 eq	38.0767	20.7854	34.3820	17.0647
Land use	m^2a crop eq	549.2214	338.8979	214.3683	8.2378
Marine ecotoxicity	kg 1,4-DCB	97.9995	53.6260	53.4555	10.1950
Marine eutrophication	kg N eq	0.7963	0.3761	0.4256	0.0094
Mineral resource scarcity	kg Cu eq	3.0111	2.3531	2.2905	1.5856
Ozone formation, Human health	kg NOx eq	7.2633	4.9688	6.3253	3.9087
Ozone formation, Terrestrial ecosystems	kg NOx eq	7.4060	5.0697	6.4516	3.9908
Stratospheric ozone depletion	kg CFC11 eq	0.0026	0.0012	0.0019	0.0006
Terrestrial acidification	kg SO2 eq	7.2667	4.4825	5.3097	2.4872
Terrestrial ecotoxicity	kg 1,4-DCB	2588.7050	1533.6105	2277.8076	1191.8306
Water consumption	m^3	58.3522	37.9019	22.5164	2.4433

The data for the Durgapur landfill site, as presented above, is analyzed and compared with the data from the Howrah landfill site in Section- (4.8.2).

4.10.1.2. Howrah Landfill Site

At the Howrah Landfill site, the biomining process is applied to 1 ton of legacy waste, which features a different composition compared to the Durgapur site. Specifically, the amount of Refuse-Derived Fuel (RDF) is 16.7% less at Howrah. In this process, RDF, with a calorific value of 16.736 MJ and weighing 299.11 kg, can replace 189.62 kg of coal, which has a calorific value of 26.4 MJ. Additionally, 23.6% more traditional soil is replaced by Good Earth at Howrah compared to Durgapur.

Do-Nothing Scenario: This scenario considers all components of the waste, including the emissions from burning coal in cement factories and the impact of natural soil as subgrade materials. The full range of effects from RDF, coal, and natural soil are included in the environmental impact assessment.

Scenario 1: In this scenario, 299.11 kg of RDF is sent to a cement factory or brick kiln to replace coal. However, the impacts of natural soil and Good Earth are still considered. This change eliminates the associated emissions from coal burning, shifting the focus to the environmental effects of utilizing RDF in industrial applications, without relying on fossil fuels.

Scenario 2: Here, 517.77 kg of traditional soil is replaced by an equivalent amount of Good Earth, used as subgrade material for road construction. This scenario considers both the emissions from coal burning and the presence of RDF in the landfill, providing a detailed assessment of the impacts of replacing natural soil with Good Earth.

Combined scenario: In this scenario, the analysis excludes the impact of 517.77 kg of natural soil and the emissions associated with burning 189.62 kg of coal. The assessment concentrates on the environmental effects without considering these two specific elements.

For the Howrah landfill site, a thorough assessment of the environmental impacts associated with different waste management strategies has been conducted, focusing on their effects on energy consumption and emissions. Each strategy's environmental footprint has been comprehensively evaluated to provide a clear understanding of its implications at the Howrah landfill site, as presented in detail the accompanying Table 22.

Table 22: Environmental Effects of Durgapur Landfill Sites

Impact category	Reference unit	Do Nothing Scenario a - IN	RDF sent to Cement Factory or Brick Kiln - IN	Good Earth sent for subgrade material - IN	Combined Scenario 1 & Scenario 2
Fine particulate matter formation	kg $PM_{2.5}$ eq	2.835	1.432	2.305	0.891
Fossil resource scarcity	kg oil eq	482.477	343.738	429.578	282.067

Impact category	Reference unit	Do Nothing Scenario a - IN	RDF sent to Cement Factory or Brick Kiln - IN	Good Earth sent for subgrade material - IN	Combined Scenario 1 & Scenario 2
Freshwater ecotoxicity	kg 1,4-DCB	76.015	49.832	31.545	6.237
Freshwater eutrophication	kg P eq	0.233	0.072	0.203	0.046
Global warming	kg CO_2 eq	1962.732	1302.547	1555.955	871.854
Human carcinogenic toxicity	kg 1,4-DCB	67.537	43.559	58.789	33.823
Human non-carcinogenic toxicity	kg 1,4-DCB	1958.992	1147.611	950.015	160.560
Ionizing radiation	kBq Co-60 eq	33.100	19.530	28.632	15.035
Land use	m^2a crop eq	624.654	441.775	186.429	7.743
Marine ecotoxicity	kg 1,4-DCB	101.597	66.343	43.354	9.213
Marine eutrophication	kg N eq	0.860	0.490	0.375	0.009
Mineral resource scarcity	kg Cu eq	2.938	2.341	2.045	1.401
Ozone formation, Human health	kg NOx eq	6.640	4.674	5.547	3.459
Ozone formation, Terrestrial ecosystems	kg NOx eq	6.771	4.768	5.658	3.531
Stratospheric ozone depletion	kg CFC11 eq	0.002	0.001	0.002	0.001
Terrestrial acidification	kg SO2 eq	7.028	4.723	4.547	2.203
Terrestrial ecotoxicity	kg 1,4-DCB	2336.345	1453.373	1967.689	1053.834
Water consumption	m^3	66.660	48.690	19.781	2.187

4.10.2. Comparison Analysis of the Impact Data

The environmental impact assessment of landfill mining of legacy waste at the Durgapur and Howrah landfill sites is essential for evaluating the effectiveness and sustainability of this waste management strategy. Landfill mining involves the excavation and processing of waste from old landfill sites to recover valuable materials, reduce waste volume, and mitigate environmental contamination. Scenario-1 (RDF sent to brick kiln and cement factory) represents a more controlled and potentially optimized process, while Scenario-2 (Good earth sent for subgrade material) may less efficient methods. The combined scenario, which incorporates features from both scenario-1 and scenario-2, shows a significant reduction in environmental impacts, ranging from 65% to 95%. By analysing the effects of these scenarios on critical environmental parameters, this study aims to provide a thorough understanding of how landfill mining influences environmental outcomes.

Detailed analysis of each environmental impact parameters is presented below:

4.10.2.1. Fine Particulate Matter Formation

The combustion of fossil fuel like coal, diesel etc. releases fine particulate matter ($PM_{2.5}$) into the atmosphere.

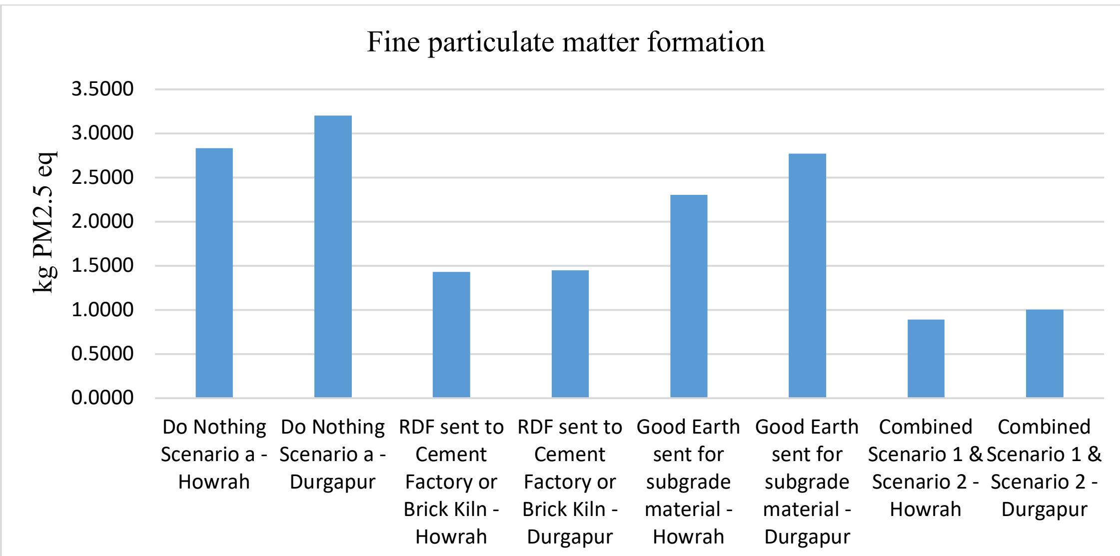


Figure 46: Fine Particulate Matter Formation

In Do nothing Scenario, the diesel burning effects for processing 1 ton of waste using a trommel screen are the same for both sites. The higher value for Durgapur site is attributed to its coal consumption (16.71%) greater than that at the Howrah landfill site. Fine Particulate Matter has adverse effects on human health and can lead to respiratory and cardiovascular issues. In the combined scenario for both sites, the concentration of fine particulate matter is reduced by approximately 69%, which benefits human health (Figure 46).

4.10.2.2. Fossil Resource Scarcity

Fossil resource scarcity refers to the diminishing availability of finite and non-renewable fossil fuels like coal, oil, and natural gas. As these resources are exhausted, their extraction and use become more challenging and costly, resulting in economic, environmental, and geopolitical issues.

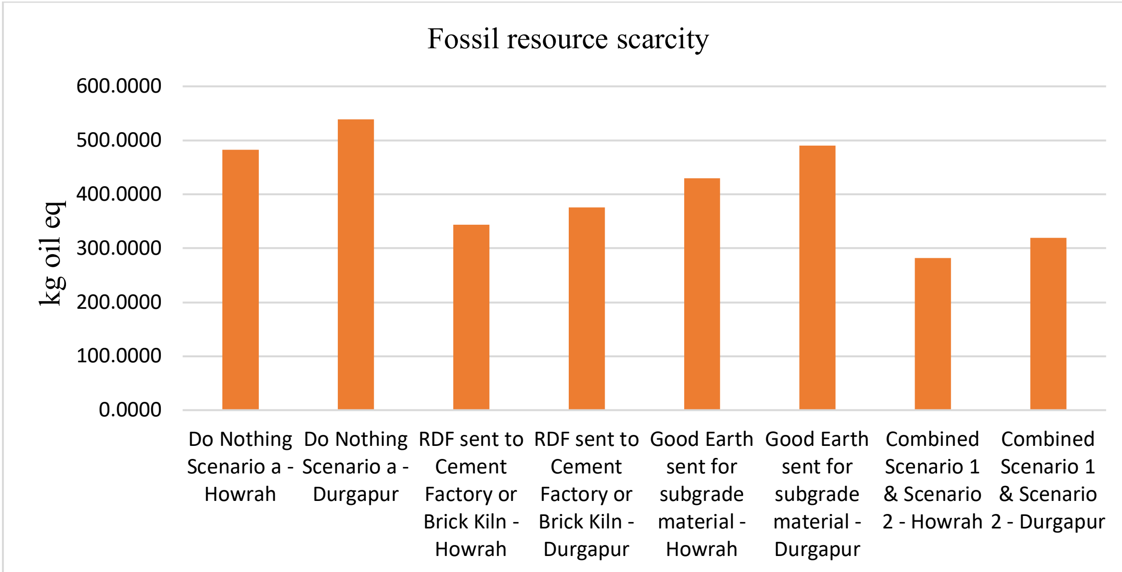


Figure 47: Fossil Resource Scarcity

The situation is similar to the formation of fine particulate matter from coal and diesel burning. Plastic waste, which is derived from petrochemicals and fossil fuels, also contributes to resource scarcity. At the Durgapur landfill site, the amount of plastic waste is 21.4% higher compared to other sites, increasing the impact on fossil resource scarcity (Figure 47).

4.10.2.3. Freshwater Ecotoxicity

Freshwater ecotoxicity is measured using the unit "kg 1,4-DCB." This unit represents the ecotoxicity of different substances relative to 1,4-Dichlorobenzene, which serves as a reference point for comparison. Figure 48 depicts the effects of freshwater ecotoxicity.

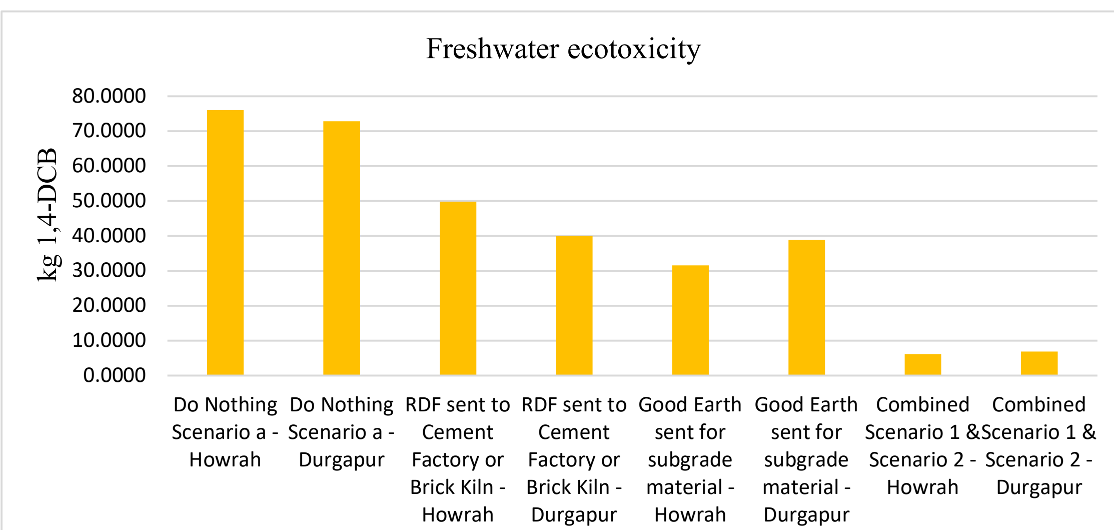


Figure 48: Freshwater Ecotoxicity

High amounts of plastics in landfills in both Durgapur and Howrah significantly impact freshwater systems by leaching toxic additives and monomers into water bodies. Their degradation products, such as microplastics, can absorb and re-release harmful chemicals, further contaminating aquatic environments. The textile industry, particularly with synthetic fabrics, also contributes to freshwater ecotoxicity through the disposal of dyes, chemicals, and microfibers, which often end up in landfills and leach into water systems. In contrast, coconut husks are biodegradable and typically have a lower direct environmental impact; however, improper processing and disposal can still adversely affect water quality.

4.10.2.4. Freshwater Eutrophication

The unit "kg P eq" measures the impact of nutrient enrichment on freshwater bodies, leading to excessive algae and plant growth, expressed in terms of phosphorus equivalents.

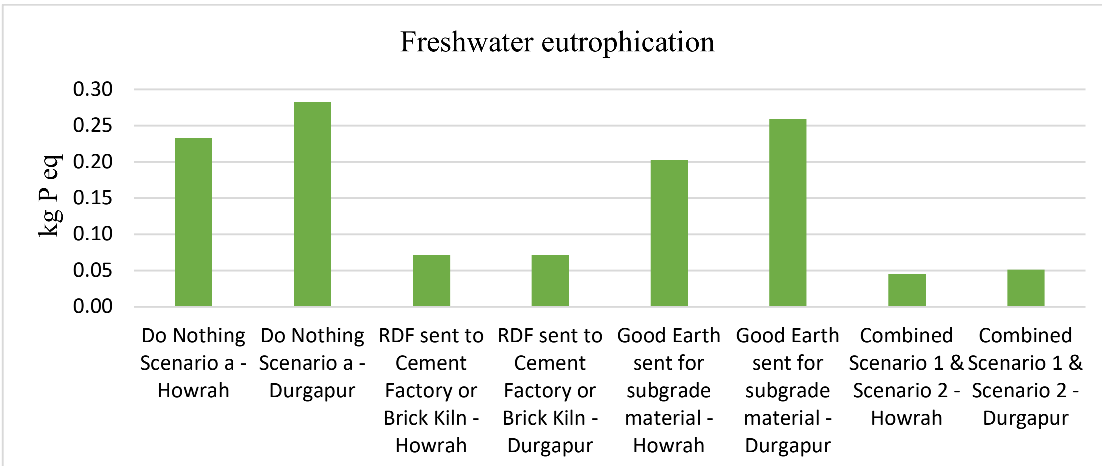


Figure 49: Freshwater Eutrophication

The primary contributors to freshwater eutrophication from municipal solid waste are food, yard waste and paper and cardboard, along with municipal sludges. In Durgapur landfill site, the increased organic waste compared to Howrah causes 0.05 kg P equivalent more pollution, shown in Figure 49.

4.10.2.5. Global Warming

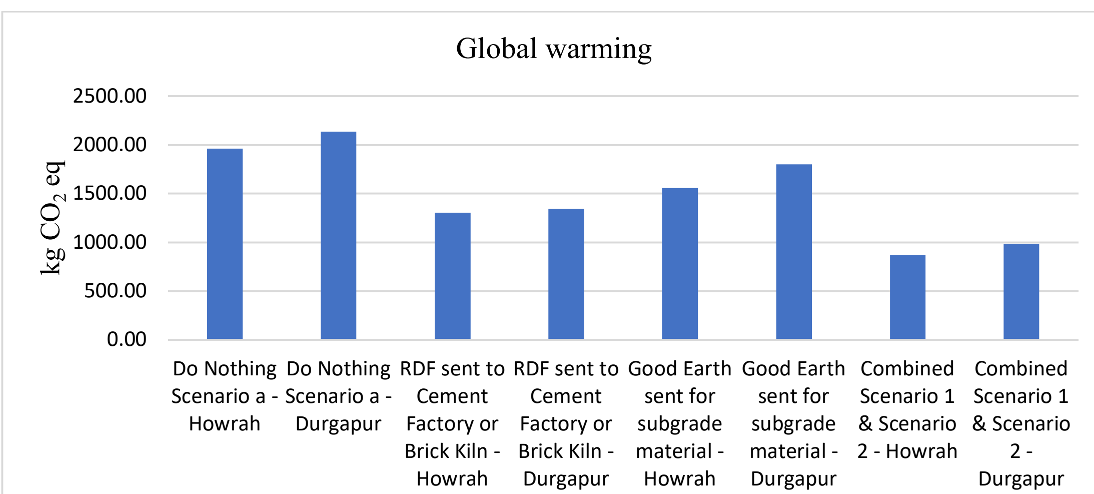


Figure 50: Global Warming

The fossil fuels coal and diesel are major contributors to global warming due to their high emissions of CO_2, methane, and other greenhouse gases. Additionally, the degradation of plastic waste in landfills is another significant factor, as it releases methane, a potent greenhouse gas that exacerbates global warming.

In the context of 1,000 kg of legacy waste, the Durgapur landfill site contains 195.6 kg of plastic waste, while the Howrah landfill site has 153.75 kg of plastic waste. Despite having less plastic waste, the Howrah site exhibits a lower global warming impact due to better waste management practices and consumption patterns. Furthermore, because the Howrah landfill is older than the Durgapur site, it is essential to examine whether the plastic waste has decomposed and released microplastics. This evaluation is important to understand the full environmental impact, as older landfills can have different leaching behaviours compared to newer ones.

In a combined scenario, both the Durgapur and Howrah landfill sites would replace an average of 208 kg of coal per ton of legacy waste. This replacement leads to a reduction in global warming potential, with the Durgapur landfill seeing a decrease of 53.92% and the Howrah landfill experiencing a reduction of 55.58%, shown in Figure 50. This significant reduction highlights how substituting coal with refuse-derived fuel (RDF) can lower overall greenhouse gas emissions. By using RDF instead of coal, both landfill sites can significantly reduce their global warming impact, highlighting a more sustainable approach to waste management.

4.10.2.6. Human Carcinogenic Toxicity

Asbestos, heavy metals, old electronics, batteries, and some household products can release persistent organic pollutants (POPs) like PCBs, dioxins, and furans, which are known carcinogens. These substances accumulate in the environment and the food chain, posing significant health risks.

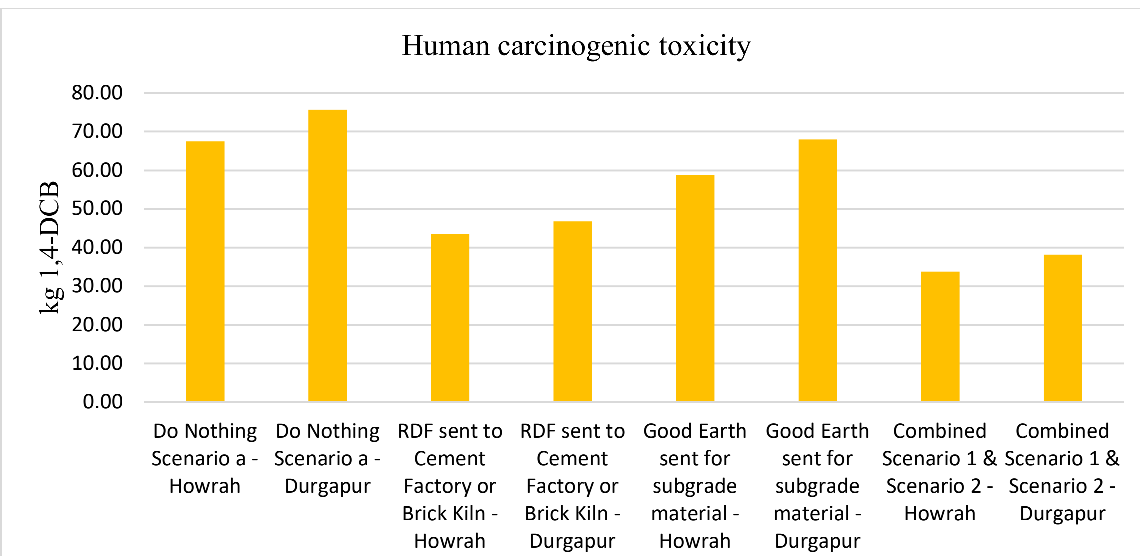


Figure 51: Human Carcinogenic Toxicity

The combined waste management strategy of sending RDF to cement factories or brick kilns and using Good Earth as subgrade material is the most effective method for mitigating human carcinogenic toxicity. This approach achieves the lowest observed levels of toxicity, with 1,4-

Dichlorobenzene (1,4-DCB) concentrations of 38.2134 kg at the Durgapur landfill site and 33.823 kg at the Howrah landfill site, shown in Figure 51. These figures indicate a significant reduction in health risks related to carcinogenic pollutants. Prioritizing this combined strategy can significantly enhance environmental and public health outcomes by effectively addressing and reducing carcinogenic risks.

4.10.2.7. Human Non-carcinogenic Toxicity

Legacy waste ingredients, coal burning, and diesel use contribute to various forms of non-carcinogenic toxicity. Legacy waste can cause acute and chronic health problems, reproductive issues, neurotoxicity, and skin irritation. Coal and diesel burning lead to respiratory and cardiovascular diseases and can also affect reproductive and neurological health, as well as skin irritation. Figure 52 illustrates the effects of human non-carcinogenic toxicity.

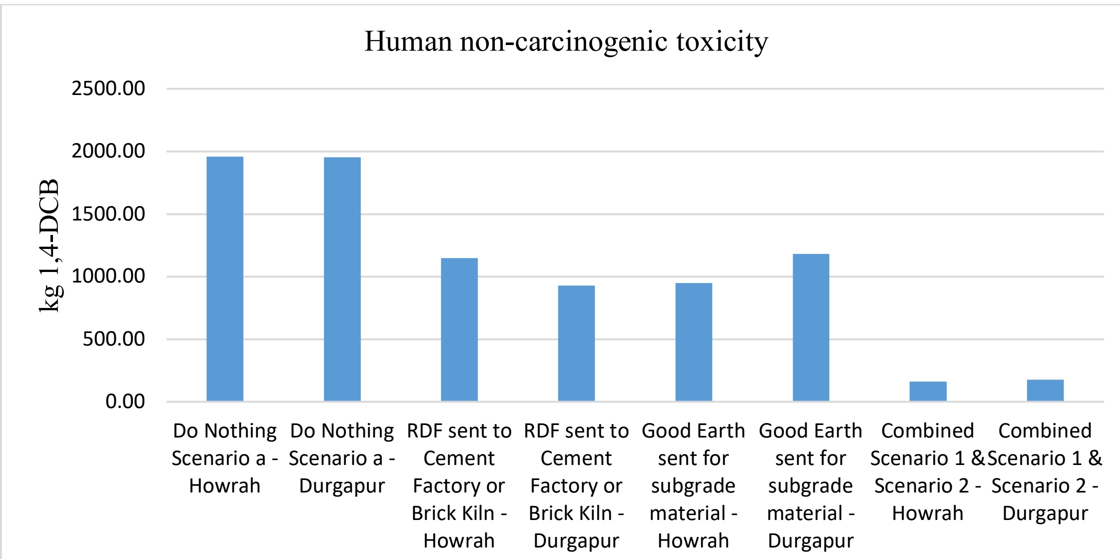


Figure 52: Human Non-carcinogenic Toxicity

In the combined scenario, human non-carcinogen toxicity is reduced by an average of 91% at both sites. This substantial decrease highlight that the combined management efforts have been highly effective in mitigating the harmful effects of non-carcinogenic substances.

4.10.2.8. Ionizing Radiation

The unit kBq stands for kilobecquerel, and kBq Co-60 indicates the level of cobalt-60's radioactivity, which tells how many decays are occurring per second and the amount of ionizing radiation being emitted.

Coal burning is unique due to the release of radioactive elements contained in the coal. The notable cases are natural materials like soil and stones, which can contain trace amounts of naturally occurring radioactive materials. Since stones are often left in landfills after waste management, the reduction of ionizing radiation in these scenarios is limited to less than 50%. Therefore, specific measures should be implemented to minimize this impact. Figure 53 illustrates the effects of ionizing radiation.

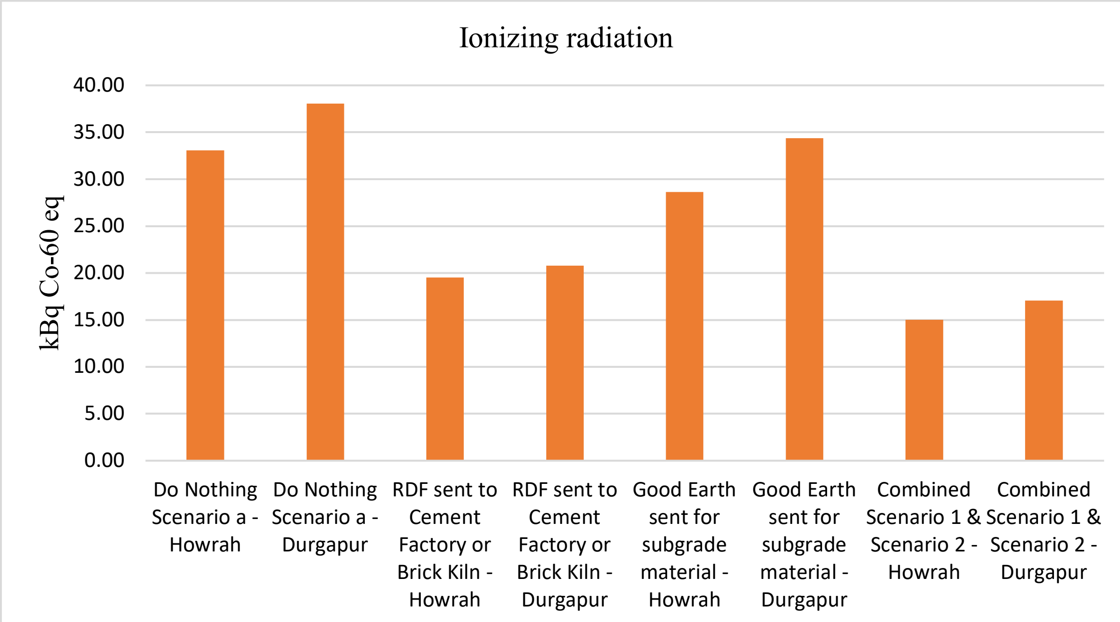


Figure 53: Ionizing Radiation

4.10.2.9. Land Use

The unit m²a crop eq stands for "square meters per annum crop equivalent." It represents the area of land, measured in square meters, required to produce a given crop over the course of one year.

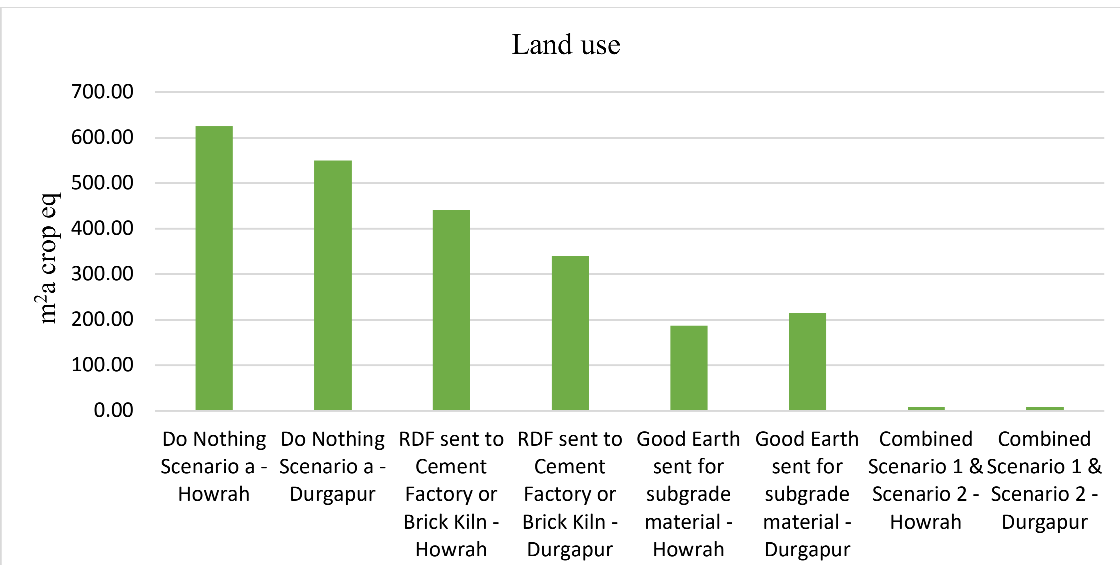


Figure 54: Land Use

At Howrah landfill site, the amount of good earth ingredients is 23.6 % more compared to the Durgapur landfill site. That's why Howrah landfill site take more land area, shown in Figure 54. In the combined scenario, most of the waste is redirected to cement factories or brick kilns or used as subgrade material. As a result, 97% to 98% of the landfill space is freed up, which can then be utilized for new waste disposal or other purposes.

4.10.2.10. Marine Ecotoxicity

Plastics, coal burning, and construction and demolition debris are among the most significant contributors to marine ecotoxicity. Plastics, including microplastics, severely impact marine ecosystems by being ingested by marine organisms, leading to physical harm and toxic chemical exposure. Coal burning releases heavy metals like mercury into the atmosphere, which eventually settle in marine environments, causing bioaccumulation and ecological disruption. Similarly, construction and demolition debris can contain hazardous materials that leach toxins into the ocean, harming marine life. While materials such as jute bags, glass, and coconut husks pose minimal risk due to their biodegradability and inert properties, textiles, especially synthetics, and metals can still contribute to marine pollution through microplastic release and heavy metal contamination.

At both the Durgapur and Howrah landfill sites, legacy waste materials are effectively managed, and coal burning has been replaced with Refuse-Derived Fuel (RDF). This transition helps reduce marine ecotoxicity, shown in Figure 55.

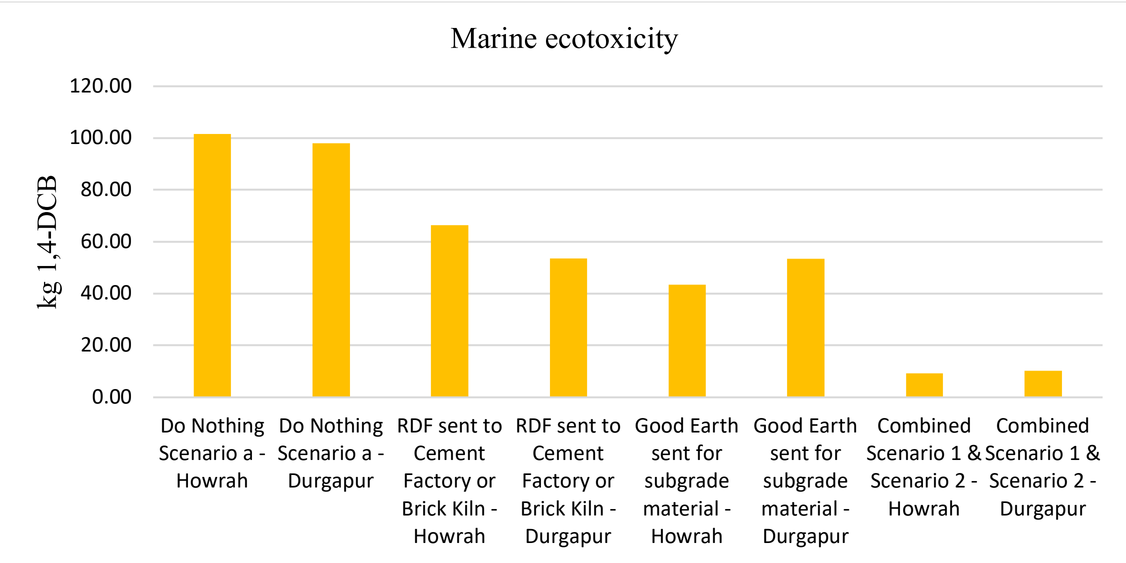


Figure 55: Marine Ecotoxicity

4.10.2.11. Marine Eutrophication

The unit "kg N equivalent" is used to measure marine eutrophication. It represents the amount of nitrogen, in kilograms, that contributes to nutrient enrichment in marine environments, leading to problems such as algal blooms and oxygen depletion.

Legacy waste ingredients such as good earth, construction and demolition debris, and pollutants from coal and diesel burning can contribute significantly to nutrient enrichment in marine environments. Good earth runoff carries nitrogen and phosphorus into the sea, exacerbating eutrophication. While materials like plastics, textiles, and metals do not directly contribute to nutrient enrichment, their degradation and improper disposal can still impact marine ecosystems in other ways. The biomining process and the utilization of its by-products help to reduce marine eutrophication by an average of 99% at both landfill sites.

The effects marine eutrophication is shown in Figure 56.

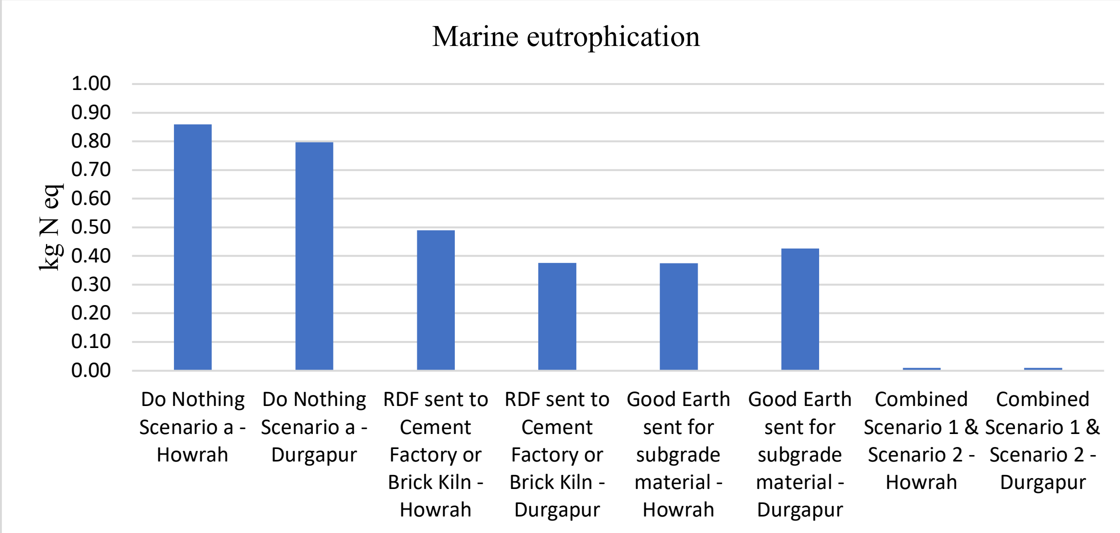


Figure 56: Marine Eutrophication

4.10.2.12. Mineral Resource Scarcity

The unit "kg Cu equivalent" is used to measure mineral resource scarcity. It represents the amount of copper, in kilograms, required to assess the scarcity of mineral resources.

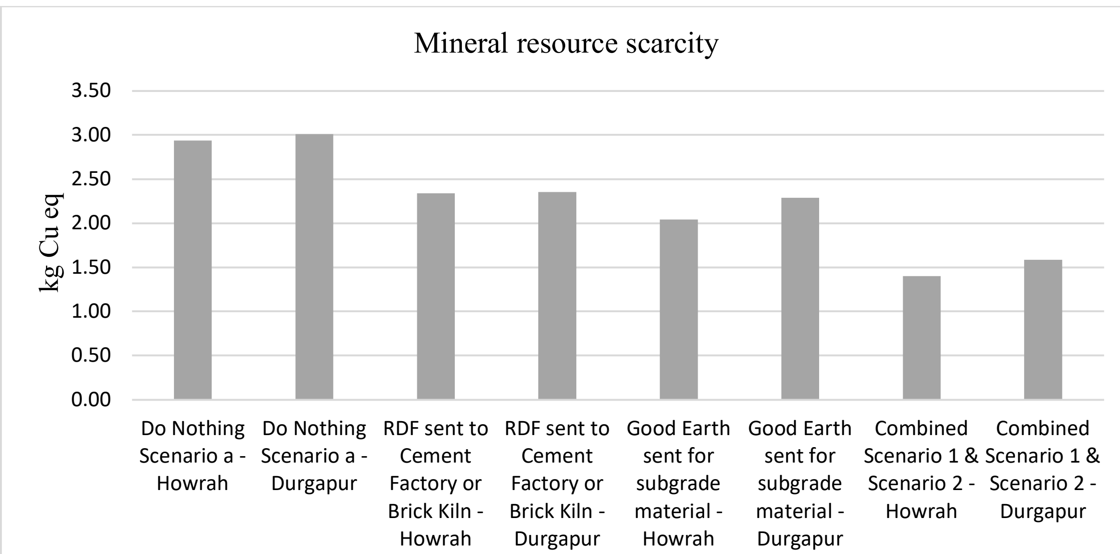


Figure 57: Mineral Resource Scarcity

Plastics and textiles contribute to environmental pollution through microplastics, which can disrupt ecosystems and potentially affect areas where minerals are extracted. In contrast, materials such as jute bags, wood, glass, stones, and coconut husks have minimal direct impact on mineral resources. The total quantities of plastic and textile waste are 296.8 kg in Durgapur and 219.75 kg in Howrah, both of which significantly contribute to mineral resource scarcity. The impacts of both sites are shown in Figure 57.

4.10.2.13. Ozone Formation, Human Health

The unit "kg NOx eq" is used to assess the impact on ozone formation. It quantifies the equivalent amount of nitrogen oxides (NOx) in kilograms that contributes to ground-level ozone formation, which can negatively affect the environment and human health.

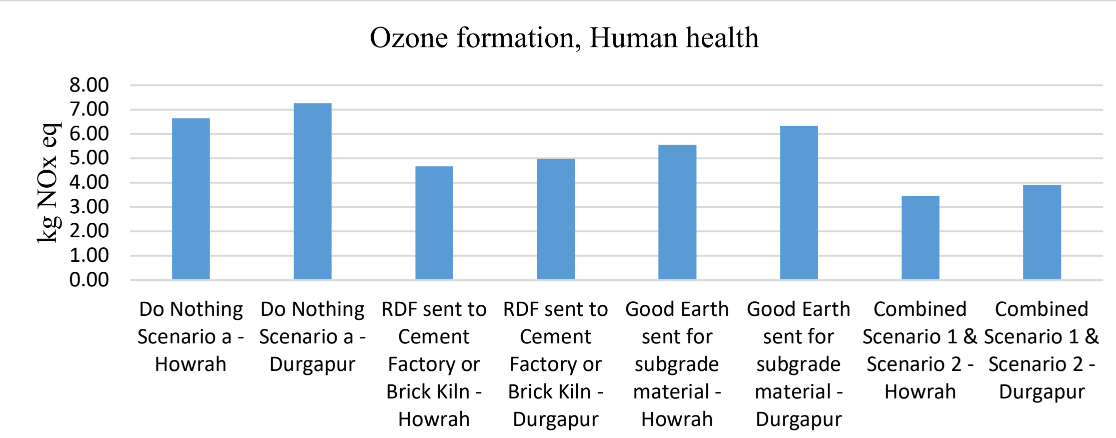


Figure 58: Ozone Formation, Human Health

Coal and diesel burning are significant contributors to ground-level ozone, releasing nitrogen oxides (NOx) and volatile organic compounds (VOCs) that are key precursors to ozone formation. This pollution can lead to serious respiratory issues and other health problems. Materials like wood, when burned, and construction and demolition debris, which can release dust and VOCs, also contribute to ozone formation, though their impact is less direct. Addressing these issues through better waste management and pollution control is essential to mitigating ozone-related health risks. Figure 58 illustrates the impacts of ozone formation at both sites.

4.10.2.14. Ozone Formation, Terrestrial Ecosystems

Ozone formation in terrestrial ecosystems occurs when nitrogen oxides (NOx) and volatile organic compounds (VOCs) react with sunlight, creating ground-level ozone.

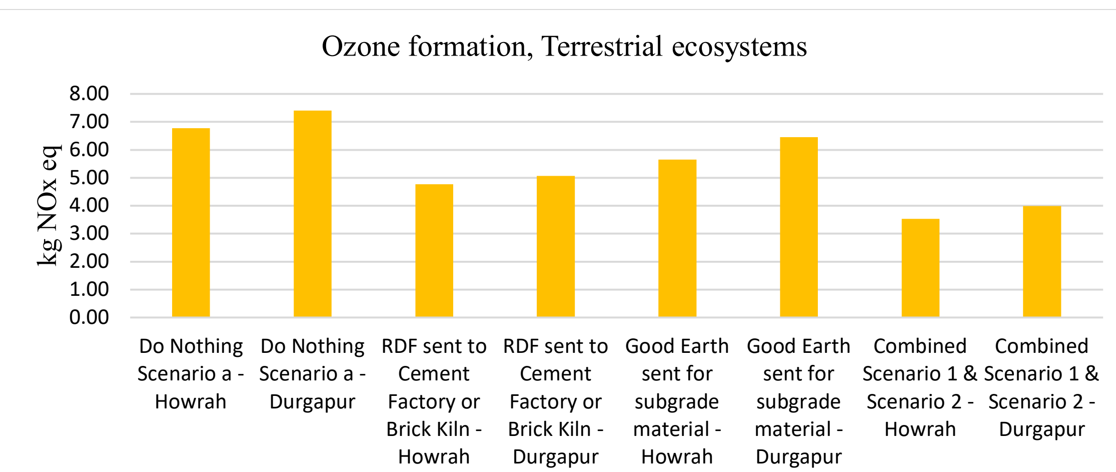


Figure 59: Ozone Formation, Terrestrial Ecosystems

Coal and diesel burning are major contributors to ozone formation. Materials such as glass, stones, and biodegradable items like coconut husks have minimal impact on ozone formation in terrestrial ecosystems. This can lead to damage to vegetation, disrupt plant growth, and affect soil quality. In the do-nothing scenario, ozone formation in terrestrial ecosystems is 6.77 kg NOx equivalent for Howrah and 7.41 kg NOx equivalent for Durgapur. However, this value is reduced by an average of 48% when waste is redirected to cement factories or brick kilns and used as subgrade material. Figure 59 displays the impacts of both sites.

4.10.2.15. Terrestrial Acidification

The unit "kg SO_2 eq" measures terrestrial acidification by quantifying the equivalent amount of sulphur dioxide (SO_2) in kilograms that represents its potential acidifying impact on terrestrial ecosystems.

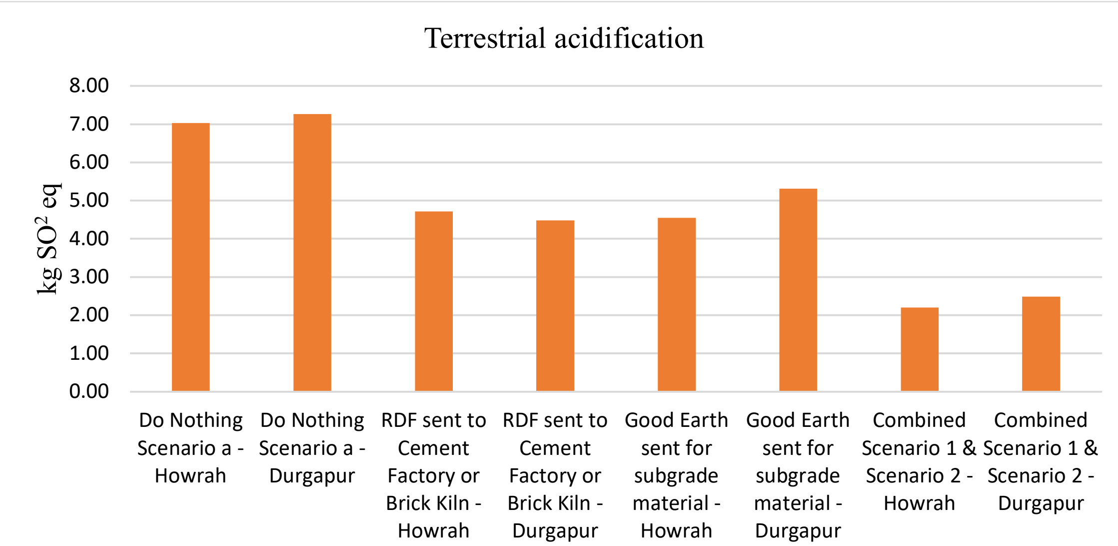


Figure 60: Terrestrial Acidification

Terrestrial acidification is significantly influenced by emissions from coal and diesel burning, which release sulphur dioxide (SO_2) and nitrogen oxides (NOx) that contribute to acid rain and soil degradation. While burning plastics and wood has a lower impact on terrestrial acidification due to less acidic pollutant release, the effects are less severe compared to fossil fuels. The Durgapur landfill site contains a higher amount of Refuse-Derived Fuel (RDF) ingredients compared to the Howrah site. As a result, the impact of terrestrial acidification at Durgapur is reduced by 5.52% more than at Howrah when waste is redirected to cement factories or brick kilns as RDF. The impacts of both sites are illustrated in Figure 60.

4.10.2.16. Stratospheric Ozone Depletion

The unit "kg CFC-11 eq" measures stratospheric ozone depletion by quantifying the ozone-depleting potential equivalent to kilograms of CFC-11 (trichlorofluoromethane).

Plastics, textiles, wood, and metals have minimal direct impact on stratospheric ozone, although burning these materials can release small amounts of pollutants that might contribute to ozone depletion indirectly. Coal and diesel burning have a lower impact, as they release pollutants that can affect atmospheric conditions, though their direct role in ozone depletion is relatively minor compared to traditional ozone-depleting substances. Materials like good earth (soil), jute bags, glass, stones, and coconut husks have virtually no impact on stratospheric ozone. The impacts of both sites are illustrated in Figure 61.

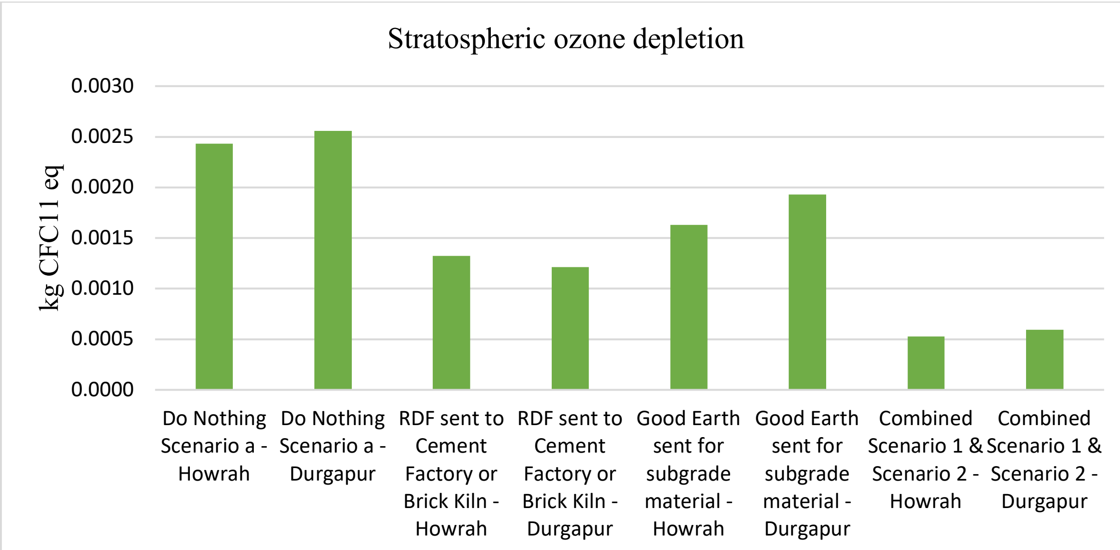


Figure 61: Stratospheric Ozone Depletion

4.10.2.17. Terrestrial Ecotoxicity

Coal and diesel burning are major contributors, as they release pollutants such as sulfur dioxide (SO_2), nitrogen oxides (NOx), and particulate matter, which can degrade soil quality and disrupt plant and animal life. Plastics can leach harmful chemicals into the soil as they break down, while synthetic textiles may contribute to terrestrial ecotoxicity through the release of microplastics. Construction and demolition debris can also impact ecosystems by introducing dust and contaminants into the environment.

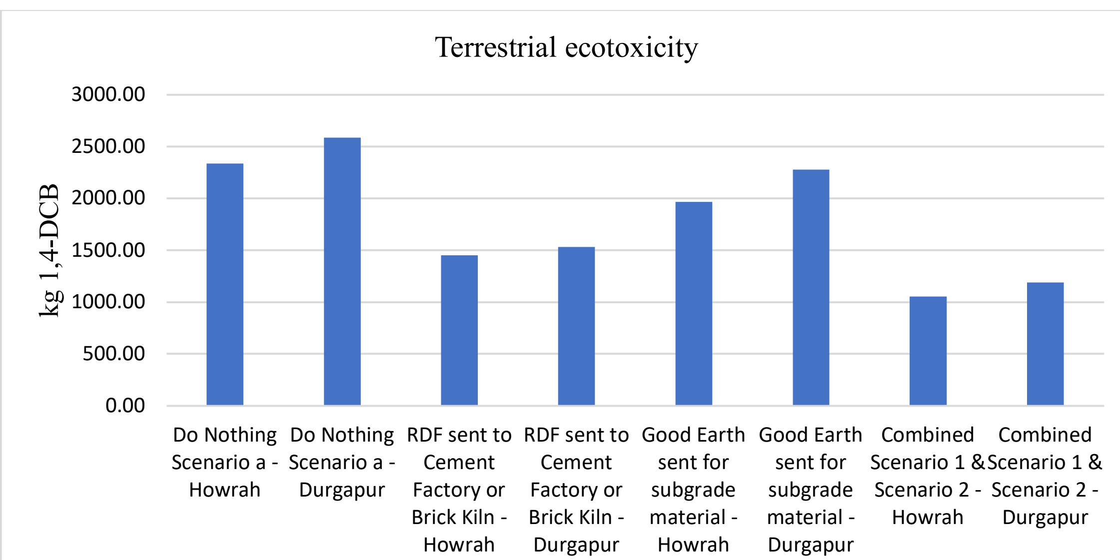


Figure 62: Terrestrial Ecotoxicity

At the Howrah landfill site, using Good Earth as subgrade material alone reduces the impact by 15.76%. When the RDF (Refuse-Derived Fuel) is additionally sent to a cement factory or brick kiln, the overall impact is reduced by 54.89%. For the Durgapur site, the impact reduction with Good Earth is 12%, and the overall reduction in impact is 53.96%, shown in Figure 62.

4.10.2.18. Water Consumption

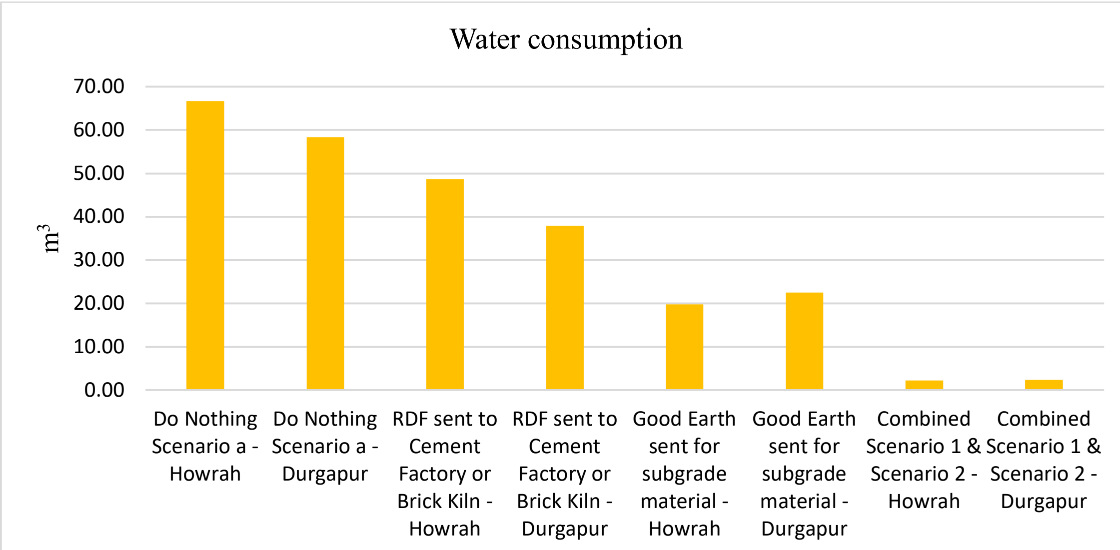
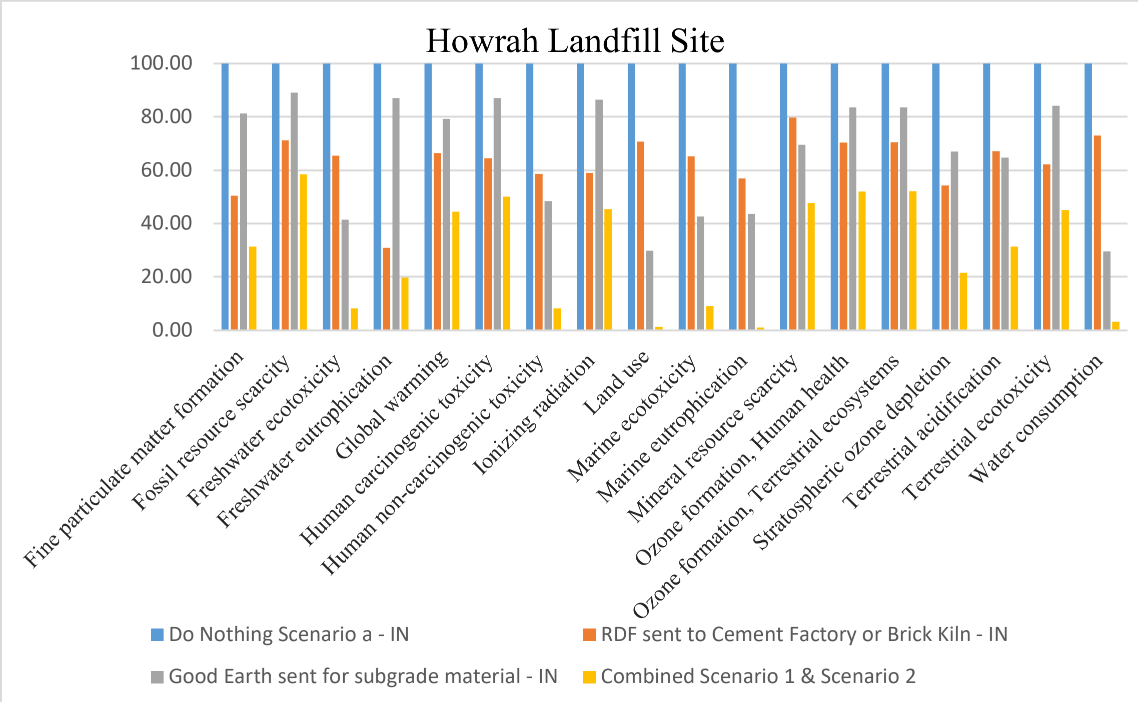


Figure 63: Water Consumption

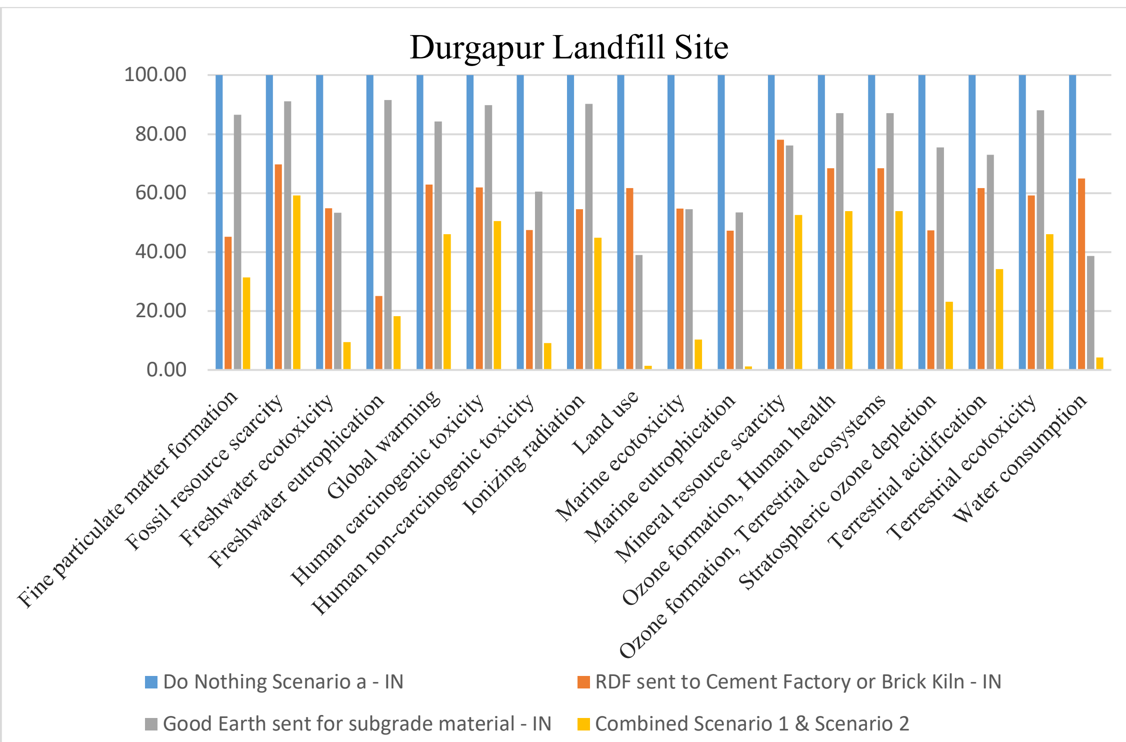
In the "Do Nothing" scenarios, water consumption is highest, with Howrah at 66.66 m^3 and Durgapur at 58.35 m^3. When RDF is sent to cement factories or brick kilns, water use drops considerably to 48.69 m^3 in Howrah and 37.90 m^3 in Durgapur, reflecting a reduction of approximately 27% and 35% respectively. Utilizing Good Earth for subgrade material further decreases water consumption to 19.78 m^3 in Howrah and 22.52 m^3 in Durgapur, marking a reduction of about 70% and 61% respectively compared to the "Do Nothing" scenario. The combined approach of sending RDF to cement or brick kilns and using Good Earth leads to the greatest reduction in water consumption, with Howrah achieving a 97% reduction and Durgapur a 96% reduction compared to the "Do Nothing" scenario, shown in Figure 63.

4.10.2.19. Summery

Implementing effective waste management strategies, such as RDF utilization or sending Good Earth for subgrade material, significantly reduces most environmental impacts compared to the Do-Nothing scenarios. The combined scenario of RDF and Good Earth management presents the most substantial benefits, minimizing impacts on fine particulate matter, global warming, resource scarcity, and other environmental categories. For both the Durgapur and Howrah landfill sites, the key environmental impact categories for various scenarios are presented as percentages relative to the Do-Nothing scenario, which is considered as 100%. The percentages for the reduction scenarios are calculated based on the impacts of the Do-Nothing scenario and are illustrated in the below Figure 64-(a & b).



(a)



(b)

Figure 64: Key Environmental Impact Categories for Different Scenarios (**a-** Howrah Landfill Site & **b-** Durgapur Landfill Site)

4.10.3. Sensitivity Analysis

The sensitivity analysis for the Do-Nothing scenario is assessed using the IPCC GWP 100a indicator. Previous studies have identified RDF and good earth ingredients as key factors affecting the environment. However, since this sensitivity analysis is focused on CO_2 emissions, it is essential to determine whether transportation-related CO_2 generation plays a significant role. Therefore, the CO_2 emissions associated with transportation are calculated and presented below.

4.10.3.1. CO_2 Generation Due to Transportation of RDF

In India, trucks used for transporting RDF typically have an average Gross Vehicle Weight (GVW) of approximately 28 tons, with a payload capacity of 20 tons. Table 23 shows the average fuel consumption rates for these trucks. According to Singh et al. (2021) and Gajjar et al. (2015), the combustion of 1 liter of diesel results in the emission of 2.64 kg of CO_2.

Table 23: Fuel Consumption

GVW (ton)	Axle Configuration	Speed of vehicle (Km/hr.)	Fuel consumption (L/100 Km)		Average fuel consumption (L/100 Km)	
			Upper weight limit	Lower weight limit	Upper weight limit	Lower weight limit
25-31	8×2	40	22.1	19.5	26.1	21.8
		60	26.4	24.2		
	8×4	40	20.1	15.7		
		60	35.7	27.8		

Based on the above table, the average fuel consumption per 100 km is 26.1 liters for the upper weight limit and 21.8 liters for the lower weight limit. Since the distance from the landfill site to the cement factory is greater than to the brick kiln, the longer distance to the cement factory is considered for extreme cases. Consequently, the average CO_2 emissions are calculated based on a round trip to the cement factory.

Table 24: Avg. CO_2 Generation due to transportation of RDF from Howrah Landfill Site

Industry Type	Average fuel consumption (L/100 Km)	Average distance from Howrah Landfill site (Km)	Fuel consumption per round trip (L)	CO_2 generation per round trip (Kg)	CO_2 generation per ton of material (Kg)	Avg. CO_2 generation per ton of material (Kg)
Cement Factory	26.1 (Upper weight limit)	250 (West Bengal)	130.5	344.52	17.22	32.15
		400 (Odisha)	208.8	551.232	27.56	

Industry Type	Average fuel consumption (L/100 Km)	Average distance from Howrah Landfill site (Km)	Fuel consumption per round trip (L)	CO_2 generation per round trip (Kg)	CO_2 generation per ton of material (Kg)	Avg. CO_2 generation per ton of material (Kg)
		750 (Chhattisgarh)	391.5	1033.56	51.68	
	21.8 (Lower weight limit)	250 (West Bengal)	109	287.76	14.39	40.29
		400 (Odisha)	174.4	460.42	23.02	
		750 (Chhattisgarh)	327	863.28	43.16	

Table 25: Avg. CO_2 Generation due to transportation of RDF from Durgapur Landfill Site

Industry Type	Average fuel consumption (L/100 Km)	Average distance from Howrah Landfill site (Km)	Fuel consumption per round trip (L)	CO_2 generation per round trip (Kg)	CO_2 generation per ton of material (Kg)	Avg. CO_2 generation per ton of material (Kg)
Cement Factory	26.1 (Upper weight limit)	100 (West Bengal)	52.2	137.81	6.89	21.82
		250 (Odisha)	130.5	344.52	17.23	
		600 (Chhattisgarh)	313.2	826.85	41.34	
	21.8 (Lower weight limit)	100 (West Bengal)	43.6	115.1	5.76	18.23
		250 (Odisha)	109	287.76	14.39	
		600 (Chhattisgarh)	261.6	690.62	34.53	

Based on Table 24 and Table 25, the average CO_2 emissions due to transportation of RDF from landfill to cement factories are about only 1-2% of the total global warming potential of waste management for the do-nothing scenario. Therefore, CO_2 emissions from RDF transportation are not a significant factor in the sensitivity analysis.

4.10.3.2. CO_2 Generation Due to Management of RDF and Good Earth

At the Howrah landfill site, the amount of RDF ingredients is 299.17 kg and good earth is 517.77 kg, which together account for 81.69% per ton of waste. Meanwhile, at the Durgapur site, these values account for 75.47% per ton of waste, with RDF ingredients being 16.69% higher than at Howrah. The quantities of RDF and good earth in biomined waste were increased or decreased by ±15%, for conducting sensitivity analysis by adjusting the total quantity of biomined waste to 1000 kg.

For the analysis, five scenarios are created: the reference scenario, which is the do-nothing case, and four additional scenarios - RDF increased by 15%, RDF decreased by 15%, good earth increased by 15%, and good earth decreased by 15%.

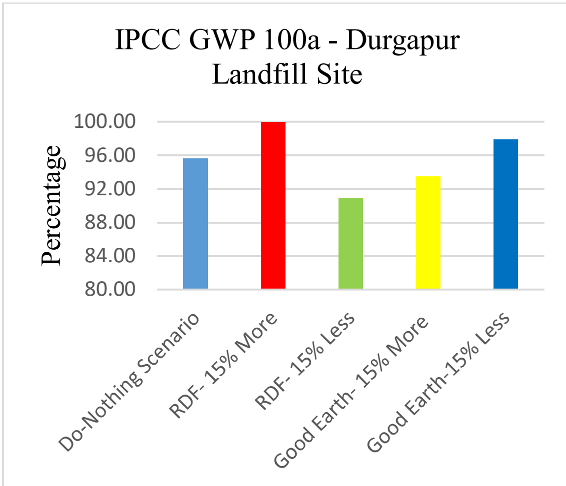
4.10.3.3. Results of Sensitivity Analyses for Durgapur and Howrah Landfill Sites

The results of sensitivity analyses, based on Global Warming Potential (GWP) as measured by the IPCC GWP 100a, are presented in detail in Table 26 for both sites. These values are illustrated in a bar chart (Figure 65), where the RDF-15% More scenario shows the highest value, set at 100%. The values for the other scenarios are calculated relative to this baseline.

Table 26: Global Warming Potential Value (Kg CO_2 Equivalent)

Landfill Site	Do-Nothing Scenario	RDF- 15% More	RDF- 15% Less	Good Earth- 15% More	Good Earth- 15% Less
Durgapur	1933.48	2021.95	1838.39	1890.13	1979.74
Howrah	1691.17	1703.52	1679.94	1577.2	1824.34

At the Durgapur landfill site, a 15% reduction in RDF content results in a 4.92% decrease in Global Warming Potential (GWP), while a 15% reduction in Good Earth content leads to a 2.39% increase in GWP compared to the Do-nothing scenario. At the Howrah landfill site, which has a higher proportion of Good Earth, reducing Good Earth content by 15% causes a 7.3% increase in GWP compared to Do-nothing scenario, as the RDF content adjusts relative to the reduced waste volume. Conversely, increasing Good Earth content by 15% results in a 6.25% decrease in GWP compared to Do-nothing scenario.



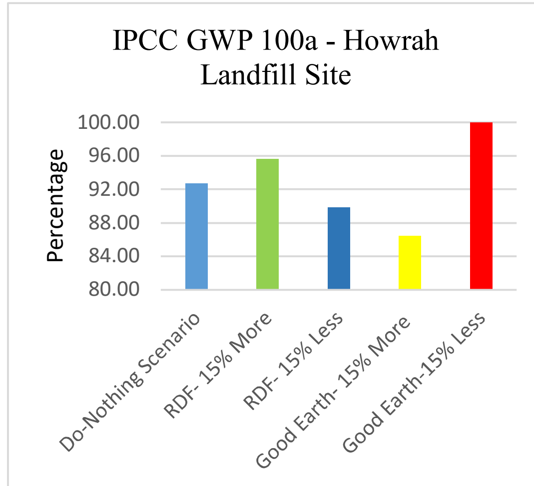


Figure 65: GWP value at Durgapur and Howrah Landfill Site

The analysis shows that global warming potential is significantly affected by the RDF ingredients. When the RDF value is reduced by 15%, the overall global warming potential decreases, even when adjusted by the good earth values, as the contribution of good earth to global warming is less compared to RDF. Conversely, when the good earth value is decreased by 15%, the RDF value increases, leading to a higher overall global warming effect compared to the do-nothing scenario. This study concludes that both the quantities of RDF and good earth are sensitive factors in this waste management process.

4.10.4. Uncertainty Analysis

Uncertainty analysis is crucial in evaluating the environmental impacts of the landfill mining process through Life Cycle Assessment (LCA) using ReCiPe midpoint indicators. Given the inherent variability and uncertainty in environmental data and modelling assumptions, it is essential to conduct a thorough analysis to ensure the robustness and reliability of the findings.

To address this, a Monte Carlo simulation with 1000 iterations with 95% confidence level is applied. This approach facilitates the exploration of potential outcomes and evaluates how variations in input parameters influence the LCA results. The simulation outcomes for the "Do Nothing" scenario at the Howrah and Durgapur sites are detailed in Tables 27 and Table 28, respectively.(Results for all other scenarios are presented in Appendix-I and Appendix-II).

Table 27: Monte Carlo Simulation Results for the "Do-Nothing" Scenario of Howrah Landfill Site

Impact category	Reference unit	Result	Minimum	Maximum	Mean	S.D.	Median
Fine particulate matter formation	kg $PM_{2.5}$ eq	2.835	2.771	3.369	2.855	0.055	2.846
Fossil resource scarcity	kg oil eq	482.477	478.457	491.576	482.863	1.692	482.751
Freshwater ecotoxicity	kg 1,4-DCB	76.015	40.862	443.116	91.728	37.524	81.833

Impact category	Reference unit	Result	Minimum	Maximum	Mean	S.D.	Median
Freshwater eutrophication	kg P eq	0.233	0.229	3.264	0.251	0.120	0.234
Global warming	kg CO_2 eq	1962.732	1888.591	2134.485	1971.796	36.407	1967.978
Human carcinogenic toxicity	kg 1,4-DCB	67.537	65.716	6486.213	107.362	269.532	68.325
Human non-carcinogenic toxicity	kg 1,4-DCB	1958.992	1101.807	11978.253	2286.145	1113.29	1963.052
Ionizing radiation	kBq Co-60 eq	33.100	32.449	34.424	33.181	0.297	33.150
Land use	m^2a crop eq	624.654	573.855	676.323	624.800	15.320	624.545
Marine ecotoxicity	kg 1,4-DCB	101.597	55.152	597.243	122.216	50.021	109.469
Marine eutrophication	kg N eq	0.860	0.724	1.210	0.891	0.070	0.887
Mineral resource scarcity	kg Cu eq	2.938	2.822	3.175	2.951	0.056	2.947
Ozone formation, Human health	kg NOx eq	6.640	6.342	11.465	6.764	0.425	6.650
Ozone formation, Terrestrial ecosystems	kg NOx eq	6.771	6.472	11.596	6.894	0.425	6.781
Stratospheric ozone depletion	kg CFC11 eq	0.002	0.002	0.003	0.002	0.000	0.002
Terrestrial acidification	kg SO_2 eq	7.028	6.691	8.849	7.086	0.197	7.062
Terrestrial ecotoxicity	kg 1,4-DCB	2336.34	2299.51	2527.502	2347.74	25.713	2343.87
Water consumption	m^3	66.660	20.571	123.717	67.907	14.369	67.200

Table 28: Monte Carlo Simulation Results for the "Do-Nothing" Scenario of Durgapur Landfill Site

Impact category	Reference unit	Result	Minimum	Maximum	Mean	S.D.	Median
Fine particulate matter formation	kg $PM_{2.5}$ eq	3.202	3.152	3.430	3.217	0.036	3.211
Fossil resource scarcity	kg oil eq	538.909	535.957	545.009	539.183	1.284	539.082

Impact category	Reference unit	Result	Minimum	Maximum	Mean	S.D.	Median
Freshwater ecotoxicity	kg 1,4-DCB	72.870	47.057	260.796	85.417	28.008	78.496
Freshwater eutrophication	kg P eq	0.283	0.280	33.196	0.336	1.073	0.284
Global warming	kg CO_2 eq	2137.46	2073.66	2315.31	2145.96	29.40	2142.49
Human carcinogenic toxicity	kg 1,4-DCB	75.68	74.03	8217.85	111.61	307.77	76.18
Human non-carcinogenic toxicity	kg 1,4-DCB	1952.90	1304.31	9563.02	2213.88	818.15	1983.05
Ionizing radiation	kBq Co-60 eq	38.077	37.568	39.095	38.149	0.235	38.130
Land use	m^2a crop eq	549.221	515.321	596.136	549.644	12.310	549.108
Marine ecotoxicity	kg 1,4-DCB	98.000	64.155	360.007	114.489	37.177	105.017
Marine eutrophication	kg N eq	0.796	0.683	1.107	0.820	0.056	0.814
Mineral resource scarcity	kg Cu eq	3.011	2.919	3.171	3.021	0.042	3.018
Ozone formation, Human health	kg NOx eq	7.263	7.041	9.182	7.352	0.268	7.272
Ozone formation, Terrestrial ecosystems	kg NOx eq	7.406	7.184	9.325	7.495	0.268	7.415
Stratospheric ozone depletion	kg CFC11 eq	0.003	0.002	0.003	0.003	0.000	0.003
Terrestrial acidification	kg SO_2 eq	7.267	6.959	8.085	7.311	0.137	7.290
Terrestrial ecotoxicity	kg 1,4-DCB	2588.70	2553.76	2702.57	2596.93	18.77	2593.76
Water consumption	m^3	58.352	25.348	106.357	58.989	11.009	58.681

Based on the simulation results, the overall implications for both landfill sites, Howrah and Durgapur, are discussed below.

4.10.4.1. Environmental Impact Management

Durgapur shows higher and more consistent impacts across many categories, which suggests a need for improved environmental management practices. Specifically, Durgapur should focus on areas such as global warming, fossil resource scarcity, and human health impacts. Implementing advanced waste treatment technologies, enhancing resource recovery, and improving operational efficiencies could help mitigate these impacts.

Howrah has relatively lower mean impacts but exhibits significant variability, indicating inconsistent performance or varying waste types or landfill age. To address this, Howrah should aim for more consistent waste management practices and operational procedures to reduce variability and achieve more predictable environmental outcomes. Implementing source segregation to homogenise waste materials, following standardized procedures for waste managements and regular monitoring could help in achieving stable performance across all impact categories.

4.10.4.2. Uncertainty and Variability

Durgapur shows less variability across impacts, suggesting more stable but higher overall impacts. This stability can be advantageous for implementing consistent improvements but requires significant changes to reduce high impacts. Focused interventions and long-term strategies could be employed to manage and reduce these stable but high impacts.

Howrah exhibits higher variability, which can make it challenging to predict environmental impacts accurately. The broad range of impacts indicates that the site might be dealing with varying waste types or operational conditions that contribute to fluctuating environmental outcomes. Addressing this variability requires a detailed understanding of the factors causing these fluctuations and implementing targeted measures to stabilize performance. Improved data collection, risk assessment, and adaptation of best practices could help in reducing variability and achieving more consistent environmental performance.

4.10.4.3. Focus Areas for Improvement

Both Howrah and Durgapur have areas where impacts are notably high, but Durgapur's greater impacts in many categories indicate a need for more targeted improvements. Key areas include reducing particulate matter, greenhouse gas emissions, and managing carcinogenic substances more effectively.

By addressing these key issues and focusing on areas with the highest environmental impact, both Howrah and Durgapur can improve their landfill operations and reduce their overall environmental footprint.

4.11. Effectiveness of Integrating Biomining Techniques for Landfill Sites

Implementing effective waste management strategies, such as the utilization of Refuse Derived Fuel (RDF) in cement factories or brick kiln as alternative of natural coal and the use of Good Earth for subgrade material of roads, leads to significant improvements across various environmental impact categories.

4.11.1. Refuse Derived Fuel (RDF) Utilization

- **Energy Recovery:** RDF is produced from the combustible fraction of municipal solid waste and can be used as a substitute for fossil fuels in industrial processes, such as cement manufacturing or brick kilns. Studies show that RDF can replace up to 50% of traditional fossil fuels in cement kilns, leading to substantial reductions in greenhouse gas emissions (González et al., 2019).This substitution not only helps in reducing the consumption of fossil fuels but also decreases greenhouse gas emissions associated with their use.

- **Reduction in Landfill Use:** By converting waste into RDF, the amount of waste sent to landfills is reduced. According to research by Vassilev et al. (2018), RDF production can decrease landfill use by up to 30%, which in turn minimizes associated environmental issues such as leachate generation and methane emissions. This reduction contributes to the mitigation of landfill expansion and its environmental impacts.

4.11.2. Utilization of Good Earth for Subgrade Material of Roads

- **Resource Efficiency:** Using Good Earth (clean soil excavated from construction sites) as subgrade material in construction projects reduces the need for virgin soil materials. This practice helps in conserving natural resources and reduces the environmental impact associated with soil material extraction and transportation. According to studies by Rees and Wackernagel (2020), Good Earth usage can lead to a reduction in the demand for new construction materials by up to 25%.
- **Land Reclamation:** Reusing Good Earth promotes sustainable land management by repurposing excavated soil, which otherwise might contribute to soil erosion or land degradation.

4.11.3. Combined Approach of RDF and Good Earth Management

The integrated strategy of combining RDF utilization with the use of Good Earth offers the most comprehensive environmental benefits:

4.11.3.1. Air Quality Improvement

- **Lower Emissions:** RDF usage in industrial processes helps to lower emissions of particulate matter and other pollutants compared to traditional fossil fuels. Literature by Yang et al. (2022) indicates that RDF can lower particulate emissions by approximately 20% compared to traditional fossil fuels. When combined with Good Earth usage, the overall air quality improves due to reduced construction and land disturbance activities that might otherwise contribute to dust and emissions.

4.11.3.2. Resource Use Optimization

- **Reduced Fossil Fuel Dependency:** RDF helps in minimizing the dependency on fossil fuels, leading to lower fossil resource scarcity. Additionally, using Good Earth reduces the demand for new construction materials, thus conserving natural resources and reducing the environmental impact of material extraction.
- **Minimized Waste:** Both RDF and Good Earth strategies reduce the volume of waste sent to landfills, promoting a circular economy where waste products are reused and recycled.

4.11.3.3. Global Warming Mitigation

- **Lower Carbon Footprint:** RDF has a lower carbon footprint compared to fossil fuels, contributing to reduced greenhouse gas emissions. The use of Good Earth for construction also avoids emissions associated with the production and transportation of new materials, further mitigating global warming.

4.11.3.4. Public Health and Environmental Protection

- **Health Benefits:** By reducing pollutants and greenhouse gases, these strategies contribute to improved air quality and lower health risks associated with pollution. The decreased landfill use also reduces potential hazards related to leachate and methane emissions.
- **Ecosystem Preservation:** Properly managed waste reduces the impact on ecosystems, helping to preserve biodiversity and prevent environmental degradation. Research by Patel et al. (2023), highlights that proper management of RDF and Good Earth helps maintain ecosystem health by preventing soil erosion and minimizing land disturbance.

The combined approach of RDF utilization and Good Earth management is a powerful strategy for enhancing environmental sustainability. It addresses multiple impact categories effectively, offering significant benefits in air quality, resource conservation, and climate change mitigation. This integrated approach not only supports environmental protection but also contributes to public health by reducing pollution and conserving natural resources. Adopting these practices highlights the importance of comprehensive waste management strategies in achieving long-term sustainability and environmental management.

4.12. Landfill Gas Generation

The amount of gas generated from a landfill is determined by the annual volume of waste landfilled, using the LandGEM (Version 3.1beta-Dec-2023) software. To estimate the annual landfilled waste volume, it is crucial to consider the population living in the area and their per capita waste generation. Population estimates are derived using different models due to the differing population growth patterns in Howrah and Durgapur cities.

For Howrah City, the population is projected using the logistic growth model, as detailed in the Table 29 below

Previous Census Data of Howrah city (https://www.citypopulation.de/):

- 1991: P0 = 37,29,644
- 2001: P1 = 42,73,099
- 2011: P2 = 48,50,029

Based on the previous census data, the saturation density, m, and n values have been calculated. The obtained values are:

- Saturation Density (Ps) = 1,21,31,276
- m = 2.2527
- n = -0.020267

Table 29: Waste Landfilled per annum in Howrah Landfill Site

Year	Population	Per capita generation per day (kg)	Per capita generation per day (ton)	Total generation per annum (ton)
2011	4850029	1818760.88	1818.76	663847.72
2012	4909211	1840954.15	1840.95	671948.26
2013	4968622	1863233.43	1863.23	680080.2
2014	5028252	1885594.62	1885.59	688242.04
2015	5088089	1908033.53	1908.03	696432.24
2016	5148122	1930545.94	1930.55	704649.27
2017	5208340	1953127.54	1953.13	712891.55
2018	5268731	1975773.99	1975.77	721157.51
2019	5329282	1998480.89	1998.48	729445.52
2020	5389983	2021243.78	2021.24	737753.98
2021	5450822	2044058.18	2044.06	746081.24
2022	5511785	2066919.55	2066.92	754425.63
2023	5572862	2089823.30	2089.82	762785.51
2024	5634040	2112764.84	2112.76	771159.17
2025	5695305	2135739.52	2135.74	779544.93
2026	5756647	2158742.68	2158.74	787941.08

Durgapur is a growing city, and its population estimation is based on the geometric increase model.

Previous Census Data of Durgapur city (https://www.citypopulation.de/):

- 1991: P0 = 4,25,836
- 2001: P1 = 4,93,405
- 2011: P2 = 5,66,517

Table 30: Average Percentage Growth Rate per Decade

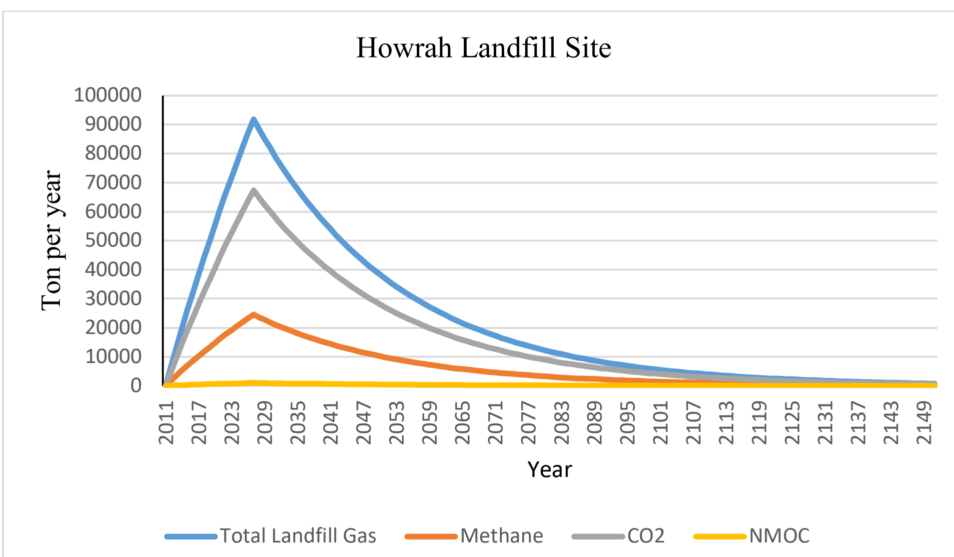
Year	Population	Increment in population	% incremental in population
1991	425836		
		67569	15.86737617
2001	493405		
		73112	14.81784741
2011	566517		

From Table 30, the values of 'k_1' and 'k_2' are 15.8673 and 14.8178, respectively. Based on these values, the average percentage growth per decade (k) is 15.3336. Using this average growth rate, the population of Durgapur and the annual amount of waste landfilled are calculated in Table 31.

Table 31: Waste Landfilled per annum in Durgapur Landfill Site

Year	Population	Per capita generation per day (kg)	Per capita generation per day (ton)	Total generation per annum (ton)
2011	566517	212443.88	212.44	77542.01
2012	574657	215496.30	215.50	78656.15
2013	582914	218592.58	218.59	79786.29
2014	591289	221733.34	221.73	80932.67
2015	599785	224919.24	224.92	82095.52
2016	608402	228150.91	228.15	83275.08
2017	617144	231429.01	231.43	84471.59
2018	626011	234754.22	234.75	85685.29
2019	635006	238127.20	238.13	86916.43
2020	644130	241548.64	241.55	88165.25
2021	653385	245019.24	245.02	89432.02
2022	662773	248539.71	248.54	90717.00
2023	672295	252110.76	252.11	92020.43
2024	681955	255733.13	255.73	93342.59
2025	691753	259407.53	259.41	94683.75
2026	701693	263134.74	263.13	96044.18

Based on the waste generation data from the Howrah and Durgapur landfill sites, LandGEM (Version 3.1beta-Dec-2023) was utilized to calculate the total landfill gas emissions, including methane, carbon dioxide, and non-methane organic carbon (NMOC). During the calculations, the default values for methane generation rate (k, per year) and potential methane generation capacity (L0, m³/ton) are considered. The results for both landfill sites are illustrated in the charts below (Figure 66).



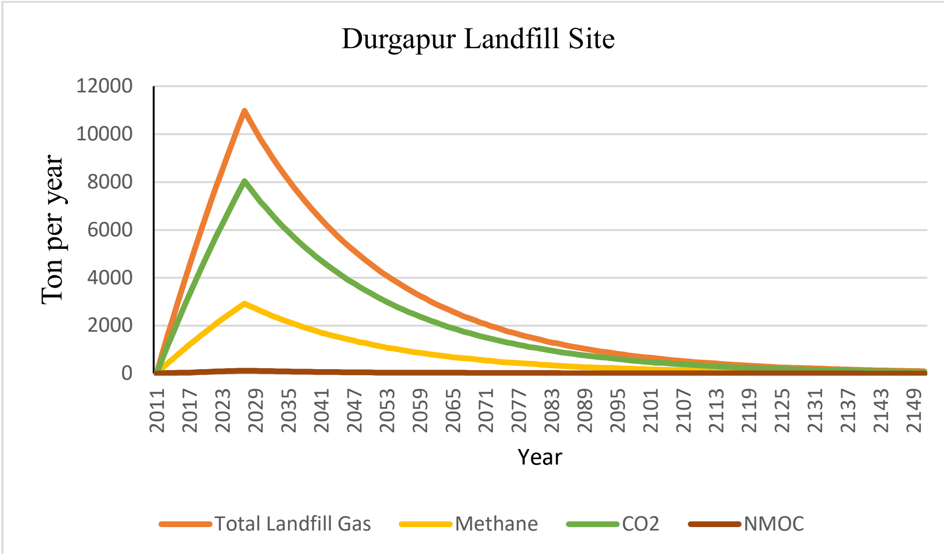


Figure 66: Gas Emission Data of Howrah and Durgapur Landfill Site

The charts for both landfill sites show the total landfill gas, methane, carbon dioxide, and NMOC emissions, which are summarized in Table 32. The data reveals a pattern in the gas generation relative to the total amount of waste landfilled. Based on this trend, the emissions from 630,000 tons of waste, which will be biomined over the course of a year, have been calculated.

Table 32: Gas Emission Data

	Waste (ton)	Total Landfill Gas (ton)	Methane (CH_4) (ton)	Carbon Dioxide (CO_2) (ton)	Non-Methane Organic Carbon (ton)
Howrah Landfill Site	11608385.8	3174061.77	847825.99	2326235.77	36441.72
Durgapur Landfill Site	1383766.26	378355.1	101062.7	277292.4	4343.933
Waste biomined per year	630000	172257.2	46011.75	126245.5	1977.702

The CO_2 emissions from 630,000 tons of waste are 126,245.5 tons. This amount is used as carbon emission reduction credits in the cost-benefit analysis.

4.13. Cost Benefit Analysis

This chapter examines the economic feasibility of the proposed strategy, assessing both its financial benefits and potential costs. Direct and environmental costs are quantified based on data obtained from landfill surveys. Secondary data from scientific literature and relevant websites are utilized to analyse raw material costs and other expenses. The chapter concludes with a comparison of costs, specifically examining the use of refuse-derived fuel in cement and brick kilns as alternatives to coal and considering good earth as a substitute for natural soil in subgrade materials in roads. This comparison helps to determine the economic viability of the proposed strategy.

The cost components are divided into five categories: Material Costs, Operation and Maintenance Costs, Transportation Costs, Labour Costs, and Environmental Benefits.

4.13.1. Amount of Waste Biomined in a Year

For calculating the cost benefit of the project, the amount of waste processed through biomining is a crucial parameter. This is because the volume of waste directly impacts processing costs and the potential yield of valuable resources. Handling larger amounts of waste requires more extensive processing capabilities, leading to higher operational expenses.

In West Bengal, the rainy season is typically considered to last for 2 months, during which all biomining operations are suspended. A typical month in the region consists of 26 working days. Throughout the year, there are a total of 250 working days. According to field survey data, each working day spans 8 hours, and operations are conducted with 90% efficiency.

First, the total number of working hours in a year:

$$= (\text{Working hours per day} \times \text{Working days per year})$$

$$= (8\text{hours/day} \times 250\text{days/year})$$

$$= 2000 \text{ hours/year}$$

From the field survey data, it was found that the average amount of waste biomined per hour is 350 tons.

Next, the total amount of waste biomined in a year, considering the efficiency:

$$= (\text{Average amount biomined per hour} \times \text{Total working hours per year} \times \text{Efficiency})$$

$$= 350\text{tons/hour} \times 2000\text{hours} \times 0.90$$

$$= 6{,}30{,}000 \text{ tons}$$

4.13.2. Material Costs

For this biomining project, the cost components considered under Material Costs are land cost, cost of coal, and cost of good earth.

4.13.2.1. Land Cost

The requirement of land area for a biomining processing setup is approximately 2 Katha, which equals 1440 square feet. According to WBSIDCL (2024), the rate of lease at Howrah is 1111.11 INR per sq. ft. and for Purba Bardhaman, the rate is 451.39 INR per sq. ft for 99 Years. The total land cost for 99 years and cost per year are shown in Table 33.

Table 33: Cost of Land

Site Name	Total Cost	Cost per year	
		INR	USD
Howrah	15,99,998	16,161	193.60
Durgapur	6,50,001	6,566	78.66

• 1 USD = 83.51 INR on 5th July 2024

4.13.2.2. Coal Replacement Cost

The amount of coal replaced by RDF annually is listed in Table 34 considering the calorific value of coal used in cement plant is 6309.75 kcal/kg (Ecoinvent 97) and cost is 7000 INR per ton (https://www.indiamart.com). The calorific value of RDF is considered 4000 kcal/kg, and the cost is 1200 INR per ton (https://www.indiamart.com) for calculation purposes, though real time data obtained from the bomb calorimeter test was obtained as 4188.31 kcal/kg in Howrah landfill site and 4333.36 kcal/kg in Durgapur landfill site.

Table 34: Cost of Coal and RDF

Landfill Site	Item	Amount in ton per year (ton/year)	Calorific Value (Kcal)	Cost	
				INR	USD
Howrah	RDF	1,88,433	753732000000	22,61,19,600	27,07,695
	Coal	119455.12	753732000000	83,61,85,840	1,00,13,003
Durgapur	RDF	2,26,233	904932000000	27,14,79,600	1,08,36,211
	Coal	143418.04	904932000000	1003926280	1,20,21,630

• 1 USD = 83.51 INR on 5th July 2024

For Howrah Landfill Site, the amount of benefit for utilising RDF instead of coal in cement factory per annum:

= (83,61,85,840 - 22,61,19,600)

= 61,00,66,240 INR

= 73,05,307.62 USD

For Durgapur Landfill Site, the amount of benefit for utilising RDF instead of coal in cement factory per annum:

= (100,39,26,280 - 27,14,79,600)

= 73,24,46,680 INR

= 87,70,766.13 USD

4.13.2.3. Cost of Good Earth

In current road construction projects, the cost of soil is significantly influenced by the Government policies that restrict the use of borrow pit soil, necessitating the consideration of soil as lead. For distances greater than 5 km from the landfill site, field surveys indicate that the cost of soil, including transportation, ranges from ₹350 to ₹400 per cubic meter. This includes the price of transporting the soil from the source to the construction site. Conversely, the cost of good earth, suitable for construction, is approximately ₹120 per cubic meter, which reflects the base price before transportation expenses are factored in, as per field survey data. The cost of good earth annually is listed in Table 35.

Table 35: Cost of Good Earth

Landfill Site	Amount in ton per year (ton/year)	Amount in per cubic meter	Cost	
			INR	USD
Howrah	326151	203844.4	2,44,61,325	2,92,915
Durgapur	249228	155767.5	1,86,92,100	2,23,831

• 1 USD = 83.51 INR on 5th July 2024

4.13.3. Transportation Costs

Transportation costs are crucial for the seamless movement of materials to and from the landfill mining site. These expenses primarily include fuel costs.

4.13.3.1. Fuel Costs Due to Transportation

For the cost-benefit analysis, the transportation costs from the Howrah and Durgapur landfill sites to the desired destination are directly impacted by the diesel price in West Bengal, which was 91.76 INR per litre as of July 5th, 2024, according to a report by NDTV, 2024. Trucks commonly used for transporting RDF in India have an average Gross Vehicle Weight (GVW) of about 28 tons, with a payload capacity of 20 tons (International Council of Clean Transportation, 2017). To enhance cost-effectiveness and strategic decision-making, we are prioritizing the cement factory because it is situated further away from the landfill site compared to the brick kiln. The calculations for site-specific fuel consumption are listed in detail in Table 36 and Table 37.

***Table 36*:** Fuel Costs Due to Transporting RDF from the Howrah Landfill Site to the Cement Factory

Industry Type	Average fuel consumption (L/100 Km)	Average distance from Howrah Landfill site (Km)	Fuel consumption per round trip (L)	Fuel consumption per ton of RDF (L)	Avg. Fuel consumption per ton of RDF (L)	Fuel Cost (INR)
Cement Factory	26.1 (Upper weight limit)	250 (West Bengal)	130.5	6.53	12.18	1118
		400 (Odisha)	208.8	10.44		
		750 (Chhattisgarh)	391.5	19.58		
	21.8 (Lower weight limit)	250 (West Bengal)	109	5.45	10.17	933
		400	174.4	8.72		

Industry Type	Average fuel consumption (L/100 Km)	Average distance from Howrah Landfill site (Km)	Fuel consumption per round trip (L)	Fuel consumption per ton of RDF (L)	Avg. Fuel consumption per ton of RDF (L)	Fuel Cost (INR)
		(Odisha)				
		750 (Chhattisgarh)	327	16.35		

For Howrah landfill site, the average fuel cost per annum:

= {(1118 + 933)/2} * 630000

= 64,60,65,000 INR

= 77,36,378.88 USD

Table 37: Fuel Costs Due to Transporting RDF from the Durgapur Landfill Site to the Cement Factory

Industry Type	Average fuel consumption (L/100 Km)	Average distance from Howrah Landfill site (Km)	Fuel consumption per round trip (L)	Fuel consumption per ton of RDF (L)	Avg. Fuel consumption per ton of RDF (L)	Fuel Cost (INR)
Cement Factory	26.1 (Upper weight limit)	100 (West Bengal)	52.2	2.61	8.27	759
		250 (Odisha)	130.5	6.53		
		600 (Chhattisgarh)	313.2	15.66		
	21.8 (Lower weight limit)	100 (West Bengal)	43.6	2.18	6.90	633
		250 (Odisha)	109	5.45		
		600 (Chhattisgarh)	261.6	13.08		

For Durgapur landfill site, the average fuel cost per annum:

= {(759 + 633)/2} * 630000

= 43,84,80,000 INR

= 52,50,628.67 USD

4.13.4. Labour Wages

To sustain the biomining project, the minimum required number of labours and their associated wages are listed in detail in Table 38. All data have been collected from field surveys conducted at the Howrah and Durgapur landfill sites.

Table 38**:** Labour Wages

Type	**Numbers**	**Cost per Month (INR)**	**Total cost per year**	
			INR	**USD**
Trommel Operator	1	28,000	3,36,000	4,023
Trommel Helper	2	12,000	2,88,000	3,448
Excavator Driver	2	22,000	5,28,000	6,323
Truck Driver	2	15,000	3,60,000	4,311
Weighbridge Operator	1	15,000	1,80,000	2,156
Labour	5	10,000	6,00,000	7,185
Security Guard	2	10,000	2,40,000	2,874
		Total	25,32,000	30,320

• 1 USD = 83.51 INR on 5th July 2024

4.13.5. Operation & Maintenance Costs

Operation and maintenance costs are essential for ensuring the ongoing functionality and efficiency of a biomining project. These costs include expenses related to machinery, equipment, repairs, and general operational needs.

4.13.5.1. Machinery Costs

For operating a biomining project, the minimum machinery required is one trommel/power screen, two excavators, two trucks. Machinery costs are shown in Table 39.

Table 39: Machinery Cost

Machinery Name	Cost		Average Cost	Total Cost	Yearly depreciation (Consider 10 years lifetime and no salvage value)	
	Reference	INR	INR	INR	INR	USD
Trommel	https://www.indiamart.com	40,00,000-55,00,000	47,50,000	47,50,000	4,75,000	5,687.9

Machinery Name	Cost		Average Cost	Total Cost	Yearly depreciation (Consider 10 years lifetime and no salvage value)	
	Reference	INR	INR	INR	INR	USD
Excavators	https://dir.indiamart.com	52,00,000-68,00,000	60,00,000	1,20,00,000	12,00,000	14,369.5
Trucks	https://trucks.cardekho.com	28,00,000-40,00,000	34,00,000	68,00,000	6,80,000	8,142.7
Weighbridge	https://www.indiamart.com	3,00,000-4,00,000	3,50,000	3,50,000	35,000	419.1

• 1 USD = 83.51 INR on 5th July 2024

Total cost required for machinery:

= (4,75,000 + 12,00,000 + 6,80,000 + 35,000)

= 23,90,000 INR

= 28619.3 USD

4.13.5.2. Fuel Costs Due to Machine Operation

Based on a field survey, a trommel consumes an average of 12 Liters of diesel per hour of operation, while excavators use about 15 Liters per hour. In India, a 32-ton truck typically averages 5 km per Liter of diesel on highways (https://trucks.cardekho.com). However, trucks working at landfill sites cover a relatively short distance, averaging around 10 km per day, which results in a daily diesel consumption of approximately 3 to 5 Liters per truck. All costs are calculated in Table 40, with the consideration of an 8-hour workday and 250 working days per year.

Table 40: Fuel Cost Due to Machine Operation

Machinery Name	**No of Units**	**Diesel used per day (Litre)**	**Diesel used per annum (Litre)**	**Cost**	
				INR	**USD**
Trammel	1	96	24000	2160000	25865.17
Excavators	2	240	60000	5400000	64662.91
Trucks	2	8	2000	180000	2155.43

• Diesel price = 90.00 INR per Liter on 5th July 2024 (https://www.india.com/)
• 1 USD = 83.51 INR on 5th July 2024

Total machine operation cost:

= (21,60,000 + 54,00,000 + 18,0000)

= 77,40,000 INR

= 92,683.51 USD

4.13.5.3. Repair and Maintenance Cost

Repair and maintenance costs refer to the expenses incurred to keep equipment, machinery, infrastructure, or vehicles in good operating condition. These costs typically include routine servicing, unexpected repairs due to wear and tear or breakdowns, and occasionally, upgrades to extend the useful life or improve efficiency. Post (2022) suggests that the total maintenance and repair costs over the lifespan of a machine should approximate 75% of its initial cost. Therefore, the annual repair and maintenance costs for the setup, machinery, and vehicle combined are estimated at 17,92,500 INR or 21,464.5 USD (1 USD = 83.51 INR on 5th July 2024).

4.13.5.4. Working Capital

Following the research methodology like that of Tam (2008), the working capital is determined to be 15% of the total operating costs, encompassing maintenance, fuel and labour expenses. Consequently, the annual working capital is estimated at 6,67,79,175 INR or 7,99,654.8 USD for Durgapur landfill site and 9,76,74,937 INR or 11,74,683.5 USD for Howrah landfill site.

4.13.6. Environmental Benefits

Environmental benefits represent the positive impacts of the landfill mining project on the environment. These benefits can include land reclamation and carbon emissions reduction.

4.13.6.1. Land Space Generated

The biomining process not only extends the landfill's lifespan but also creates opportunities for reclaiming the space, turning former waste sites into valuable assets for sustainable development and community enhancement, while also ensuring that the land can be effectively managed for future waste disposal needs. The area required for a landfill based on waste carrying capacity is shown in Table 41.

Table 41: Land Required for Landfill (Solid wastes management manual, 2016)

Waste carrying capacity (million tons)	Area (Ha)
< 1.0	15-20
1.0 - 2.0	20-30
2.0 - 3.0	30-40
> 3.0	> 40

From the calculation, the amount of waste biomined in a year is 6,30,000 tons or 0.630 million tons. From Table 42, the area required for 0.630 million tons waste is approximately 17 Ha or 1829863 sq ft.

Table 42. Cost due to Land Space Generated

Landfill Name	Area (Sq. ft.)	Cost per sq. ft.	Cost	
		INR	INR	USD
Howrah	67,812.64	1,111.11	75347302	9,02,255
Durgapur	67,812.64	451.39	30609947	3,66,542

• 1USD = 83.51 INR on 5th July 2024

4.13.6.2. Carbon Emissions Reduction (CER) Credit

In India, the Multi Commodity Exchange (MCX) operates as a commodity exchange market specializing in trading carbon credits based on carbon equivalents. One Carbon Emission Reduction (CER) credit corresponds to one metric ton of CO_2. The CER value is based on the 2009 estimate from the United States Environmental Protection Agency (USEPA), which was $13.80 [Sprague et al., 2009]. As of 2024, this valuation is approximately 1,653 INR.

Landfill gas emissions are typically reported as carbon dioxide equivalent (CO_2e). Methane (CH_4) has a Global Warming Potential (GWP) 21 times greater than CO_2, so its equivalency factor is 21. This means the cost of methane is roughly 34,713 INR.

Table 43 below shows the total carbon emissions reduction credit (CER) cost for both methane (CH_4) and carbon dioxide (CO_2). But this study only considers the CER credit related to CO_2.

Table 43: Cost Due to CER Credit

Parameter	Amount (tons)	Cost	
		INR	USD
Carbon dioxide (CO_2)	126247.40	20,86,86,952.20	2,498,945.66
Methane (CH_4)	46012.46	159,72,30,523.98	1,91,26,218.70

• 1USD = 83.51 INR on 5th July 2024

4.13.7. Summary

The costs and benefits associated with the Howrah and Durgapur landfill sites for biomining project are detailed in Table 44.   .

Table 44: Summary of The Associated Costs of The Project

Description		Howrah		Durgapur	
		Benefit (+)	**Expenditure (-)**	**Benefit (+)**	**Expenditure (-)**
Land cost			16161		6566
Machinery cost			2390000		2390000
Fuel Cost Due to Machine Operation			7740000		7740000
Fuel Cost Due to Coal Transportation			646065000		438480000
Coal Replacement Cost		610066240		732446680	
Cost of Good Earth		24461325		18692100	
Labour wages			2532000		2532000
Repair and maintenance			1792500		1792500
Working capital			97674937		66779175
Land Space Generated		75347302		30609947	
Carbon Emissions Reduction (CER) Credit		208686952.2		208686952.2	
Total	INR	91,85,61,819.2	75,82,10,598	99,04,35,679	51,97,20,241
	USD	1,09,99,423.05	90,79,279.104	1,18,60,084.77	62,23,449.18

• 1USD = 83.51 INR on 5th July 2024

Based on the above data, the net benefit, cost-benefit ratio, and net present value (NPV) have been calculated and shown in Table 45.

In Net Present Value (NPV) calculations, the discount rate is a crucial factor. The World Bank indicates that the 10-12% discount rate typically applied to projects is a nominal rate that may not fully capture the real opportunity cost of capital or the risks involved (Belli et al., 1998). For this project, an average discount rate of 11% is being used.

Table 45: Cost-Benefit and NPV Summary

Site Name	Net Benefit (INR)	Cost-Benefit Ratio	Net Present Value (NPV)	
			INR	USD
Howrah	16,03,51,221.2	1.211	6,93,22,572.45	8,30,111.03
Durgapur	47,07,15,438.2	1.906	37,25,64,154.68	44,61,311.87

• 1USD = 83.51 INR on 5th July 2024

4.13.7.1. Overview of Cost-Benefit Ratio

Both landfill sites under consideration exhibit a cost-benefit ratio greater than 1 (Table 45), indicating that the anticipated benefits of biomining each site exceed the associated costs. However, the magnitude of the cost-benefit ratio for each site differs, reflecting the relative attractiveness of each project.

- **Howrah Landfill Site:** Cost-Benefit Ratio = 1.211
- **Durgapiur Landfill Site:** Cost-Benefit Ratio = 1.906

The Durgapur Landfill Site has a higher cost-benefit ratio than the Howrah Landfill Site. This means that for every rupee spent on the Durgapur project, the return is 1.906 INR in benefits, whereas the Howrah project offers a return of 1.211 INR for every rupee spent. This implies that the Durgapur site is relatively more efficient at converting investment into benefits.

4.13.7.2. Overview of Net Present Value (NPV)

Both projects have a positive Net Present Value (NPV), indicating that they are expected to generate more value than their respective investment costs, thus representing good investment opportunities.

- **Howrah Landfill Site:** NPV = 6,93,22,572.45 INR
- **Durgapur Landfill Site:** NPV = 37,25,64,154.68 INR

The Durgapur site has a significantly higher NPV of 37,25,64,154.68 INR compared to Howrah's 6,93,22,572.45 INR. Specifically, the Durgapur site's NPV is approximately 5.37 times greater than that of the Howrah site. This suggests that the Durgapur site is expected to generate a higher total value in present-day terms, making it a potentially more profitable investment.

4.13.7.3. Comparative Profitability Analysis of Durgapur vs. Howrah Landfill Sites

The Durgapur landfill site proves to be a more profitable project compared to the Howrah site based on cost-benefit ratios and net present value (NPV). The key factors contributing to the higher profitability of the Durgapur site are as follows:

- **Transportation Costs:** The distance from the Howrah landfill site to the cement factory is greater than that from the Durgapur site. This increased distance results in an additional expenditure of 20,75,85,000 INR for transporting refuse-derived fuel (RDF) to the cement factory for the Howrah site.
- **Coal Replacement:** At the Durgapur landfill site, the percentage of RDF per ton of waste is higher compared to the Howrah site. Consequently, the Durgapur site replaces more coal, leading to a profit of 73,24,46,680 INR, whereas the Howrah site generates a profit of 61,00,66,240 INR from coal replacement.
- **Working Capital Requirements:** The Howrah landfill site requires ₹30,895,762 INR more in working capital to operate its biomining project compared to the Durgapur site, which increases the overall expenditure of the Howrah project.

Conversely, the Howrah landfill site benefits from a 30.88% higher yield of good earth, resulting in an additional profit of 57,69,225 INR compared to the Durgapur site. This is particularly advantageous given the higher land costs in the Howrah municipality area, where the value of the generated land space is 4,47,37,355 INR more than that of the Durgapur site. However, the biomining projects at both the Howrah and Durgapur landfill sites are profitable.

Chapter 5: Conclusion and Recommendation

5.1. General

In this chapter, the effectiveness of the strategy implemented in the project is assessed, focusing on its environmental sustainability and economic impact. The analysis encompasses various factors, including the strategy's success in achieving sustainability goals and its financial feasibility. Major challenges associated with the strategy are discussed, along with practical recommendations to address these issues and support successful implementation. These recommendations are intended to benefit both the environment and society in various ways. Additionally, the chapter identifies potential areas for future research and development to further advance the study and its applications.

5.2. Conclusion

In conclusion, the biomining project at both the Durgapur and Howrah landfill sites has demonstrated significant environmental and economic benefits. The psychochemical and geotechnical properties of the materials meet the MORTH range and are suitable for use as subgrade material in road construction. Although the Maximum Dry Density (MDD) of the good earth from both sites is close to the lower limit of 1.6 gm/cc, it still meets acceptable standards. Additionally, the heavy metals found in the samples are within USEPA 1994 and VLAERBO 2007 limits, and soluble salts and leachable heavy metals are well below standard values, minimizing the risk of water resource pollution. However, ongoing management and frequent testing are recommended.

The life cycle assessment indicates that proper utilization of the biomined products significantly reduces environmental impact. In the "combined scenario" where Refuse-Derived Fuel (RDF) is sent to cement factories or brick kilns and good earth is used as subgrade material, both landfill sites can replace an average of 208 kg of coal per ton of legacy waste. This substitution results in a notable reduction in global warming potential, with the Durgapur site achieving a 53.92% decrease and the Howrah site a 55.58% reduction. The sensitivity analysis further reveals that in the "do-nothing scenario", CO_2 emissions from RDF transportation are minimal, accounting for just 1-2% of the total global warming potential. The primary factors influencing environmental impacts are RDF and good earth.

The composition analysis of legacy waste shows that the Durgapur landfill has a higher percentage of materials suitable for RDF production compared to Howrah. Specifically, Durgapur contains 359.1 kg of RDF per ton of waste, while Howrah has 299.11 kg. Consequently, the Durgapur site can replace more coal with RDF, offering a greater energy advantage and reducing dependence on fossil fuels. The cost-benefit analysis reveals that coal replacement generates an additional benefit of 12,23,80,440 INR for the Durgapur site compared to Howrah. Although transportation costs for RDF to the cement factory increase by 20,75,85,000 INR for the Howrah site. Additionally, trading carbon credits through the Multi Commodity Exchange (MCX) brings significant financial benefits, with Durgapur earning 6,93,22,572.45 INR and Howrah 37,25,64,154.68 INR.

Both sites, through the use of RDF as fuel and good earth as subgrade material, achieve a cost-benefit ratio greater than 1 and a positive net present value, indicating profitability and success of the biomining project. Therefore, the biomining project at both Durgapur and Howrah landfills is environmentally sustainable and economically advantageous.

Although the research was based on two landfills as case study, the methodology demonstrated here can be applied to similar types of biomining projects worldwide.

5.3. Limitations of the Study

Despite the promising results of the biomining project, several limitations must be acknowledged:

• **Variability in Material Properties:** The psychochemical and geotechnical properties of the biomined materials from the Durgapur and Howrah landfill sites exhibited some variability. The Maximum Dry Density values, for instance, were slightly below the MORTH range's lower limit (MORTH, 2013). This variability can affect the consistency of the materials when used in construction projects (Kumar et al., 2020). The utilization of biomined soil in subgrade applications may require prior treatment, if organic matter, heavy metals and leachable salts exceed the standard limits.

• **Sampling and Testing Frequency:** The study relied on a limited number of samples for analysis. Although the results are generally within acceptable standards, periodic testing and a larger sample size would provide more comprehensive data and ensure ongoing compliance with safety and environmental standards (Smith & Jones, 2019).

• **Transportation Costs:** Increased transportation costs for RDF from the Howrah site to the cement factory were noted, which impacts the overall economic benefit (Patel et al., 2021). This limitation could affect the feasibility of scaling up the project or replicating it at other sites with similar logistical challenges.

• **Long-Term Environmental Impact:** While the study indicates significant reductions in global warming potential and other environmental benefits, long-term impacts are not fully assessed. The sustainability of the biomining process and its environmental effects over extended periods require further investigation (Brown & Green, 2018).

• **Economic Assumptions:** The cost-benefit analysis is based on current market conditions and assumptions about future coal prices and carbon credit trading (National Renewable Energy Laboratory, 2022). Fluctuations in these factors could affect the project's economic viability over time.

• **Site-Specific Factors:** The findings are specific to the Durgapur and Howrah landfill sites considering various relevant assumptions. Different landfill conditions, waste compositions, and local regulations may lead to varying results in other locations, limiting the generalizability of the study's conclusions (Singh & Sharma, 2021).

• **Regulatory and Management Challenges:** The study assumes consistent adherence to proper management practices and regulatory compliance. Any lapses in these areas or changes in regulatory requirements could impact the project's success and environmental benefits (World Health Organization, 2020).

Addressing these limitations in future research and project implementation will help enhance the effectiveness and applicability of biomining technologies in waste management and resource recovery.

5.4. Policy Recomendations

Based on the findings and limitations of the biomining project at the Durgapur and Howrah landfill sites, the following policy recommendations are proposed to enhance the effectiveness and scalability of similar projects:

- Implement mandatory periodic testing and comprehensive sampling protocols for biomined materials. Increasing the frequency of testing will provide accurate data, allowing for timely adjustments and ensuring compliance with safety and environmental standards.
- Establish a subsidy program or financial incentives to offset RDF transportation costs, particularly in regions with high expenses. Additionally, explore logistical improvements, such as implementing train services with dedicated goods wagons, to further reduce these costs. These measures will make RDF utilization more economically feasible and encourage broader adoption.
- Conduct regular economic impact assessments that consider fluctuating market conditions, coal prices, and carbon credit trading. Develop flexible policy frameworks that can adapt to these economic changes, ensuring the continued viability and economic benefits of biomining projects.
- Invest in research and development to advance biomining technologies and address current limitations. Supporting innovation in waste management and resource recovery methods will lead to technological advancements that enhance the efficiency and sustainability of biomining practices.
- The government should focus on raising awareness about the benefits of biomining and the significant opportunities available in this emerging market. By highlighting the potential, the government can generate interest and encourage investors to support and invest in biomining projects.

5.5. Future Scope

To enhance the success of the biomining projects at Durgapur and Howrah, the following recommendations are proposed:

- **Optimize Subgrade Materials**: Test blending 20% construction materials with good earth to improve geotechnical properties for subgrade material in road and civil engineering uses.
- **Enhance Testing Procedures**: Expand direct shear testing to assess material strength under various normal stresses for more accurate engineering evaluations.
- **On-Site Energy Production**: Explore installing incineration plants to generate electricity for site operations, reducing costs and improving sustainability.
- **Economic Analysis of RDF Pelletization**: Conduct a thorough cost analysis of RDF pellet production, including raw materials, processing, transportation, and the impact of transport distance.
- **Broaden Lifecycle and Sensitivity Analysis**: Include additional environmental and economic factors in lifecycle assessments to strengthen project evaluations.
- **Refine Emissions and Cost Analysis**: Focus carbon emission reduction (CER) calculations on considering methane costs for a comprehensive emissions and financial analysis.
- **Leachate Emission Cost**: Determine the cost associated with leachate emissions for evaluating project financial benefits.
- **Implement Ongoing Monitoring**: Establish a framework for continuous monitoring and periodic reassessment of environmental and economic impacts, updating strategies based on new data and technology.

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Appendix:

Appendix-I

Simulation Result: Scenario-1 RDF sent to Cement Factory or Brick Kiln - Howrah

Impact category	Reference unit	Result	Minimum	Maximum	Mean	Standard deviation	Median
Fine particulate matter formation	kg PM2.5 eq	1.4321	1.362	1.791	1.452	0.049	1.444
Fossil resource scarcity	kg oil eq	343.7385	339.340	350.554	344.069	1.636	343.949
Freshwater ecotoxicity	kg 1,4-DCB	49.8324	18.124	411.213	65.173	37.672	56.079
Freshwater eutrophication	kg P eq	0.0719	0.067	2.870	0.087	0.118	0.073
Global warming	kg CO_2 eq	1302.5470	1228.103	1472.740	1312.189	38.133	1308.914
Human carcinogenic toxicity	kg 1,4-DCB	43.5590	41.892	4867.184	73.401	196.567	44.051
Human non-carcinogenic toxicity	kg 1,4-DCB	1147.6111	318.387	12700.667	1527.872	1161.740	1172.363
Ionizing radiation	kBq Co-60 eq	19.5295	18.907	20.604	19.613	0.293	19.594
Land use	m2a crop eq	441.7748	402.380	499.231	442.261	15.771	442.019
Marine ecotoxicity	kg 1,4-DCB	66.3428	24.709	563.828	86.793	50.449	74.237
Marine eutrophication	kg N eq	0.4902	0.335	0.825	0.521	0.072	0.517
Mineral resource scarcity	kg Cu eq	2.3406	2.221	2.526	2.352	0.052	2.347
Ozone formation, Human health	kg NOx eq	4.6744	4.392	7.921	4.789	0.375	4.676
Ozone formation, Terrestrial ecosystems	kg NOx eq	4.7683	4.486	8.016	4.883	0.375	4.771
Stratospheric ozone depletion	kg CFC11 eq	0.0013	0.001	0.002	0.001	0.000	0.001
Terrestrial acidification	kg SO2 eq	4.7227	4.361	5.811	4.779	0.184	4.757
Terrestrial ecotoxicity	kg 1,4-DCB	1453.3732	1418.430	1626.893	1465.256	24.758	1461.244
Water consumption	m3	48.6895	3.509	99.384	50.118	14.030	49.499

Simulation Result: Scenario- 2 Good Earth sent for Subgrade Material - Howrah

Impact category	Reference unit	Result	Minimum	Maximum	Mean	Standard deviation	Median
Fine particulate matter formation	kg PM2.5 eq	2.3052	2.3052	2.3053	2.3052	0.0000	2.3052
Fossil resource scarcity	kg oil eq	429.5778	429.5777	429.5787	429.5779	0.0001	429.5779
Freshwater ecotoxicity	kg 1,4-DCB	31.5446	31.1815	34.1882	31.7057	0.3610	31.6208
Freshwater eutrophication	kg P eq	0.2028	0.2028	0.2430	0.2030	0.0017	0.2028
Global warming	kg CO_2 eq	1555.9551	1555.4911	1557.5340	1556.0062	0.3199	1555.9360
Human carcinogenic toxicity	kg 1,4-DCB	58.7886	58.7750	84.4161	59.1099	1.6736	58.7952
Human non-carcinogenic toxicity	kg 1,4-DCB	950.0154	941.6036	1040.1707	953.7398	10.7715	950.6650
Ionizing radiation	kBq Co-60 eq	28.6318	28.6299	28.6420	28.6322	0.0016	28.6318
Land use	m2a crop eq	186.4291	186.4291	186.4293	186.4291	0.0000	186.4291
Marine ecotoxicity	kg 1,4-DCB	43.3545	42.8745	46.5182	43.5680	0.4778	43.4510
Marine eutrophication	kg N eq	0.3749	0.3744	0.3775	0.3751	0.0004	0.3750
Mineral resource scarcity	kg Cu eq	2.0449	2.0448	2.0449	2.0449	0.0000	2.0449
Ozone formation, Human health	kg NOx eq	5.5466	5.5466	5.5467	5.5467	0.0000	5.5466
Ozone formation, Terrestrial ecosystems	kg NOx eq	5.6582	5.6581	5.6582	5.6582	0.0000	5.6582
Stratospheric ozone depletion	kg CFC11 eq	0.0016	0.0016	0.0016	0.0016	0.0000	0.0016
Terrestrial acidification	kg SO2 eq	4.5468	4.5468	4.5473	4.5469	0.0001	4.5469
Terrestrial ecotoxicity	kg 1,4-DCB	1967.6889	1967.6827	1968.1501	1967.6965	0.0196	1967.6927
Water consumption	m3	19.7805	19.7805	19.7809	19.7806	0.0000	19.7805

Simulation Result: Combined Scenario 1 & Scenario 2 - Howrah

Impact category	Reference unit	Result	Minimum	Maximum	Mean	Standard deviation	Median
Fine particulate matter formation	kg PM2.5 eq	0.8912	0.8912	0.8919	0.8912	0.0001	0.8912
Fossil resource scarcity	kg oil eq	282.0672	282.0667	282.0697	282.0673	0.0004	282.0673
Freshwater ecotoxicity	kg 1,4-DCB	6.2372	5.2136	15.9737	6.8086	1.2037	6.4809
Freshwater eutrophication	kg P eq	0.0458	0.0458	0.0685	0.0461	0.0016	0.0458
Global warming	kg CO_2 eq	871.8543	870.3216	878.0378	872.0561	1.0240	871.8639
Human carcinogenic toxicity	kg 1,4-DCB	33.8232	33.7825	284.7348	34.9616	9.5351	33.8391
Human non-carcinogenic toxicity	kg 1,4-DCB	160.5598	136.7124	405.9540	172.0085	32.2048	162.5310
Ionizing radiation	kBq Co-60 eq	15.0353	15.0291	15.0670	15.0363	0.0045	15.0354
Land use	m2a crop eq	7.7428	7.7427	7.7433	7.7429	0.0001	7.7428
Marine ecotoxicity	kg 1,4-DCB	9.2129	7.8686	21.0659	9.9603	1.5693	9.5256
Marine eutrophication	kg N eq	0.0088	0.0073	0.0160	0.0094	0.0012	0.0092
Mineral resource scarcity	kg Cu eq	1.4008	1.4008	1.4008	1.4008	0.0000	1.4008
Ozone formation, Human health	kg NOx eq	3.4589	3.4589	3.4591	3.4589	0.0000	3.4589
Ozone formation, Terrestrial ecosystems	kg NOx eq	3.5314	3.5313	3.5315	3.5314	0.0000	3.5314
Stratospheric ozone depletion	kg CFC11 eq	0.0005	0.0005	0.0005	0.0005	0.0000	0.0005
Terrestrial acidification	kg SO2 eq	2.2027	2.2026	2.2052	2.2028	0.0002	2.2028
Terrestrial ecotoxicity	kg 1,4-DCB	1053.8343	1053.8151	1054.7339	1053.8558	0.0478	1053.8443
Water consumption	m3	2.1874	2.1872	2.1883	2.1874	0.0001	2.1874

Appendix-II

Simulation Result: Scenario-1 RDF sent to Cement Factory or Brick Kiln - Durgapur

Impact category	Reference unit	Result	Minimum	Maximum	Mean	S.D.	Median
Fine particulate matter formation	kg PM2.5 eq	1.446	1.390	1.719	1.461	0.039	1.454
Fossil resource scarcity	kg oil eq	376.102	372.972	381.265	376.415	1.338	376.329
Freshwater ecotoxicity	kg 1,4-DCB	39.996	15.634	249.126	52.005	27.737	44.725
Freshwater eutrophication	kg P eq	0.071	0.068	17.351	0.099	0.550	0.073
Global warming	kg CO_2 eq	1344.503	1281.265	1507.704	1351.027	28.538	1348.798
Human carcinogenic toxicity	kg 1,4-DCB	46.861	45.495	6597.188	78.420	260.750	47.219
Human non-carcinogenic toxicity	kg 1,4-DCB	927.213	328.605	7589.112	1179.236	805.569	975.909
Ionizing radiation	kBq Co-60 eq	20.785	20.243	21.753	20.856	0.238	20.844
Land use	m2a crop eq	338.898	301.737	379.204	339.649	12.261	339.579
Marine ecotoxicity	kg 1,4-DCB	53.626	22.004	336.977	69.414	36.732	60.372
Marine eutrophication	kg N eq	0.376	0.282	0.659	0.398	0.053	0.391
Mineral resource scarcity	kg Cu eq	2.353	2.256	2.506	2.363	0.042	2.358
Ozone formation, Human health	kg NOx eq	4.969	4.761	7.444	5.060	0.292	4.971
Ozone formation, Terrestrial ecosystems	kg NOx eq	5.070	4.860	7.546	5.161	0.292	5.073
Stratospheric ozone depletion	kg CFC11 eq	0.001	0.001	0.001	0.001	0.000	0.001
Terrestrial acidification	kg SO2 eq	4.483	4.200	5.456	4.523	0.146	4.501
Terrestrial ecotoxicity	kg 1,4-DCB	1533.610	1506.421	1681.213	1542.280	20.789	1538.634
Water consumption	m3	37.902	2.509	70.441	38.403	10.899	37.910

Simulation Result: Scenario- 2 Good Earth sent for Subgrade Material - Durgapur

Impact category	Referen ce unit	Result	Minimu m	Maximu m	Mean	S.D.	Median
Fine particulate matter formation	kg PM2.5 eq	2.7727	2.7727	2.7729	2.7727	0.0000	2.7727
Fossil resource scarcity	kg oil eq	490.613	490.613	490.614	490.613	0.0001	490.613
Freshwater ecotoxicity	kg 1,4-DCB	38.8807	38.5727	43.2932	39.0861	0.4426	38.9611
Freshwater eutrophication	kg P eq	0.2592	0.2592	0.2765	0.2594	0.0007	0.2592
Global warming	kg CO_2 eq	1801.71 67	1801.23 21	1803.734 1	1801.78 78	0.3105	1801.72 64
Human carcinogenic toxicity	kg 1,4-DCB	68.0236	68.0099	283.5441	68.7347	8.4600	68.0281
Human non-carcinogenic toxicity	kg 1,4-DCB	1181.65 11	1173.50 54	1285.390 1	1185.85 77	12.308 4	1182.03 56
Ionizing radiation	kBq Co-60 eq	34.3820	34.3799	34.3901	34.3822	0.0014	34.3818
Land use	m2a crop eq	214.368 3	214.368 3	214.3684	214.368 3	0.0000	214.368 3
Marine ecotoxicity	kg 1,4-DCB	53.4555	53.0479	59.0915	53.7257	0.5884	53.5606
Marine eutrophication	kg N eq	0.4256	0.4252	0.4283	0.4258	0.0004	0.4257
Mineral resource scarcity	kg Cu eq	2.2905	2.2905	2.2905	2.2905	0.0000	2.2905
Ozone formation, Human health	kg NOx eq	6.3253	6.3253	6.3253	6.3253	0.0000	6.3253
Ozone formation, Terrestrial ecosystems	kg NOx eq	6.4516	6.4516	6.4517	6.4516	0.0000	6.4516
Stratospheric ozone depletion	kg CFC11 eq	0.0019	0.0019	0.0019	0.0019	0.0000	0.0019
Terrestrial acidification	kg SO2 eq	5.3097	5.3097	5.3104	5.3097	0.0001	5.3097
Terrestrial ecotoxicity	kg 1,4-DCB	2277.80 76	2277.80 02	2277.979 8	2277.81 45	0.0149	2277.81 05
Water consumption	m3	22.5164	22.5164	22.5167	22.5164	0.0000	22.5164

Simulation Result: Combined Scenario 1 & Scenario 2 - Durgapur

Impact category	Reference unit	Result	Minimum	Maximum	Mean	S.D.	Median
Fine particulate matter formation	kg PM2.5 eq	1.0058	1.0058	1.0064	1.0058	0.0000	1.0058
Fossil resource scarcity	kg oil eq	319.0353	319.0348	319.0377	319.0354	0.0004	319.0354
Freshwater ecotoxicity	kg 1,4-DCB	6.8819	5.8597	14.7947	7.4154	1.1630	7.0931
Freshwater eutrophication	kg P eq	0.0515	0.0514	0.1373	0.0518	0.0029	0.0515
Global warming	kg CO_2 eq	984.8353	983.2055	989.6717	985.0294	0.9208	984.8845
Human carcinogenic toxicity	kg 1,4-DCB	38.2134	38.1729	107.1642	38.9427	3.7989	38.2313
Human non-carcinogenic toxicity	kg 1,4-DCB	177.8858	154.7146	450.1934	189.5954	35.1497	179.0343
Ionizing radiation	kBq Co-60 eq	17.0647	17.0587	17.0930	17.0657	0.0048	17.0646
Land use	m2a crop eq	8.2378	8.2377	8.2382	8.2378	0.0001	8.2378
Marine ecotoxicity	kg 1,4-DCB	10.1950	8.8536	20.4311	10.8971	1.5527	10.4458
Marine eutrophication	kg N eq	0.0094	0.0080	0.0201	0.0100	0.0012	0.0097
Mineral resource scarcity	kg Cu eq	1.5856	1.5855	1.5856	1.5856	0.0000	1.5856
Ozone formation, Human health	kg NOx eq	3.9087	3.9087	3.9089	3.9087	0.0000	3.9087
Ozone formation, Terrestrial ecosystems	kg NOx eq	3.9908	3.9907	3.9910	3.9908	0.0000	3.9908
Stratospheric ozone depletion	kg CFC11 eq	0.0006	0.0006	0.0006	0.0006	0.0000	0.0006
Terrestrial acidification	kg SO2 eq	2.4872	2.4871	2.4892	2.4872	0.0002	2.4872
Terrestrial ecotoxicity	kg 1,4-DCB	1191.83	1191.812	1192.978	1191.85	0.0591	1191.84
Water consumption	m3	2.4433	2.4431	2.4441	2.4433	0.0001	2.4433