Development of LCA Framework for Solid Waste Management (SWM) Technologies in India

Supported by:

Office of the Principal Scientific Adviser to the Government of India

Prepared by:

IISc Bangalore, IIT Madras, and IIT (BHU) Varanasi

May 2026

Indian Institute of Science Bangalore

Principal Investigators

Prof. G. L. Sivakumar Babu
Department of Civil Engineering

Prof. Lakshminarayana Rao
Center for Sustainable Technologies

Prof. Chanakya Hoysall
Center for Sustainable Technologies

Research Associates

Dr. Prakash Singh

Dr. Anusree Nalladiyil

Indian Institute of Technology Madras

Principal Investigators

Prof. Indumathi M. Nambi
Department of Civil Engineering

Prof. Vinu R
Department of Chemical Engineering

Research Associates

Dr. Arun Sathyan

Ms. Gayathri N

Indian Institute of Technology (BHU) Varanasi

Principal Investigators

Prof. R. S. Singh
Department of Chemical Engineering and Technology

Prof. Ravi Jaiswal
Department of Chemical Engineering and Technology

Dr. Amrita Dwivedi
Department of Humanistic Studies

Research Associates

Dr. Pranjal Tripathi

Dr. Yogesh Kumar Vishwakarma

Acknowledgements

The project team expresses its sincere gratitude to Prof. Ajay Kumar Sood, Principal Scientific Adviser (PSA) to the Government of India, for funding and facilitating this project- "Development of a Life Cycle Assessment (LCA) Framework for Solid Waste Management Technologies in India". We also gratefully acknowledge Dr. Parvinder Maini, Scientific Secretary (Office of the PSA), for her valuable guidance and steadfast support throughout the initiative. Furthermore, we extend our appreciation to Dr. Hafsa Ahmad and her team, whose proactive engagement and seamless coordination were instrumental in ensuring the smooth progress and successful completion of this project.

The authors are also thankful to the expert committee members (Prof. M. S. Mohan Kumar, Dr. Monoranjan Mohanty, Prof. Ajay Kalamdhad, Prof. Anurag Garg, Prof. Vimal Chandra Srivastava, Dr. B. S. Chaudhary, and Ms. P. Bineesha, and Ms. Shravanti Jeevan) for their constructive suggestions, technical guidance, and valuable feedback throughout the course of the project. Their insights greatly contributed to strengthening the scientific quality and practical relevance of the framework developed under this study.

The authors sincerely thank the municipal authorities and Urban Local Bodies (ULBs) of Bengaluru, Mysuru, Tumkur, Delhi, Varanasi, and Chennai for extending their cooperation during field investigations, providing access to waste management facilities, and sharing relevant operational data and reports required for this study.

The authors gratefully acknowledge the Green Aadhaar team for their valuable contribution to the development of the GHG Calculator application based on the inputs from IIT Madras, IISc Bengaluru and IIT(BHU) Varanasi. We thank Dr. Abhijit Bhakte for his technical support and prompt actions to update the app based on the requirements and inputs from various stakeholders. Special thanks also go to Mr. Nikhil Panchal, Founder and CEO of Green Aadhaar, for the valuable inputs and support extended during the discussions.

We express our appreciation to the plant operators and technical personnel associated with various waste treatment technologies, including composting facilities, biomethanation plants, material recovery facilities, waste-to-energy plants, landfill sites, leachate treatment facilities, and biomining projects, for their valuable inputs, operational insights, and support during site visits and data collection.

Finally, the project team appreciates all stakeholders, institutions, and individuals who directly or indirectly contributed to the successful completion of this work.

Executive Summary

This study titled "Development of LCA Framework for Solid Waste Management (SWM) Technologies in India" presents a comprehensive approach to improving waste management practices in India through the application of Life Cycle Assessment (LCA). Conducted by IISc Bangalore, IIT Madras, and IIT BHU with support from the Office of the Principal Scientific Advisor, the study addresses the growing challenge of municipal solid waste (MSW), which exceeds 150,000 TPD due to rapid urbanization, population growth, and changing consumption patterns. It highlights that current waste management systems in India are largely inefficient and heavily dependent on landfilling and open dumping, leading to significant environmental and public health concerns.

To overcome these challenges, an LCA-based framework is developed that evaluates the environmental impacts of waste management technologies across the entire lifecycle—from waste generation and collection to processing and final disposal. The framework integrates Material Flow Analysis (MFA) and considers key environmental indicators such as greenhouse gas emissions, energy consumption, and pollution. It enables systematic comparison of various treatment options, including composting, bio-methanation, recycling, waste-to-energy, and landfilling, thereby supporting evidence-based decision-making.

The framework is applied to case studies representing different urban scales such as Bangalore (Tier I), Mysore (Tier II), Tumkur (Tier III), Delhi (Tier I), Varanasi (Tier II) and Chennai (Tier I) using both primary data from field surveys and secondary data from institutional sources. The findings reveal that landfilling is the dominant contributor to environmental impacts, primarily due to methane emissions, while resource recovery pathways such as recycling, composting, and bio-methanation offer significant environmental benefits by reducing emissions and substituting conventional energy and materials. However, the effectiveness of these systems is constrained by poor source segregation and limited processing capacity, resulting in a substantial proportion of waste still being disposed of in landfills.

The report emphasizes the need for improved waste segregation, expansion of decentralized treatment technologies, and integration of the informal sector to enhance recycling efficiency. It also highlights the importance of landfill gas capture systems to mitigate emissions and recommends the adoption of digital tools for better data collection and monitoring. Overall, the study concludes that implementing an LCA-based SWM framework can provide a scientific and holistic basis for policy and planning, enabling India to transition toward more sustainable, resource-efficient, and environmentally responsible waste management systems aligned with circular economy principles.

Tracking MSW flow in India is complex due to rapid urbanization and the informal sector's dominant role in collection and sorting, which leads to undocumented material pathways and underreported waste diversion. This results in significant data gaps, with many zones failing to report accurate waste volumes, and recycling rates often based on estimates rather than verified data. Consequently, GHG emission reporting by ULBs is inconsistent, hindered by varied methodologies, generic emission models, lack of localized waste composition data, and difficulty measuring fugitive methane emissions from unmanaged dumpsites. Without standardized protocols and site-specific data, India's municipal GHG inventories remain theoretical, complicating climate mitigation efforts.

To overcome these challenges, an LCA-based web application (GHG Emission Calculator) is developed that evaluates the environmental impacts of waste management technologies across the entire lifecycle— from waste generation and collection to processing and final disposal. GHG emission calculator enables systematic comparison of various treatment options, including composting, bio-methanation, recycling, waste-to-energy, and landfilling, thereby supporting evidence-based decision-making. The application also features scenario comparison allowing users to visualize multiple scenarios based on carbon footprint as a key metric, while allocating wastes to different waste treatment options.

A stakeholder workshop was organized in IIT Madras on Feb. 16, 2026 to demonstrate the features and use of the GHG calculator to various stakeholders, including academic, industry, start-ups, ULBs and policymakers. This is also a key deliverable of the project to strengthen climate-smart solid waste management planning using scientific tools, data transparency and technology integration. The inputs from the stakeholders were then implemented in the current version of the application. This report outlines the basic features of the GHG calculator including the dashboard, various user levels, data entry, background calculations and different output formats. The validation of the app for data from Tambaram and Avadi Municipalities in Chennai is described in detail. The user manual of the web-based app is also given as an annexure.

Finally, the recommendations that translate the study findings into actionable measures for improving municipal solid waste management performance in urban local bodies, corporations and cities are discussed. It objectively identifies priority interventions that can reduce environmental burdens, strengthen data reliability, and support evidence-based decision-making.

Table of Content

Volume I- Life Cycle Assessment (LCA) of Solid Waste Management Systems 1

Chapter 1 Introduction 3

1.1 Background: Overview of Municipal Solid Waste (MSW) in India 3

1.2 Life Cycle Assessment (LCA): Concepts and Importance 3

1.3 Need for LCA-Based SWM Framework in India 4

1.4 Project Consortium and Division of Responsibilities 6

1.5 Scope and Organization of the Report 7

Chapter 2 Methodology 9

2.1 Overall Research Framework 9

2.2 Study Area (Cities and Sites) 9

2.3 Data Collection Strategy 10

2.4 Material Flow Analysis (MFA) Approach 10

2.5 Assumptions 11

Chapter 3 Current Waste Management Practices 13

3.1 Preamble 13

3.2 Methodology 13

3.3 Case Study: Tier I City – Bangalore 13

3.4 Case Study: Tier II City – Mysore 20

3.5 Case Study: Tier III City – Tumkur 25

3.6 Case Study: Delhi (Tier I city) 30

3.7 Case Study: Varanasi (Tier II city) 39

3.8 Case study: Chennai (Tier I city) 46

3.9 Discussion 53

3.10 Summary 55

Chapter 4 Composting 59

4.1 Preamble 59
4.2 . Methodology 59
4.3 Result and discussions 65
4.4 Practical implications..76
4.5 Summary 78
Chapter 5 Biogas/Bio-methanation Plants 89
5.1 Preamble 89
5.2 Methodology 89
5.3 Results and Discussion: Part I Bangalore 100
5.4 Results and Discussion: Part II Chennai 118
5.5 Practical implications...127
5.6 Summary 129
Chapter 6 Waste-to-energy Plants 141
6.1 Preamble 141
6.2 Methodology 141
6.3 Results and Discussions 149
6.4 Practical Implications..164
6.5 Summary 166
Chapter 7 Recycling Facility 177
7.1 Preamble 177
7.2 Methodology 177
7.3 Results and discussion 181
7.4 Practical implications...188
7.5 Summary 190
Chapter 8 Leachate Treatment 193
8.1 Preamble 193
8.2 Methodology 193

8.3 Results and discussion 197
8.4 Circular economy perspective in leachate management 199
8.5 Practical Implications..202
8.6 Summary 205
Chapter 9 Landfill with and without Bioremediation 207
9.1 Preamble 207
9.2 Materials and Methods..207
9.3 Result and Discussion 220
9.4 Practical implications 235
9.5 Summary 236
Chapter 10 Biomining..241
10.1 Preamble 241
10.2 Methodology 241
10.3 Results and discussion 247
10.4 Practical implications 256
10.5 Summary 258
Volume II- Development of Greenhouse Gas (GHG) Emission Calculator App..........261
Chapter 1 Introduction 263
1.1 Overview 263
1.2 Objectives 264
Chapter 2 GHG Calculator App 265
2.1 Preamble 265
2.2 Dashboard 266
2.3 User Guide 268
2.4 GHG Emissions Calculation 271
2.5 Scenario Comparison 283
2.6 My Files 284

2.7 User Management 285

2.8 Database 286

2.9 Profile 287

Chapter 3 Case Study 289

3.1 Preamble 289

3.2 Baseline Waste Management Data for Avadi and Tambaram 289

3.3 Transportation Module Input Data 290

3.4 Composting Module Input Data 291

3.5 Anaerobic Digestion Module Input Data 293

3.6 Recycling Module Input Data 294

3.7 Incineration Module Input Data 298

3.8 Landfilling Module Input Data 301

Chapter 4 Results GHG Calculator 305

4.1 Preamble 305

4.2 City-wise Waste Management Profile 305

4.3 GHG Emission Results 307

4.4 Scenario Comparison 315

Chapter 5 Stakeholder Workshop 327

5.1 Stakeholder Workshop on Sustainable Solid Waste Management through Life Cycle Assessment (LCA) 327

5.2 Stakeholder Feedback and Actions Taken 332

5.3 Field Visit to Selected Solid Waste Management Facilities in Chennai 333

Chapter 6 Conclusion 335

Annexure I- User Manual for the GHG Emission Calculator App 339

Volume III Overall Project Outcomes and Recommendations 379

Chapter 1 Recommendations 381

1.1 Introduction to the Recommendations 381

1.2 Key Challenges Identified....................383
1.3 Recommendations for Data Collection and Monitoring....................385
1.4 Recommendations for Digital Data Management....................388
1.5 Recommendations for Segregation and Material Flow Management....................389
1.6 Recommendation on Treatment Technologies....................391
1.7 Policy and Institutional Recommendations....................397
1.8 Recommendations for LCA-Based Planning Tools....................398
1.9 Implementation: Prioritization and Roadmap....................400
1.10 Conclusions....................402

List of Figures

Volume I- Life Cycle Assessment (LCA) of Solid Waste Management Systems

Fig. 1.1 Life cycle assessment framework for solid waste management 5

Fig. 1.2 System boundary of fresh municipal solid waste management system 6

Fig. 3.1 Bengaluru urban region 14

Fig. 3.2 Material recovery facility in Bengaluru 15

Fig. 3.3 WTE plant in Bidadi, Bengaluru 16

Fig. 3.4 Biogas plant in Bengaluru 16

Fig. 3.5 Material flow analysis of MSW in Bangalore 18

Fig. 3.6 Mysuru city map 20

Fig. 3.7. Material flow analysis of municipal solid waste in Mysuru 23

Fig. 3.8 Tumkur city map 25

Fig. 3.9 MRF facility 27

Fig. 3.10 Bailing unit and bailed materials 27

Fig. 3.11 Windrow composting and processing unit 28

Fig. 3.12 Landfill receiving composting reject 28

Fig. 3.13 Material flow analysis of municipal solid waste in Tumkur 29

Fig. 3.14 Delhi city map 31

Fig. 3.15 Composting plant at Bawana, New Delhi 34

Fig. 3.16 WTE plant at Bawana, New Delhi 35

Fig. 3.17 Landfill site in Ghazipur, New Delhi 36

Fig. 3.18 Material Flow Analysis of current waste management practices in Delhi 37

Fig. 3.19 Varanasi city map 40

Fig. 3.20 Fresh waste profile at Varanasi 41

Fig. 3.21 MRF facility at Varanasi 42

Fig. 3.22 Composting facility and RDF collection at Varanasi 42

Fig. 3.23 Bio-methanization facility 43

Fig. 3.24 WTE facility and RDF collection at Varanasi 43

Fig. 3.25 Material Flow Analysis of current waste management practices in Varanasi 44

Fig. 3.26 Chennai city map 47

Fig. 3.27 Composition of waste from sites a) Kodungaiyur and b) Perungudi 48

Fig. 3.28 Windrow composting plant at Madhavaram 49

Fig. 3.29 Biomethanation plant (SWMS Pvt. Ltd.), Chetpet 50

Fig. 3.30 Incineration plant at Koyambedu 51
Fig. 3.31 Material flow analysis of current waste management practices in Chennai.............52
Fig. 4.1 System boundary of the compost plant life cycle assessment 60
Fig. 4.2 Impact on global warming from compost plant based on organic fraction of municipal solid waste a) scenario 1 – composting without energy recovery from leachate b) scenario 2 - composting with energy recovery from leachate (biogas to electricity) c) scenario 3 - composting with energy recovery from leachate (upgraded biomethane used as vehicle fuel) 67
Fig. 4.3 Influence of variation in different parameters on global warming of compost plant based on organic fraction of municipal solid waste a) feedstock transportation distance b) compost production c) leachate production d) chemical oxygen demand (COD) of leachate e) fertilizer substitution by compost f) fertilizer substitution by leachate/liquid fermented organic manure (LFOM) g) fossils substitution by biogas/bio-CNG 71
Fig. 4.4 Contribution of different impact categories from compost plant based on organic fraction of municipal solid waste a) scenario 1 – composting without energy recovery from leachate b) scenario 2 - composting with energy recovery from leachate (biogas to electricity) c) scenario 3 - composting with energy recovery from leachate (upgraded biomethane used as vehicle fuel) 75
Fig. 5.1 System boundary of the biogas plant life cycle assessment 90
Fig. 5.2 Impact on global warming from biogas plant based on organic fraction of municipal solid waste a) scenario 1 - flaring of biogas b) scenario 2 - biogas to electricity c) scenario 3 - biogas directly used as cooking fuel d) scenario 4 - upgraded biomethane used as cooking fuel and e) scenario 5 - upgraded biomethane used as vehicle fuel 103
Fig. 5.3 Influence of variation in different parameters on global warming from biogas plant based on organic fraction of municipal solid waste a) feedstock transportation distance b) biogas yield and c) purification losses d) fertilizer substitution by fermented organic manure (FOM) e) fertilizer substitution by liquid fermented organic manure (LFOM) f) fossils substitution by biogas/bio-CNG in respective scenarios 108
Fig. 5.4 Damage category and single point score of different scenarios of biogas plant based on organic fraction of municipal solid waste 113
Fig. 5.5 Economic indicators of different scales of bio-CNG plants A) Without subsidy - a) Net present value b) Payback period and c) Internal rate of return B) With subsidy – d) Net present value e) Payback period and f) Internal rate of return 116
Fig. 5.6 System boundary and scenarios considered for LCA of biogas plant......................119

Fig. 5.7 Process contribution of global warming potential of three scenarios of biogas plant 125
Fig. 5.8 Sensitivity analysis: influence of various parameters a) Distance of waste collection, b) Methane loss, and c) Methane yield on GWP of biogas plant 126
Fig. 6.1 Process flow of various Scenarios of waste to energy plant based on municipal solid waste 143
Fig. 6.2 Impact on global warming from waste to energy plant a) producing only power without carbon capture b) coupled with combined heat and power with carbon capture and storage c) coupled with combined heat and power with carbon capture and utilization (Waste composition A) represents 60% biogenic mass of GCV – 1650 kcal/kg and moisture 36% B) represents 40% biogenic mass of GCV – 2000 kcal/kg and moisture 36% C) represents 20% biogenic mass of GCV – 2350 kcal/kg and moisture 25%) 151
Fig. 6.3 Influence of variation in different parameters on global warming of different scenarios of waste-to-energy plants a) biogenic fraction b) plant efficiency c) CO_2 emissions d) CO_2 capture rate e) Coal-based electricity substitution f) CO_2 substitution 154
Fig. 6.4 Contribution of each process to the life cycle environmental impacts (Mid-point score) of waste-to-energy plants a) producing power only without carbon capture b) coupled with combined heat and power with carbon capture and storage c) coupled with combined heat and power with carbon capture and utilization 157
Fig. 6.5 Damage category and single point score of different Scenarios of waste-to energy plants (S1: producing only without carbon capture, S2: coupled with combined heat and power with carbon capture and storage, and S3 coupled with combined heat and power with carbon capture and utilization) and different waste composition (Set 1: 60% biogenic mass of GCV – 1650 kcal/kg and moisture 36% Set 2 represents 40% biogenic mass of GCV – 2000 kcal/kg and moisture 36% Set 3 represents 20% biogenic mass of GCV – 2350 kcal/kg and moisture 25%) 159
Fig. 6.6 Economic indicators of waste-to-energy plant varying gross calorific values (GCVs) and moisture contents, a) Net present value b) Payback period and c) Internal rate of return 161
Fig. 7.1 Material flow of recyclables 183
Fig. 7.2 Plastic waste fraction collected in a MRF facility in Bangalore 184
Fig. 8.1 Field visit to Bellahalli leachate treatment plant (2025) 194
Fig. 8.2 Schematic diagram of leachate treatment process in Bellahalli LTP 195
Fig. 8.3 Global warming of the leachate plant 201

Fig. 8.4 EP of the leachate plant 202
Fig. 9.1 System boundary of the different scenarios for life cycle assessment, a) Open dumping, b) Sanitary landfill with leachate treatment, c) Sanitary landfill with leachate recirculation and LFG flaring, d) Sanitary landfill with leachate recirculation and electricity generation from LFG, e) Sanitary landfill with leachate recirculation and bioCNG (BCNG) used as vehicle fuel or as cooking fuel..212
Fig. 9.2 Methane generation from OD (W/O_LR) and SLF (W_LR), a) Yearly methane generation rate, b) Cumulative percentage methane generation 221
Fig. 9.3 Impact on global warming from different landfilling scenarios a) Open dumping, b) Sanitary landfill with leachate treatment, c) Sanitary landfill with leachate recirculation and LFG flaring, d) Sanitary landfill with leachate recirculation and electricity generation from LFG, e) Sanitary landfill with leachate recirculation and bioCNG (BCNG) used as vehicle fuel, f) Sanitary landfill with leachate recirculation and bioCNG (BCNG) used as cooking fuel.225
Fig. 9.4 Comparison of global warming of different treatment scenarios of municipal solid waste in dumpsites/landfills 227
Fig. 9.5 Damage category and single point score of different landfill scenarios..................230
Fig. 9.6 Comparison of the total cost for the management of 1 ton of MSW for six different scenarios, considering different revenue sources (a), Distribution of the cost between components of different landfilling scenarios (b) 232
Fig. 9.7 Comparison of net present value (a) and payback period (b) for different landfilling scenarios...235
Fig. 10.1 a) Mandur dumpsite location w.r.t to Bengaluru city, b) Mandur biomining site..242
Fig. 10.2 Biomining process at Mandur site with recovered waste fraction........................243
Fig. 10.3 System boundary of Biomining (Scenario 1) 245
Fig. 10.4 System boundary of Biomining (Scenario 2) 246
Fig. 10.5 Global warming of Biomining (Scenario 1) 248
Fig. 10.6 Global warming of biomining (Scenario 2)...249
Fig. 10.7 Global warming when RDF (6.2 GJ/t) is replacing different type of fuel pet coke (36 J/t) High rank coal (27 GJ/t) and Low rank coal (18 GJ/t) 251
Fig. 10.8 Influence of grid emission factor on the GW of the stationary electric trommel ...252
Fig. 10.9 Sensitivity analysis of GHG emissions with increasing shares of solar energy integration 253
Fig. 10.10 Dumpsite age v/s carbon credit potential 256

Volume II- Development of Greenhouse Gas (GHG) Emission Calculator App

Fig. 1.1 System boundary including the major municipal solid waste treatment pathways..264
Fig. 2.1 The homepage of the developed GHG Calculator platform....................................265
Fig. 2.2 Dashboard interface showing city waste management and GHG emissions............267
Fig. 2.3 Dashboard interface showing waste collection statistics and waste distribution 267
Fig. 2.4 Dashboard interface showing waste composition and material recovery indicators 268
Fig. 2.5 Workflow of the GHG Calculator 270
Fig. 2.6 Emission estimation pathways considered in the GHG Calculator..........................283
Fig. 2.7 Scenario comparison framework for alternative waste management pathways.......284
Fig. 2.8 My Files interface for managing saved GHG assessment files 285
Fig. 2.9 Profile interface for entering city-level and process-specific input data 288
Fig. 4.1 GHG calculator interface showing the waste management profile of Avadi 309
Fig. 4.2 GHG calculator interface showing the waste management profile of Tambaram ...313
Fig. 4.3 Scenario comparison module showing waste allocation for Avadi..........................316
Fig. 4.4 Waste collection and waste composition metrics considered for BAU and all other scenarios of Avadi..316
Fig. 4.5 Scenario-wise waste allocation in Avadi 317
Fig. 4.6 Greenhouse gas emissions under alternative scenarios in Avadi 317
Fig. 4.7 Gas-wise emission comparison for Avadi scenarios 318
Fig. 4.8 Scenario waste allocation interface for Tambaram 321
Fig. 4.9 Waste collection and waste composition metrics under different scenarios for Tambaram 321
Fig. 4.10 Scenario-wise waste allocation in Tambaram 322
Fig. 4.11 Greenhouse gas emissions under alternative scenarios in Tambaram....................322
Fig. 4.12 Gas-wise emission comparison for Tambaram scenarios......................................323

Volume III - Overall Project Outcomes and Recommendations

Fig. 1.1 Life cycle assessment (LCA) framework for solid waste management processes...381
Fig. 1.2 Effect of data quality challenges and limitations on SWM assessment 385
Fig. 1.3 A standardized approach to address data reporting gaps in LCA of SWM facilities 386
Fig. 1.4 A glimpse of GHG Calculator tool ENVISAGE...400
Fig. 1.5 Strategic phased action plan for solid waste management transformation in India .402

List of Tables

Volume I Life Cycle Assessment (LCA) of Solid Waste Management Systems

Table 2.1 Institute and cities selected for LCA study 9
Table 3.1 Global warming (GW) contribution s of solid waste management processes in Bangalore 19
Table 3.2 Global warming (GW) contributions of solid waste management processes in Mysore 23
Table 3.3 Global warming (GW) of solid waste management practices in Tumakuru 30
Table 3.4 Indicative composition of Delhi's MSW stream (as provided for this study) 32
Table 3.5 Status of Delhi's three legacy landfill sites (Source: DPCC annual reports and public disclosures, 2025–26) 35
Table 3.6 Global Warming Potential (GWP) contribution of MSW management technologies 38
Table 3.7 Global warming (GW) contribution of solid waste management processes in Chennai 53
Table 4.1 Inventory data of various composting pathways for organic municipal solid waste (per functional unit) (S1: Composting without energy recovery from leachate; S2: Composting with energy recovery (in form of electricity generation) from leachate, S3: Composting with energy recovery (in form of bio-CNG production for vehicle fuel) from leachate) 61
Table 5.1 Inventory data of various utilisation pathway of biogas based on organic fraction of municipal solid waste (per functional unit) (S1: Flaring; S2: Electricity, S3: Direct Cooking, S4: purified and bottled cooking fuel, S5: bio-CNG production for vehicle fuel) 94
Table 5.2 Data for economic analysis of different scales (from 25-500 TPD) bio-CNG plants 99
Table 5.3 Mid impact categories scores of different bio-methanation Scenarios 110
Table 5.4 Life cycle inventory and system assumptions for the biogas plant scenarios 122
Table 6.1 Inventory data for waste to energy plant for three scenarios (per functional unit) 146
Table 6.2 Data for economic analysis of 600 TPD waste to energy plant 149
Table 6.3 Mid impact categories scores of different Scenarios of waste-to-energy plants offsetting coal-based electricity (Scenario1: Without carbon capture, Scenario 2: With carbon capture and storage, Scenario 3: With carbon capture and utilisation) of waste-to-energy plant with different composition of waste type 156
Table 7.1 Ecoinvent data for production processes of different materials and their GW 179

Table 7.2 Ecoinvent data for recycling processes of different materials and their GW 180
Table 7.3 GHG emissions from primary production and recycling (data from the Ecoinvent database v 3.12) 188
Table 8.1 Life cycle inventory 197
Table 8.2 Physicochemical characteristic of leachate (Bengaluru data, n = 5) 198
Table 8.3 Gaps in existing leachate treatment regulations and recommended improvements 204
Table 9.1 Population growth and the MSW landfilled for 5 years. 208
Table 9.2 The leachate generated per year from OD and SLF 209
Table 9.3 Inventory data for emissions from different landfilling scenarios of MSW for LCA analysis (per functional unit) (S1: Open dump; S2: Sanitary landfill with leachate treatment, S3: Sanitary landfill with leachate recirculation with LFG flaring, S4: Sanitary landfill with leachate recirculation with electricity production, S5a: bio-CNG production for vehicle fuel, S5b: Bio-CNG production for bottled cooking fuel) 213
Table 9.4 Data for economic analysis of different landfilling Scenarios for 1-ton MSW 219
Table 10.1 Lifecycle inventory data 244
Table 10.2 Endpoint impacts for S1 and S2 250
Table 10.3 Expenses and revenue of biomining project at Mandur 254
Table 10.4 Issues or gap and proposed recommendation 257

Volume II- Development of Greenhouse Gas (GHG) Emission Calculator App

Table 2.1 Major emission categories considered for waste treatment pathways 271
Table 3.1 Waste generation and composition data for Avadi and Tambaram 289
Table 3.2 Transportation fuel and energy consumption data for Avadi and Tambaram 290
Table 3.3 Baseline and scenario-wise composting input parameters for Avadi and Tambaram 292
Table 3.4 Baseline and scenario-wise anaerobic digestion input parameters for Avadi and Tambaram 293
Table 3.5. Baseline and scenario-wise recycling input parameters for Avadi and Tambaram 295
Table 3.6 Baseline and scenario-wise incineration input parameters for Avadi and Tambaram 298
Table 3.7 Baseline and scenario-wise landfilling input parameters for Avadi and Tambaram 301

Table 4.1 GHG emission results for Avadi under the BAU scenario....................................309
Table 4.2 GHG emission results for Tambaram under the BAU scenario 313
Table 4.3 Process-wise GHG emissions under alternative scenarios for Avadi....................318
Table 4.4 Comparative assessment of alternative waste management scenarios for Avadi..320
Table 4.5 Process-wise GHG emissions under alternative scenarios for Tambaram 323
Table 4.6 Comparative assessment of alternative waste management scenarios for Tambaram 325

Volume III - Overall Project Outcomes and Recommendations

Table 1.1 Recommendation on various treatment technologies 391

Abbreviations and Acronyms

AD	Anaerobic Digestion
ADP	Abiotic Depletion Potential
AOW	Amount of Waste
AP	Acidification Potential
BAU	Business-As-Usual
BBMP	Bruhat Bengaluru Mahanagara Palike
BC	Black Carbon
BOD	Biochemical Oxygen Demand
BOV	Batter operated vehicle
C&D	Construction and Demolition
CaPex	Capital Expenditure
CBG	Compressed Biogas
CCS	Carbon Capture and Storage
CCU	Carbon Capture and Utilisation
CH_4	Methane
CHP	Combined Heat and Power
CMDA	Chennai Metropolitan Development Authority
CNG	Compressed Natural Gas
CO_2	Carbon dioxide
COD	Chemical Oxygen Demand
CPCB	Central Pollution Control Board
D2D	Door-to-door
DCB	Delhi Cantonment Board
DHW	Domestic Hazardous Waste
DPR	Detailed Project Report
DWCC	Dry Waste Collection Center
EF	Emission Factor
ENVISAGE	Environmental Navigation & Vision for Impact Scenario Analysis and Greenhouse Gas Estimation
EP	Eutrophication Potential
EPA WARM	United States' Environmental Protection Agency Waste Reduction Model

EPR	Extended Producer Responsibility
EQT	Emission Quantification Tool
EV	Electric Vehicle
FAETP	freshwater aquatic ecotoxicity potential
FE	freshwater eutrophication
FEP	Freshwater Eutrophication Potential
FET	Freshwater Ecotoxicity
FOD	First Order Decay
FOM	Fermented Organic Manure
FRS	Fossil Resource Scarcity
GCC	Greater Chennai Corporation
GCV	Gross Calorific Value
GHG	Greenhouse Gases
GW	Global Warming
GWP	Global Warming Potential
HCT	Human carcinogenic toxicity
HCV	Heavy Commercial Vehicle
HDPE	High-density Polyethylene
HMV	Heavy Motor Vehicle
HNCT	Human Non-Carcinogenic Toxicity
HTP	Human Toxicity Potential
ICAR-IIHR	Indian Council of Agricultural Research-Indian Institute of Horticultural Research
IGES	Institute for Global Environmental Strategies
IPCC	Intergovernmental Panel on Climate Change
IRR	Internal Rate of Return
KPCL	Karnataka Power Corporation Limited
LCA	Life Cycle Assessment
LCI	Life Cycle Inventory
LCIA	Life Cycle Impact Assessment
LCV	Light Commercial Vehicle
LDPE	Low-Density Polyethylene
LFG	Landfill Gas

LMV	Light Motor Vehicle
LPG	Liquefied Petroleum Gas
LTP	Leachate Treatment Plant
MAETP	Marine Aquatic Ecotoxicity Potential
MBR	Membrane Bio Reactor
MCC	Micro Composting Centres
MoEFCC	Ministry of Environment, Forest and Climate Change
MoHUA	Ministry of Housing and Urban Affairs
MSME	Micro, Small, and Medium Enterprises
MSW	Municipal Solid Waste
N2O	Dinitrogen monoxide
NCT	National Capital Territory
NCV	Net Calorific Value
NDMC	New Delhi Municipal Council
OD	Open Dumping
OFMSW	Organic Fraction of Municipal Solid Waste
OPex	Operational Expenditure
PP	Polypropylene
PSA	Principal Scientific Advisor
PVC	Polyvinyl chloride
RDF	Refuse Derived Fuel
RO	Reverse Osmosis
RoW	Rest of World
RRC	Resource Recovery Centre
SLCP	Short-Lived Climate Pollutant
SLF_LR_BCNG	Sanitary Landfilling with Bio-CNG production
SLF_LR_ELE	Sanitary Landfilling with electricity generation
SLF_LR_F	Sanitary Landfilling with Leachate Recirculation and Flaring
SWM	Solid Waste Management
TA	Terrestrial Acidification
TDS	Total Dissolved Solids
TE	Terrestrial Ecotoxicity
TS	Total Solids

TTC	Tumkur City Corporation
ULB	Urban Local Body
VS	Volatile Solids
WTE	Waste to Energy
WWTP	Waste Water Treatment Plant
ZWM	Zero Waste Management

Volume I

Life Cycle Assessment (LCA) of Solid Waste Management Systems

Office of the Principal Scientific Adviser
to the Government of India

Chapter 1

Introduction

1.1 Background: Overview of Municipal Solid Waste (MSW) in India

Municipal Solid Waste (MSW) in India refers to the waste generated from households, commercial establishments, institutions, and public spaces in urban areas. With rapid urbanization, population growth, and changing lifestyles, the quantity and complexity of waste generated in Indian cities have increased significantly over the years. MSW in India is typically heterogeneous in nature, consisting largely of biodegradable waste such as food and organic matter (about 50-60%), followed by recyclable materials like paper, plastic, metal, and glass (15-25%), and inert materials such as dust and construction debris (20-30%), along with a small fraction of hazardous waste. India currently generates over 150,000 tons of municipal solid waste per day, with per capita generation ranging between 0.3 and 0.6 kilograms per day, depending on the size and economic status of the city.

The management of MSW involves collection, segregation, transportation, processing, and disposal. While door-to-door collection has improved in recent years due to government initiatives, segregation of waste at the source remains a major challenge, leading to mixed waste that reduces the efficiency of recycling and treatment processes. A large portion of waste is still disposed of through open dumping, although sanitary landfills, composting, and waste-to-energy technologies are gradually being adopted. The informal sector, including waste pickers and scrap dealers, plays a crucial role in recycling and material recovery, despite operating under unregulated and often unsafe conditions. Key challenges in MSW management in India include inadequate infrastructure, lack of public awareness, land scarcity for landfills, and environmental pollution caused by improper waste disposal practices. To address these issues, the government has introduced measures such as the Solid Waste Management (SWM) Rules, 2016, and the Swachh Bharat Mission, focusing on source segregation, scientific waste processing, and sustainable practices. Overall, improving MSW management in India requires better implementation of policies, technological advancements, and active public participation to ensure environmental sustainability and public health.

1.2 Life Cycle Assessment (LCA): Concepts and Importance

Life Cycle Assessment (LCA) is a systematic analytical method used to evaluate the environmental impacts associated with a product, process, or service throughout its entire life cycle. This life cycle typically includes all stages from raw material extraction, manufacturing, transportation, and usage, to final disposal or recycling commonly referred to as the "cradle-to-grave" approach. In some cases, a "cradle-to-cradle" perspective is adopted, where the end-of-life stage is designed to feed back into the production cycle through reuse or recycling. LCA helps in identifying and quantifying energy and material inputs, as well as environmental emissions, at each stage of the life cycle.

The concept of LCA is based on a holistic approach that considers the cumulative environmental effects rather than focusing on a single stage of a product's life. It is typically carried out in four main phases: goal and scope definition, life cycle inventory (LCI) analysis, life cycle impact assessment (LCIA), and interpretation. In summary:

- ***Goal and scope*** define the purpose of the study and system boundaries;
- ***Inventory phase*** involves data collection of inputs and outputs;
- ***Impact assessment*** evaluates potential environmental impacts such as global warming, resource depletion, and pollution; and
- ***Interpretation phase*** draws conclusions and provides recommendations.

The importance of LCA lies in its ability to support informed decision-making for sustainable development. It enables industries, policymakers, and researchers to compare alternatives, improve product design, reduce environmental footprints, and optimize resource use. LCA is widely used in waste management, energy systems, agriculture, and manufacturing sectors to identify environmentally preferable options. It also plays a critical role in developing eco-labeling, environmental product declarations, and sustainability policies. By providing a comprehensive understanding of environmental impacts across the entire life cycle, LCA contributes to minimizing negative environmental effects, promoting circular economy practices, and achieving long-term environmental sustainability.

1.3 Need for LCA-Based SWM Framework in India

India's rapidly increasing population, urbanization, and changing consumption patterns have led to a sharp rise in the quantity and complexity of municipal solid waste. Traditional waste management practices in the country have largely focused on collection and disposal, often neglecting the environmental impacts associated with different stages of waste handling. In this context, there is a strong need for an LCA-based SWM framework that evaluates waste management options holistically, from generation to final disposal, considering their environmental and economic implications (Fig. 1.1).

An LCA-based SWM framework is essential in India because it enables decision-makers to identify the most sustainable waste management strategies by comparing alternatives such as landfilling, composting, recycling, and waste-to-energy technologies. Instead of relying on conventional methods that may shift environmental burdens from one stage to another, LCA ensures that impacts such as greenhouse gas emissions, energy consumption, air and water pollution, and resource depletion are assessed comprehensively. This is particularly important in India, where improper waste disposal practices like open dumping and burning contribute significantly to environmental degradation and public health issues.

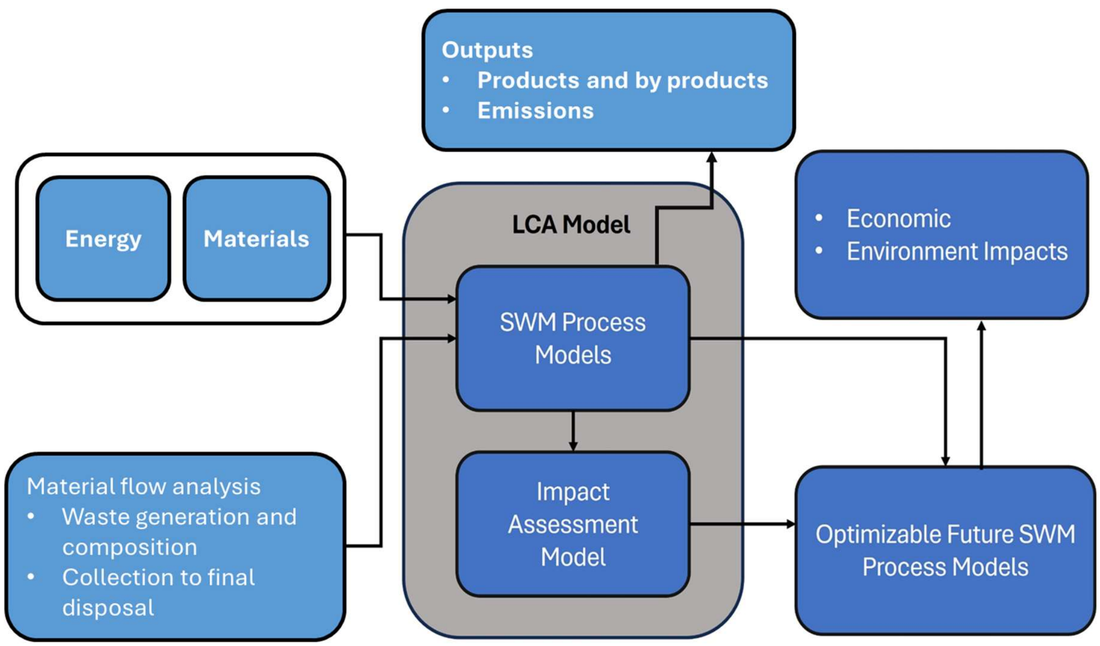


Fig. 1.1 Life cycle assessment framework for solid waste management

Furthermore, the heterogeneous composition of Indian waste, which has a high proportion of biodegradable material, requires tailored solutions that maximize resource recovery while minimizing environmental harm. An LCA-based framework can help optimize the selection of technologies such as composting and bio-methanation for organic waste, and recycling systems for dry waste, thereby improving overall efficiency (Fig. 1.2). It also supports the integration of the informal sector, which plays a crucial role in recycling but is often excluded from formal planning processes.

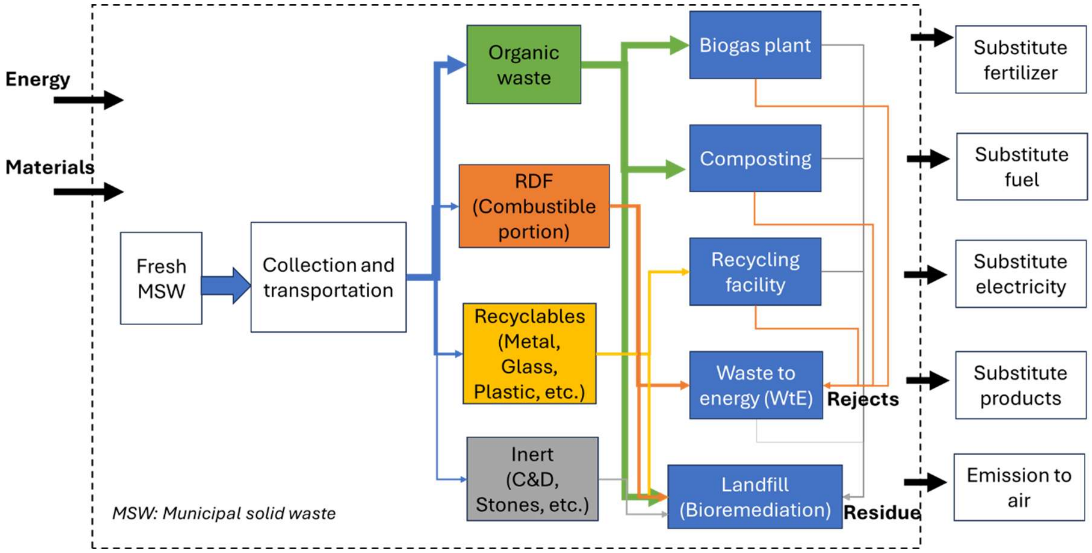


Fig. 1.2 System boundary of fresh municipal solid waste management system

The adoption of an LCA-based SWM framework is also aligned with national policies such as the Solid Waste Management Rules, 2016, and initiatives like the Swachh Bharat Mission, which emphasize sustainable and scientific waste management practices. By incorporating LCA, policymakers can develop data-driven strategies, prioritize investments, and implement region-specific solutions that account for local conditions.

In conclusion, the need for an LCA-based SWM framework in India is driven by the necessity to move beyond conventional waste management approaches toward a more sustainable, efficient, and environmentally responsible system. It provides a scientific basis for decision-making, promotes resource efficiency, reduces environmental impacts, and supports the transition toward a circular economy.

1.4 Project Consortium and Division of Responsibilities

The overall goal of the project was to provide data-driven evidence to help India transition from its current waste disposal challenges to a more sustainable and circular economy pathway.

The specific objectives of the work:

- ***Objective I:*** Identification of current waste management practices in selected sites for both fresh waste and legacy waste (Common for all teams for their respective cities)
- ***Objective II:*** LCA analysis of selected sites to identify the relative advantage of current and proposed waste management practices. (Common for all teams for their respective cities)

- ***Objective III:*** Development of a user-friendly app to enable the collection of key data from waste management facilities (Taken up by IIT Madras team)
- ***Objective IV:*** Development of proper SWMs practices based on discussions with the Urban Local Bodies (ULBs)

The specific objectives of IISc Bangalore include:

- Analysis of current waste management practices in Bangalore and recommendations
- Analysis of leachate treatment approaches and recommendations on the leachate treatment
- Legacy waste analysis and study of biomining at Mandur site (legacy site)
- Legacy waste analysis of bioremediation at Bellahalli site (legacy site)
- Results of LCA of studies for Mysore (Tier II city)
- Results of LCA of Studies for Puttur (Tier III city)

The specific objectives of IIT BHU include:

- Analysis of current waste management practices in Delhi and Varanasi.
- Legacy waste analysis of biomining at Ghazipur site (Legacy site).
- Results of LCA study for Delhi (Tier I city)
- Results of LCA study for Varanasi (Tier II city)

1.5 Scope and Organization of the Report

This report presents the development and application of a LCA-based framework for evaluating MSW management technologies under Indian conditions. The study focuses on assessing the environmental performance of existing waste treatment systems (Technology readiness level 9) using region-specific data collected from selected urban local bodies representing different city tiers in Karnataka.

The report evaluates multiple treatment technologies, including composting, biomethanation, waste-to-energy, recycling, leachate treatment, sanitary landfilling, and biomining. The analysis considers impacts associated with waste collection, transportation, processing, resource recovery, and final disposal.

The organization of the report is as follows:

- Chapter 1 introduces the background of municipal solid waste management in India, the importance of LCA, the need for an LCA-based framework, and the objectives of the project.

- Chapter 2 describes the overall research methodology, study areas, data collection strategy, material flow analysis approach, and key assumptions adopted in the study.
- Chapter 3 presents the assessment of existing waste management practices in Bengaluru, Mysuru, and Tumkur, including material flow analysis and associated greenhouse gas emissions.
- Chapter 4 evaluates composting systems and integrated leachate-to-energy recovery pathways using LCA.
- Chapter 5 presents the environmental and economic assessment of biomethanation and bio-CNG systems.
- Chapter 6 analyses waste-to-energy technologies under different operational and carbon capture scenarios.
- Chapter 7 evaluates material recovery and recycling systems for dry waste management.
- Chapter 8 assesses leachate treatment systems and their environmental implications.
- Chapter 9 compares environmental and economic impacts of different landfill management scenarios, including landfill gas recovery options.
- Chapter 10 evaluates biomining of legacy waste dumpsites and associated environmental benefits.
- Chapter 11 summarizes the major findings and provides recommendations and a roadmap for sustainable solid waste management in India.

Overall, the report aims to provide a scientific basis for decision-making and policy formulation toward environmentally sustainable and resource-efficient waste management systems.

Chapter 2
Methodology

2.1 Overall Research Framework

The overall research framework for the development of an LCA-based framework for solid waste treatment technologies in India involves a systematic and integrated approach to evaluate the environmental performance of various waste management options under Indian conditions. The framework begins with the definition of goal and scope, where the objectives of the study, system boundaries, and functional units (such as treatment of one ton of municipal solid waste) are clearly established. This is followed by a detailed LCI analysis, which includes the collection of region-specific data on waste composition, energy use, emissions, transportation, and operational parameters of different treatment technologies such as composting, bio-methanation, recycling, incineration, and landfilling. The next stage involves LCIA, where the potential environmental impacts such as global warming potential, acidification, eutrophication, and human toxicity are quantified using appropriate impact assessment methods. The framework then integrates comparative analysis to evaluate and rank different waste treatment alternatives based on environmental performance, economic feasibility, and social acceptability. Sensitivity and uncertainty analyses are also incorporated to ensure the robustness of results under varying conditions. Finally, the interpretation phase provides insights and recommendations for policymakers, urban local bodies, and stakeholders to support informed decision-making and the adoption of sustainable waste management practices. This research framework is designed to be adaptable to diverse Indian contexts, enabling the development of efficient, region-specific, and environmentally sound solid waste management strategies.

2.2 Study Area (Cities and Sites)

The study area is mentioned below:

Table 2.1 Institute and cities selected for LCA study

Institute	Cities selected
IISc Bangalore	Bangalore (Tier I), Mysore (Tier II), Tumakuru (Tier III)
IIT BHU	Delhi (Tier I), Varanasi (Tier II)
IIT Madras	Chennai (Tier I)

2.3 Data Collection Strategy

The data collection strategy for developing an LCA-based framework for solid waste treatment technologies in India involves the systematic gathering of both primary and secondary data to ensure accuracy, representativeness, and reliability of the assessment. Primary data are collected through field surveys, site visits, and direct measurements from waste management facilities such as composting plants, bio-methanation units, recycling centers, incinerators, and landfills, focusing on parameters like waste composition, energy consumption, emissions, and operational efficiency. Secondary data are obtained from government reports, research publications, municipal records, and databases such as Ecoinvent, CPCB (Central Pollution Control Board) and other relevant institutions. The strategy emphasizes region-specific data collection to capture variations in waste characteristics, climate conditions, and technological performance across different parts of India. Standardized data formats and consistent functional units are maintained to ensure comparability across treatment options. In addition, data validation, cross-checking, and gap-filling techniques are applied to address uncertainties and missing information. This comprehensive data collection approach forms the backbone of the LCA study, enabling accurate inventory analysis and meaningful environmental impact assessment.

2.4 Material Flow Analysis (MFA) Approach

The Material Flow Analysis (MFA) approach is a systematic method used to quantify and track the flow of materials within a defined system boundary over a specific period of time, making it highly relevant for solid waste management studies. In the context of developing an LCA-based framework for waste treatment technologies in India, MFA helps in mapping the generation, collection, segregation, processing, recycling, and disposal of municipal solid waste. It involves identifying key material streams such as organic waste, plastics, paper, metals, and inert materials and analyzing their movement through different stages of the waste management system. By applying the principle of mass balance, MFA ensures that inputs, outputs, and accumulations are accurately accounted for, thereby improving the reliability of data used in LCA. This approach enables the identification of inefficiencies, leakages, and potential areas for resource recovery, such as recycling and energy generation. Additionally, MFA supports decision-making by providing a clear understanding of material distribution and helping optimize waste management strategies to enhance sustainability, reduce environmental impacts, and promote circular economy practices in the Indian context.

2.5 Assumptions

The following assumptions were adopted for the development of the LCA framework and analysis of municipal solid waste management technologies in this study:

1. Waste generation rates, collection efficiencies, segregation efficiencies, and waste composition data were assumed to remain constant during the assessment period based on available field data and municipal records.
2. Transportation distances for waste collection, transfer, and disposal were estimated using average distances obtained from field surveys and stakeholder consultations.
3. Source-segregated waste was assumed to be processed according to the intended treatment pathway without significant contamination unless otherwise specified.
4. Emission factors for composting, anaerobic digestion, landfilling, transportation, electricity generation, and fuel substitution were adopted from published literature, IPCC guidelines, Ecoinvent database, and site-specific operational data.
5. Secondary data obtained from literature and databases were assumed to be representative of Indian operating conditions where site-specific data were unavailable.
6. Sensitivity analyses were carried out for key operational parameters such as transportation distance, waste composition, methane leakage, energy recovery efficiency, and fertilizer substitution rates to evaluate the robustness of the results.

Chapter 3
Current Waste Management Practices

3.1 Preamble

This chapter presents an overview of current MSW management practices across three urban tiers in Karnataka (the Tier 1 city Bengaluru, the Tier 2 city Mysuru, and the Tier 3 city Tumakuru), Delhi (Tier I city), Varanasi (Tier II city), and Chennai (Tier I city). The study further quantifies the greenhouse gas (GHG) emissions associated with waste management systems in each city. To achieve this, the following objectives are addressed:

(i) to identify and characterise existing MSW treatment practices in each city;

(ii) to develop material flow pathways for waste streams; and

(iii) to estimate GHG emissions associated with different waste treatment technologies.

3.2 Methodology

The methodology adopted in this study integrates field-based assessments with analytical modelling. Primary data were collected through site visits to waste processing and disposal facilities, complemented by consultations with key stakeholders, including municipal authorities and plant operators. Secondary data were obtained from official reports and literature sources.

The collected data were analysed to develop material flow diagrams representing waste generation, segregation, processing, and disposal pathways. Later, a LCA approach was employed to quantify the environmental impacts, GHG emissions, associated with different waste management scenarios.

3.3 Case Study: Tier I City – Bangalore

3.3.1 City profile

Bengaluru (Bangalore) is the capital city of Karnataka and is widely known as the "Silicon Valley of India" owing to its prominence as a major information technology and innovation hub. The city has a population exceeding 14 million, making it one of the megacities in India. It is the third most populous city and the fifth most populous urban agglomeration in the country. Bengaluru is situated at an average elevation of over 900 m (~ 3,000 ft) above mean sea level about 709 sq. km (Greater Bengaluru Authority website). For administrative purpose, the city is divided into five demarcated zones North, South, East, West, and Central to enable more focused and decentralized urban management (Fig. 3.1).

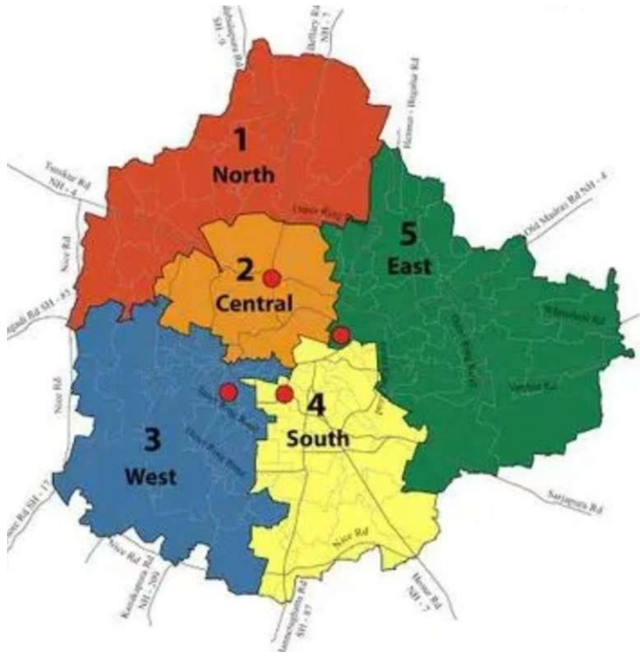


Fig. 3.1 Bengaluru urban region

3.3.2 Waste generation and collection

3.3.2.1 Waste generation

Bengaluru generates ~ 6,200 TPD of MSW. The total waste generated, about 90% is collected through the door-to-door collection system covering residential, commercial, and bulk waste generators. At source the MSW is segregated into dry waste, wet waste and sanitary waste and achieving a segregation efficiency of 60%.

3.3.2.2 Waste collection and transportation

Segregated waste is collected daily from households and commercial establishments. This is done using authorised service providers who operate under zonal contracts. Auto-tippers and pushcarts are used for residential and narrow-lane collection, while larger truck with compactors are deployed for bulk generators and secondary transportation. Collected waste is transported to designated processing centers. In certain zones, transfer stations are used to consolidate waste before long-distance transport. Bulk waste generators, including apartments, institutions, hotels, and commercial establishments, are mandated to process wet waste on-site through composting or bio-methanation and only residual waste is collected by Bengaluru corporation.

3.3.3 Waste processing and resource recovery

3.3.3.1 Dry waste collection centers (DWCC) and material recovery facility

DWCCs handles dry waste from neighborhood-level collection point focusing on gathering dry waste fractions such as plastics, paper, glass, metals, and tetra packs. These centres are equipped for preliminary sorting. There are currently 189 DWCC in Bengaluru with a capacity between 1 to 5 TPD. Recovered materials are routed to a material recovery facility while contaminated or non-recyclable dry waste is diverted to landfills or waste-to-energy facilities.

Material recovery facilities receive segregated waste from DWCC and are equipped with mechanical sorting and bailing systems (Fig. 3.2). At these facilities, dry waste is separated into plastics, paper, metals, glass, and other fractions according to the demand from recyclers. Recovered materials are then sent to authorised recyclers, while non-recyclable rejects are transported to waste-to-energy plants or landfills.

Fig. 3.2 Material recovery facility in Bengaluru

3.3.3.2 Waste to energy plant

Bengaluru has a 11.5 MW waste-to-energy plant in Bidadi that processes non-recyclable dry waste (Fig. 3.3). The operating capacity is 600 TPD, producing 150 TPD of ash residue for landfill disposal. The plant is operated by Karnataka Power Corporation Limited (KPCL) and the Bruhat Bengaluru Mahanagara Palike (BBMP).

Fig. 3.3 WTE plant in Bidadi, Bengaluru

3.3.3.3 Biomethanation plants

Bio-methanation plants receive segregated wet waste and process it through anaerobic digestion (Fig. 3.4). Bengaluru operates multiple biomethanation plants to convert wet waste into biogas and electricity. Key facilities are located in Koramangala Aramane Nagar Gandhinagar Yediyur Pattabhiram Nagar and Domlur. Each plant manages 5 tons of wet waste daily. The biomethane produced is used as a cooking gas or converted into electricity while the digestate is used as manure. The Koramangala unit is operated by Carbon Masters processes 10 tons of waste daily into Bio-CNG and supplies it to nearby restaurants as cooking gas. There is total 13 biomethanation plants in Bengaluru with net processing capacity of 70 TPD.

Fig. 3.4 Biogas plant in Bengaluru

3.3.3.4 Composting plant

Composting plants treat segregated wet waste through windrow composting. Currently, there are seven facilities with a combined processing capacity of about 1,800 TPD. Major plants are located at Kannahalli, Doddabidarakallu, and Lingadheeranahalli. The process produces stabilised compost, which is used in agricultural applications. The processing rejects are directed either to landfills or WTE plant.

3.3.3.5 Landfills

Landfills serve as the final disposal sites for residual and mixed waste in Bengaluru, with approximately 60% of the city's waste currently being landfilled. The active landfill is located at Mitaganahalli, a quarry-based site on the outskirts of the city. Major closed landfill sites include Mavallipura, Mandur, and Bellahalli.

3.3.4 Material flow analysis

Bengaluru generates approximately 6,200 TPD of MSW, of which nearly 90% is collected through the formal collection system. The total wet waste collected, 1,800 TPD is processed through centralized composting facilities. This treatment results in the generation of nearly 270 TPD of compost, which is distributed to farmers for agricultural use (Fig. 3.5). In addition, around 70 TPD of wet waste is treated through decentralized bio-methanation plants, with individual plant capacities ranging from 5-10 TPD.

In the dry waste fraction approximately 300 TPD of recyclable materials is recovered and sent for recycling while 300 TPD is sent to a waste-to-energy plant as RDF. However, a significant portion of the dry waste stream is rendered unsuitable for recycling due to contamination and inadequate source segregation resulting in its diversion to landfill facilities.

The material flow analysis highlights a continued reliance on landfill disposal. Despite the presence of multiple processing and resource recovery pathways, approximately 60% of the total collected MSW is ultimately landfilled. This highlights the urgent need for improved segregation to prevent contamination of recyclables and boost processing capacity, ultimately diverting more waste from landfills.

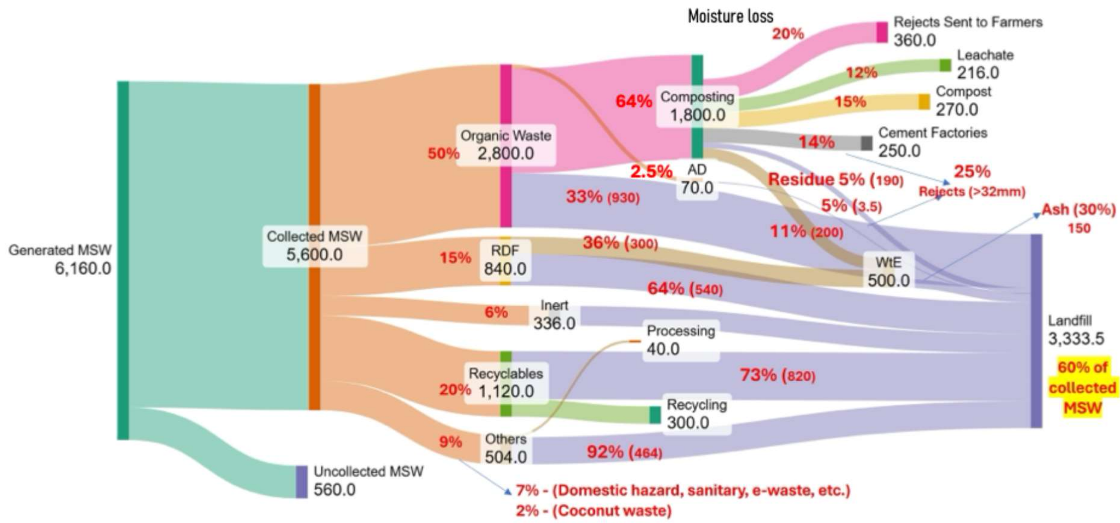


Fig. 3.5 Material flow analysis of MSW in Bangalore

3.3.5 Life cycle assessment

A LCA was carried out to account for the net emissions from the Bangalore solid waste management. The detailed LCA methodology of individual treatment process and alternate scenarios of composting, anaerobic digestion, WTE, recycling and landfill are detailed in chapters 4 to 8.

The LCA results showed a net emission of 795 kg CO_2 eq. per ton of MSW. The contributions of individual treatment processes to global warming (GW) are summarized in Table 3.1. The analysis shows that landfilling dominates the GW, contributing 4,532,880 kg CO_2 eq., which exceeds the emission reductions achieved through resource recovery processes. This high impact is primarily attributed to the large fraction of waste disposed in landfills (60%) and the absence of landfill gas (LFG) capture systems. Under these conditions, landfill sites function as uncontrolled sources of methane emissions, a greenhouse gas 27-30 times more potent than carbon dioxide over 100 years.

In contrast, resource recovery pathways provide notable climate benefits. Waste diversion through composting (−2,520 kg CO_2 eq.), biogas production (−840 kg CO_2 eq.), recycling (−15,000 kg CO_2 eq.), and waste-to-energy (−62,000 kg CO_2 eq.) results in net avoided emissions. These reductions occur primarily through material substitution, renewable energy generation, and displacement of fossil-based energy sources.

Table 3.1 Global warming (GW) contributions of solid waste management processes in Bangalore

	Waste quantity (tons)	GW (kg CO_2 eq./ton)	Net GW (kg CO_2 eq.)
Composting	1800	-1.4	-2520
Biogas plant (cooking)	70	-12	-840
WTE	500	-124	-62000
Landfilling	3333	1360	4532880
Recyclables	300	-50	-15000
Net emissions			**4452520**

Despite the presence of advanced treatment options such as bio-methanation plants and waste-to-energy facilities, their current capacity remains insufficient compared to large quantity of waste being landfilled. Consequently, the environmental benefits generated from energy recovery and recycling are suppressed by the methane emissions from landfill disposal.

These results highlight two critical priorities for reducing the climate impact of Bangalore's waste management system:

- Substantial reduction in the landfilling rate through enhanced waste segregation, recycling, and organic waste treatment.
- Implementation of landfill gas capture and utilization systems at existing landfill sites to mitigate methane emissions and recover energy.

Reducing the landfilling practice is essential to lower the greenhouse gas footprint of Bangalore's municipal solid waste management system.

3.4 Case Study: Tier II City – Mysore

3.4.1 City profile

Mysuru City, located in southern Karnataka, covers an area of approximately 156 sq. km, population of 13,45,720 and is administratively divided into 65 municipal wards and 9 zones under the Mysuru City Corporation (MCC) (Fig. 3.6). The city is a major cultural, educational, and tourism hub with seasonal population fluctuations due to tourism and festivals. MCC is the responsible Urban Local Body (ULB) for planning, implementation, operation, and monitoring of solid waste management services within city limits (Mysore city corporation official website).

Fig. 3.6 Mysuru city map

3.4.2 Waste generation and collection

3.4.2.1 Waste generation

The total municipal solid waste generation in Mysuru City is around 550 TPD, considering household waste, commercial establishments, markets, institutions, hotels, street sweeping, and horticultural waste. Collection efficiency is high, typically exceeding 80-90%.

The physical composition of MSW in Mysuru is broadly characterized as:

- Organic / biodegradable fraction: ~55%
- Paper and cardboard: ~10%

- Plastics: ~10-15%
- Textiles, rubber, leather: ~5-7%
- Inert materials (soil, silt, ceramics): ~5-10%
- Sanitary and domestic hazardous waste: ~1-2%

High organic content makes biological treatment processes such as composting and anaerobic digestion particularly relevant for the city.

3.4.2.2 Waste collection and transportation

Mysuru City has an established system of door-to-door waste collection with emphasis on source segregation into wet, dry, and sanitary waste streams. Collection is carried out using pushcarts, auto-tippers, compactors, and tipper trucks, depending on the zone and waste quantity.

Transportation involves movement of waste from collection points to centralized composting plants, material recovery facilities (MRFs), zero waste management (ZWM) centers, and sanitary landfill sites.

3.4.3 Waste processing and resource recovery

3.4.3.1 Composting facilities

Mysuru City operates three centralized composting plants:

- Vidyaranyapuram Composting Facility - 200 TPD
- Kesare Composting Facility - 200 TPD
- Rayanakere Composting Facility - 150 TPD

These facilities primarily process segregated organic waste through aerobic windrow composting. Outputs include marketable compost, rejects (>35 mm), and leachate. The city's composting facility can handle 550 TPD of organic waste, exceeding the current generation of 300 TPD.

3.4.3.2 Zero Waste Management (ZWM) Centres

ZWM centres operate at decentralized levels with capacities of 5-10 TPD, handling both wet and dry waste. Wet waste is composted locally or send to composting facilities, while dry waste is sorted and sent to authorized recyclers.

3.4.3.3 Dry Waste Collection Centres (DWCC) and Material Recovery

Dry waste collected from households and commercial sources is aggregated at DWCCs and MRFs. Recyclable fractions such as plastics, paper, metals, and glass are recovered and sent to recycling industries. Residual non-recyclable waste is sent for landfill or RDF processing.

3.4.3.4 Anaerobic digestion and emerging technologies

Anaerobic digestion plants and biomethanation projects are under implementation or planning stages to treat organic waste and generate biogas, thereby reducing landfill burden and fossil fuel use.

3.4.3.5 Landfill and residual waste management

Mysuru City utilizes an engineered sanitary landfill located at Vidyaranyapuram for disposal of processing rejects, inert waste, and non-recyclable fractions. The landfill includes liner systems, leachate collection and treatment, gas venting, and capping of legacy waste areas. Biomining and capping of old dump sites are ongoing to recover materials and reclaim land.

3.4.4 Material flow analysis

The MFA of MSW illustrates the collection, processing, and disposal pathways of waste in the city, with quantities expressed in tons per day (TPD) (Fig. 3.7). Mysore generates 610 TPD of MSW, of which about 90% is collected. The collected waste stream comprises 55% organic waste (302 TPD), 36% dry waste (RDF/recyclables, 199.25 TPD), 7.5% inert materials (41.25 TPD), and 1.5% other waste (7.5 TPD).

The organic fraction is entirely directed to composting facilities, resulting in 45 TPD compost which are send to farmers. The 30% of the reject generated from the composting is landfilled. The RDF and recyclable fraction are only partially recovered, with 45 TPD (22.5%) directed to MRFs, while the remaining 77.5% is disposed of in landfills. In addition, inert waste (41.25 TPD) and other waste (7.5 TPD) are directly landfilled. The landfill receives 233 TPD of waste, accounting for 42% of the collected MSW. This highlights the need to improve segregation efficiency and minimize rejects to reduce dependence on landfill disposal.

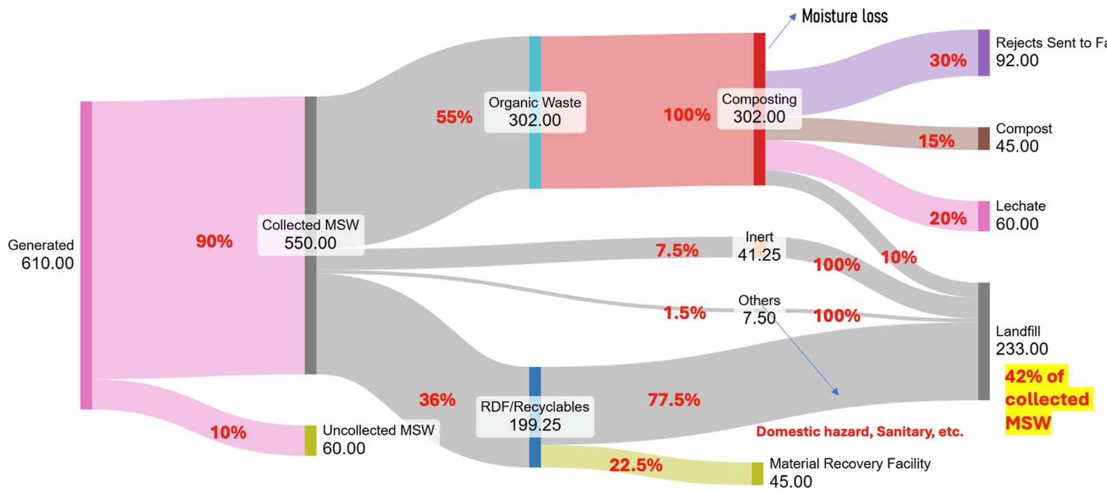


Fig. 3.7. Material flow analysis of municipal solid waste in Mysuru

3.4.5 Life cycle assessment

Mysore demonstrates a moderate climate impact, with a net emission of 571 kg CO_2 eq. per ton of municipal solid waste managed. The contributions of different treatment processes to the GW are presented in Table 3.2. The results indicate that landfilling remains the major contributor to greenhouse gas emissions, accounting for 316,880 kg CO_2 eq. despite the city diverting a significant fraction of organic waste through composting. Approximately 42% of the collected waste is disposed of in landfills, and in the absence of landfill gas capture systems, these sites act as major sources of methane emissions.

Table 3.2 Global warming (GW) contributions of solid waste management processes in Mysore

	Waste quantity (tons)	GW (kg CO_2 eq./ton)	Net GW (kg CO_2 eq.)
Composting	302	-1.4	-422.8
Landfilling	233	1360	316880
Recyclables	45	-50	-2250
Net emissions			**314207**

Mysore city relies on composting process for wet waste, which contributes −422.8 kg CO_2 equivalent in avoided emissions. This reduction is mainly attributed to the substitution of synthetic fertilisers with compost. Furthermore, material recovery through recycling contributes −2,250 kg CO_2 equivalent reflecting the environmental benefits associated with the avoidance of virgin material production. While composting and recycling provide measurable climate benefits their overall contribution remains relatively small compared to the large emissions generated from landfilling.

To further reduce the climate impact of Mysore's waste management system, the following strategies can be adopted:

- Implementation of landfill gas capture and utilization systems to mitigate methane emissions from existing landfill sites.
- Strengthening waste segregation and material recovery systems to increase recycling rates and reduce the quantity of waste sent to landfills.

Mysore's waste management system demonstrates better diversion of organic waste compared to many Indian cities, but the continued reliance on uncontrolled landfilling limits the potential climate benefits of these practices. Transitioning toward a more integrated circular waste management system, with improved recycling and methane recovery, could significantly reduce the city's overall greenhouse gas emissions.

3.5 Case Study: Tier III City – Tumkur

3.5.1 City profile

Tumkur city is located in the south-eastern part of the state of Karnataka, India, and serves as the administrative headquarters of Tumkur district. The city is situated approximately 70 km northwest of Bengaluru and is well connected by national and state highways. Geographically, Tumkur lies at an elevation of about 822 m above mean sea level, experiencing a semi-arid climatic condition. Tumkur city map is shown in (Fig. 3.8).

Fig. 3.8 Tumkur city map

Tumkur is governed by the Tumkur City Corporation (TCC), which was upgraded from a City Municipal Council to a Municipal Corporation in 2010 (Tumkur city corporation official website). The Corporation consists of 35 administrative wards and covers a total area of 102.9 km^2. Tumkur is an important industrial and educational center in Karnataka. The city has an estimated population of about ~5 lakh.

3.5.2 Waste generation and collection

3.5.2.1 Waste generation

The total municipal solid waste generation in Tumkur city is estimated to be 150 TPD. Collection efficiency is high, typically exceeding 85-90% with an average per capita municipal solid waste generation of 400 g/capita/day. The waste is collected and processed in an integrated solid waste management facility in Vasanthanarasapura, Tumkur.

3.5.2.2 Waste collection and transportation

Tumkur city has an established door-to-door municipal solid waste collection system, with an emphasis on source segregation into wet, dry, and sanitary waste streams. The segregation efficiency is ~60%, which is further improved by 80-85% through secondary manual segregation at the collection and processing stages.

Primary waste collection is carried out using 98 auto-tippers, each with a capacity of 1 m^3, deployed for door-to-door collection across the city. Secondary collection and transportation of waste are facilitated through 25 four-wheeler vehicles, 38 tractors with a capacity of 2-3 tons for roadside and bulk waste transportation, and 10 compactors with capacities ranging from 14 m^3 to 16 m^3. The haulage distance from the city to the waste processing and disposal facilities is ~20-30 km.

3.5.3 Waste processing and resource recovery

3.5.3.1 Dry waste collection centres (DWCC) and material recovery facilities

Dry waste generated from households is collected through door-to-door collection and secondary storage points and transported to dry waste collection centres (DWCCs). In Tumkur, four DWCC units are operational, which are managed by Hasiru Dala. From the DWCCs, the segregated dry waste is transferred to Material recovery facilities (MRFs) for further processing (Fig. 3.9). At these facilities, the incoming dry waste stream undergoes manual and mechanical sorting to recover recyclable fractions such as plastics, paper, cardboard, metals, and glass.

Recovered recyclable materials are dispatched to authorized recycling industries. Specifically, paper and cardboard are sent to licensed paper recyclers, while coconut shells, separated as part of the dry fraction, are supplied to local charcoal manufacturing units in Tumkur. The residual non-recyclable fraction is baled (Fig. 3.10) and processed into RDF, which is transported to cement manufacturing plants (Dalmia cement) for co-processing as an alternative fuel.

Fig. 3.9 MRF facility

Under the existing arrangement, baling equipment is provided by Dalmia Cement, and the baled plastic/RDF is transported over a distance of approximately 550 km to the cement plant for co-processing. The capital cost of baling equipment and transportation costs are borne by the cement manufacturer, while labour costs associated with RDF preparation are covered by TCC.

Fig. 3.10 Bailing unit and bailed materials

In the proposed system, TCC will float tenders for the sale of RDF to cement plants. Under this model, baling and transportation of RDF will be undertaken by TCC, and in return, extended producer responsibility (EPR) credits will be provided to TCC by the cement plants. This approach aims to improve revenue recovery, strengthen institutional control over RDF management, and align municipal operations with national EPR and circular economy frameworks.

3.5.3.2 Composting facility

The city operates centralized composting facilities that primarily treat segregated organic waste using aerobic windrow composting (Fig. 3.11). The process produces stabilized compost, along with rejects and leachate. The installed composting capacity is 200 TPD, while the actual quantity of organic waste generated is 90 TPD, indicating adequate treatment capacity at present. The compost produced is marketed for agricultural applications, whereas composting rejects are transported to nearby landfill for final disposal. Leachate generated is collected onsite.

Fig. 3.11 Windrow composting and processing unit

3.5.3.3 Landfill

The landfill facility is used for the disposal of non-recoverable waste fractions, including mixed waste that cannot be segregated at source or processing facilities, and process rejects from composting operations (Fig. 3.12). These waste streams are disposed of in separate landfill cells, to facilitate improved operational control.

Fig. 3.12 Landfill receiving composting reject

To strengthen resource recovery and reduce landfill dependency, TCC has proposed the development of integrated waste management facilities with the following capacities: Material recovery facility: 50 TPD, Biomethanation plant: 150 TPD (for source-segregated organic waste). Additionally, a leachate treatment plant (LTP) of 3 KLD capacity is proposed.

3.5.4 Material flow analysis

The MFA of MSW in TCC indicates a total waste generation of approximately 150 TPD, of which about 140 TPD (~90%) is collected through the formal municipal system, while 10 TPD (~10%) remains uncollected (Fig. 3.13). Wet waste constitutes the major fraction (90 TPD, ~64%), followed by dry waste (35 TPD, 25%), mixed waste (14 TPD), and sanitary waste (1 TPD). The wet waste stream is entirely directed to composting facilities (90 TPD). The dry waste fraction (35 TPD) is processed at the MRF. Sanitary waste (1 TPD, 0.7%) is separately collected and treated through incineration by Ramky group.

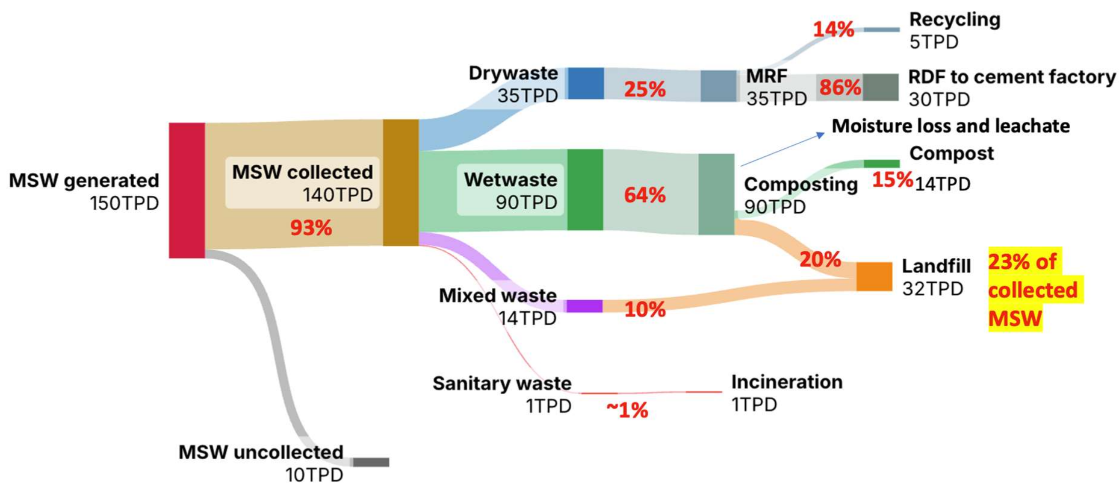


Fig. 3.13 Material flow analysis of municipal solid waste in Tumkur

3.5.5 Life cycle assessment

Tumkur had a net emission of 39, 424 kg CO_2 eq., corresponding to 282 kg CO_2 eq. per ton of municipal solid waste managed**.** The contributions of individual waste treatment processes to the GW are presented in Table 3.3**.** The results indicate that landfilling remains the primary source of emissions, contributing 43,520 kg CO_2 eq. However, the overall impact is significantly lower due to the relatively small fraction of waste sent to landfills (~ 23%). By diverting about 77% of collected waste toward resource recovery pathways, including composting, WTE (cement factories), and recycling, Tumkur minimizes methane emissions associated with landfill disposal.

Among the diversion strategies, RDF sent to cement factories provided the largest climate benefit, contributing -3,720 kg CO_2 eq. Composting (-126 kg CO_2 eq.) and recycling (-250 kg CO_2 eq.) also contribute to emission reductions by recovering nutrients and materials that would otherwise require energy-intensive production processes.

Table 3.3 Global warming (GW) of solid waste management practices in Tumakuru

	Waste processed (tons)	GW (kg CO_2 eq./ton)	GW (kg CO_2 eq.)
Composting	90	-1.4	-126
Cement factory (WTE)	30	-124	-3720
Landfilling	32	1360	43520
Recyclables	5	50	-250
Net emissions			**39424**

Tumkur's waste management system highlights the importance of prioritizing waste segregation and diversion strategies, particularly composting, recycling, and energy recovery, to reduce reliance on landfilling. Further improvements could be achieved through enhanced recycling infrastructure and the introduction of landfill gas recovery systems, which would further lower the city's greenhouse gas emissions and strengthen its transition toward a circular waste management framework.

3.6 Case Study: Delhi (Tier I city)

3.6.1 City Profile

The National Capital Territory (NCT) of Delhi represents one of the largest and most complex urban agglomerations in India, and forms one of the two study areas selected for this project alongside Varanasi. The city is located at approximately 28.61° N latitude and 77.23° E longitude, at an average elevation of about 216 meters above mean sea level, in the Indo-Gangetic plain of northern India. Delhi's semi-arid climate, characterized by hot summers, a monsoon season, and cold winters with frequent winter inversions, has a direct bearing on landfill gas generation, leachate volumes, and ambient air quality, all of which are relevant to the life cycle impact categories assessed in this study.

Delhi's population exceeds 23 million, making it one of the most densely populated metropolitan regions in the world. This scale of population, combined with high rates of in-migration, commercial activity, and a large floating population, translates directly into a correspondingly large and continuously growing municipal solid waste (MSW) generation load, and places sustained pressure on collection, transportation, and treatment infrastructure that has, in several respects, not scaled proportionately. For Municipal Solid Waste (MSW) administration, Delhi is divided into 12 municipal zones under the Municipal Corporation of Delhi (MCD) (Fig. 3.14).

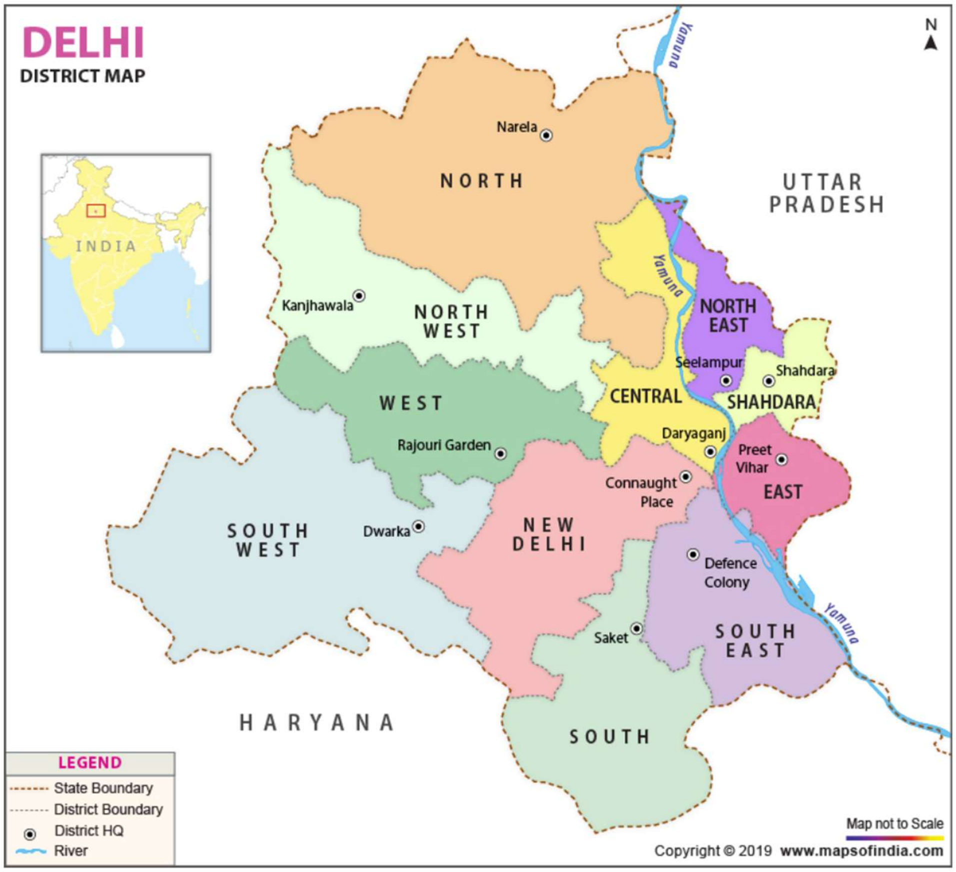


Fig. 3.14 Delhi city map

Solid waste management functions in Delhi are administered by three Urban Local Bodies (ULBs), each governing a distinct jurisdiction:

- Municipal Corporation of Delhi (MCD) formed in May 2022 through the unification of the erstwhile North, South, and East Delhi Municipal Corporations, MCD is by far the largest ULB by area and population served, and is responsible for the bulk of the city's waste generation, collection, and processing infrastructure.

- New Delhi Municipal Council (NDMC) governs the Lutyens' Delhi / New Delhi area, comprising largely government, diplomatic, and low-density residential zones.

- Delhi Cantonment Board (DCB) administers the cantonment area under the Ministry of Defence, a smaller, low-density jurisdiction.

3.6.2 Waste Generation and Composition

Delhi currently generates in excess of 11,000 tons of municipal solid waste per day, with recent official estimates placing the figure at approximately 11,852 TPD (DPCC Annual Report 2024-25), of which the overwhelming majority (~97%) arises within MCD limits, with smaller contributions from NDMC and DCB areas. This generation rate has shown a sustained upward trend over the past decade, driven by population growth, rising consumption, and urban expansion into peripheral areas.

Waste composition in Delhi is dominated by biodegradable organic matter, which constitutes approximately 50–60% of the total waste stream by weight, largely kitchen and food waste, garden/horticultural waste, and market waste. This high organic fraction is a critical determinant of the city's methane generation potential at landfills and underpins the LCA modelling of both current disposal pathways and diversion-based alternatives (composting, bio-methanation, WTE) examined in Chapter 5.

The remaining waste stream comprises recyclable fractions, plastics, paper and cardboard, glass, and metals, together with a smaller proportion of inert materials and construction and demolition (C&D) debris. A significant share of the recyclable fraction is informally recovered prior to reaching municipal collection points, through source-level segregation by waste pickers and the informal kabadiwala network, which has important implications for the accuracy of formally reported composition data and for LCA system boundary allocation.

Table 3.4 Indicative composition of Delhi's MSW stream (as provided for this study)

Waste Fraction	Approximate Share (% by weight)	Relevance to LCA
Biodegradable organics	50–60%	Landfill methane generation; feedstock for composting/bio-methanation
Plastics	included within recyclables	Recovery/recycling credits; WTE calorific contribution
Paper and cardboard	included within recyclables	Recycling credits; combustible fraction
Glass and metals	included within recyclables	Material recovery credits
Inerts / C&D debris	smaller residual share	Landfill inert mass; low emission relevance

3.6.3 Waste Collection and Transportation

Door-to-door collection has been extended across Delhi and is officially reported at 100% coverage across all three ULBs (Delhi Economic Survey, 2025–26), representing significant progress from historical open-dumping and community-bin-based systems. Collected waste is typically consolidated at Dhalaos (community collection points) and Material Recovery/Transfer Stations before onward transport by compactor vehicles and larger transport trucks to processing facilities or landfill sites.

Source segregation into wet, dry, and hazardous/domestic-hazardous fractions remains only partially implemented. While segregation is mandated under the Solid Waste Management Rules, 2016, actual compliance varies considerably across wards and housing typologies, and a substantial share of the waste stream continues to arrive at processing facilities as mixed waste.

Vehicles involved in MSW collection and transportation are JCB/Loader – 35, Hook Loaders – 184, Tripping Trucks – 40, Auto Tippers – 2543, Cycle/Tricycle – 429, E-Rickshaw – 909, Maintenance vans – 12. Nearly 93% collections were done using motorized vehicles, and the total running length was estimated to be 6000 km. 100% mechanical lifting was done using End Loaders/ Top Loaders/ Refused Compactors.

3.6.4 Waste Processing and Disposal Infrastructure

Delhi's waste processing infrastructure is a mix of centralized Waste-to-Energy plants, composting and bio-methanation facilities, material recovery facilities, and three legacy landfill sites that continue to receive both fresh and legacy waste. As of the most recent official assessment, the city's total installed processing capacity stands at approximately 7,641 TPD against a generation load of approximately 11,862 TPD a processing gap of roughly 4,200 TPD that is currently absorbed largely through landfilling of untreated waste.

3.6.4.1 Material Recovery Facilities (MRFs)

Formal MRFs in Delhi operate primarily at a decentralized, ward or zone level, together handling on the order of ~90 TPD of recyclables (paper, plastics, metals, glass) recovered from the dry waste stream. A substantial additional volume of recyclable material is recovered informally by waste pickers and the kabadiwala network at multiple points along the value chain at source, at community bins, at transfer stations, and at landfill faces before it is captured in formal municipal accounting. This informal recovery sector, while economically significant and environmentally beneficial in diverting recyclables, introduces uncertainty into formally reported composition and recovery-rate data and is addressed as a data-quality consideration in the LCA inventory.

3.6.4.2 Composting

Centralized composting capacity includes a compost plant at Bawana with a design capacity of approximately 700 TPD, at Okhla with a design capacity of approximately 1000 TPD and supplemented by a network of decentralized community/ward-level compost pits approximately 257 in number collectively processing around 558 TPD of segregated organic waste into compost (Fig. 3.15). Bio-methanation facilities, which convert segregated organic waste into biogas for energy recovery, form a smaller but growing component of the organic-waste treatment portfolio, consistent with the integrated solid waste management model being scaled up under facilities such as the Narela-Bawana Integrated Solid Waste Management Facility.

Fig. 3.15 Composting plant at Bawana, New Delhi

3.6.4.3 Waste-to-Energy (WTE) Plants

WTE incineration is currently the dominant processing route for Delhi's mixed and residual waste stream. Four WTE plants are presently operational at Okhla, Ghazipur, Bawana, and Tehkhand with a combined installed capacity of approximately ~6,100 TPD, together accounting for the majority of the city's formally processed waste and associated power generation (Fig. 3.16). Recent policy announcements indicate substantial planned capacity expansion: a new 3,000 TPD facility proposed at Narela-Bawana (targeted for completion by December 2027), a new 2,000 TPD facility proposed at Ghazipur (targeted for December 2028), and capacity expansions of 1,000 TPD each at the existing Okhla and Tehkhand plants (targeted by 2027), together intended to add approximately 7,750 TPD of new processing capacity over the coming years.

Fig. 3.16 WTE plant at Bawana, New Delhi

3.6.4.4 Landfills and Legacy Waste

Delhi's three major landfill sites, Ghazipur, Bhalswa, and Okhla, together represent one of the most severe legacy waste burdens of any Indian city (Fig. 3.17). All three sites were declared overfilled more than a decade ago but have continued to receive waste due to the absence of adequate alternative processing capacity, and all three are the subject of active, NGT-monitored biomining and remediation programmes.

Table 3.5 Status of Delhi's three legacy landfill sites (Source: DPCC annual reports and public disclosures, 2025–26)

Landfill	Established	Approx. Area	Approx. Height	Status (2026)
Ghazipur	1984	~70 acres	~65 m (213 ft)	Reached capacity in 2002; Phase-II biomining in progress; ~66.7 lakh MT waste remaining (mid-2026); processing being scaled toward 12,000 TPD; full clearance targeted by 2027–28
Bhalswa	1994	~70 acres	~60–62 m (200–203 ft)	Declared overfilled in 2006 but still receiving waste; biomining underway; full site clearance targeted by December 2026

Landfill	Established	Approx. Area	Approx. Height	Status (2026)
Okhla	1996	~62 acres	—	Legacy waste under active biomining alongside co-located WTE and compost plant operations

Biomining operations mechanized excavation, screening, and segregation of aged waste into recoverable fractions (soil-like material, combustibles/RDF, recyclables, and inert reject) are the principal legacy waste remediation strategy being pursued at all three sites, consistent with NGT directives that biomining be adopted in preference to simple capping. Land reclaimed through biomining is being progressively repurposed; the MCD has, for instance, invited proposals for the redevelopment of reclaimed land into parks and other public amenities. Nonetheless, considerable legacy volumes remain tens of lakh metric tons at Ghazipur alone as of mid-2026, and all three sites continue to pose active environmental and public health risks, including landfill fires, leachate contamination of adjoining groundwater, and fugitive methane emissions, pending full remediation.

Leachate generation and management at these sites is a particular concern given Delhi's monsoon-driven rainfall pattern and the high organic content of both fresh and legacy waste; uncontrolled leachate migration has been documented to affect groundwater quality in the vicinity of these landfills.

Fig. 3.17 Landfill site in Ghazipur, New Delhi

3.6.5 Material Flow analysis

Delhi generates nearly 11320 TPD of MSW (as per annual reports of DPCC 2023-24), of which 100% is collected through formal collection system. Nearly 74% of total waste generated is processed through four major treatment route: WTE (54%), Composting (17%), MRF (<1%), Bio-methanation (<1%) and nearly 40% waste is landfilled (Fig. 3.18). In the dry waste fraction approximately 6000 TPD is sent to 4 major WTE plants and generating nearly 80 MW of electricity from them and 800 TPD of bottom ash. The total wet waste collected, approximately 2000 TPD is processed through composting process. This treatment facility nearly generates 450 TPD of compost which is further utilized as fertilizer. In addition, nearly 50 TPD of wet waste is sent to bio-methanation facility, with individual capacity of 5 TPD.

The material flow analysis highlights nearly 40% of total generated waste is continued to be sent to landfill facilities. Despite having various treatment routes and multiple recovery pathways nearly half of the generated waste is still sent to landfill. This highlights the urgent need for better segregation frameworks to prevent diversion of waste to landfill sites.

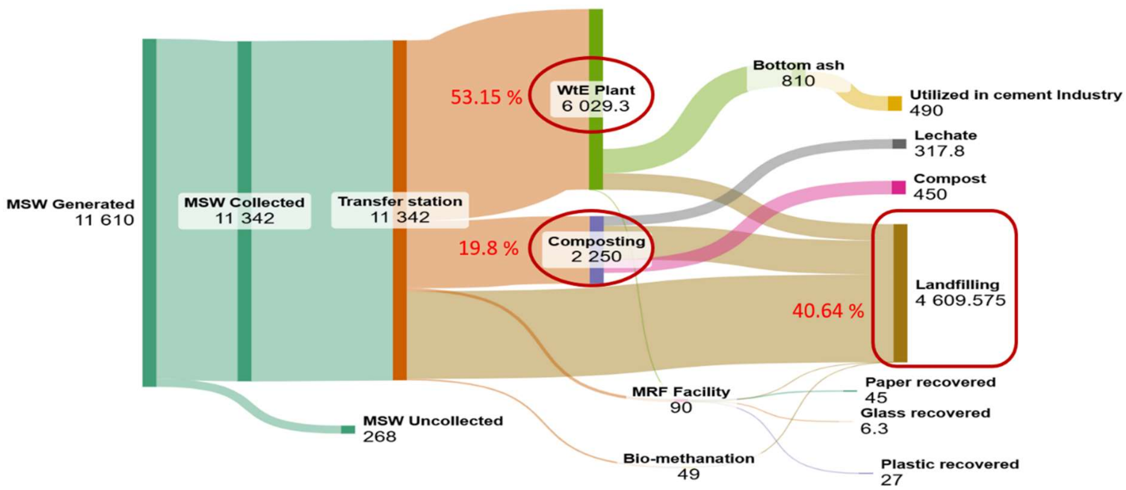


Fig. 3.18 Material Flow Analysis of current waste management practices in Delhi

3.6.6 Life Cycle Assessment

A comparative life cycle assessment (LCA) was performed to examine the environmental implications of two municipal solid waste (MSW) management configurations implemented for the Delhi region. The first configuration served as the reference (baseline) scenario 1, in which the environmental impacts arising from waste collection, transportation, treatment, and final disposal were assessed without considering the environmental benefits associated with resource recovery. In contrast, the second configuration (scenario 2) adopted a system expansion approach by integrating avoided burden credits resulting from resource recovery activities. These credits included electricity generated from waste-to-energy (WTE) and bio-methanation facilities, the substitution of chemical fertilizers through compost produced in composting plants, and the replacement of virgin raw materials through material recovery at material recovery facilities (MRFs).

The comparative evaluation demonstrated that incorporating avoided burden credits substantially improved the overall environmental performance of the MSW management system. Recovering energy, recyclable materials, and organic nutrients effectively compensated for a considerable portion of the environmental burdens associated with waste treatment and disposal processes. These findings highlight that transitioning from a disposal-oriented system toward an integrated resource recovery framework can significantly enhance environmental sustainability. Such an approach is consistent with circular economy principles, where waste is increasingly regarded as a valuable secondary resource capable of reducing dependence on primary materials and conventional energy sources.

The climate change assessment further revealed that the implementation of resource recovery strategies considerably lowered the net greenhouse gas (GHG) emissions of the waste management system. Electricity generated (80 MW) from WTE and bio-methanation facilities displaced electricity supplied by the conventional power grid, resulting in an overall reduction of approximately 25% in GHG emissions. Similarly, the utilization of compost in agricultural applications reduced emissions from composting operations by nearly 50%, primarily because compost replaces synthetic fertilizers while contributing additional carbon to soils. The largest environmental benefit was observed for landfill operations, where the capture and utilization of landfill gas (LFG) reduced GHG emissions by nearly 75% through methane recovery and energy generation. Considering methane possesses a substantially higher global warming potential than carbon dioxide, preventing its direct atmospheric release markedly improved the climate performance of the landfill system. These results collectively demonstrate that integrating energy recovery, nutrient recycling, and methane capture technologies can substantially reduce the carbon footprint of municipal solid waste management.

Table 3.6 Global Warming Potential (GWP) contribution of MSW management technologies

Waste Management Strategy	Waste Processed (TPD)	Scenario 1 GWP (kgCO2eq.)	Scenario 2 GWP (kgCO2eq.)
WTE	6023	~ 6 x 10^6	~ 4.5 x 10^6
Composting	2250	~ 2 x 10^6	~ 1 x 10^6
MRF	90	~ 1.1 x 10^3	~ - 0.5 x 10^3
Landfilling	2930	~ 7 x 10^6	~ 1.75 x 10^6

The environmental benefits of resource recovery extended beyond climate change mitigation. Across all assessed impact categories, the second scenario consistently exhibited lower environmental burdens than the baseline configuration. Electricity recovery from WTE and bio-methanation facilities reduced emissions associated with conventional fossil fuel–based electricity generation, thereby lowering acidification potential (AP) and eutrophication potential (EP). Likewise, recycling activities carried out through MRFs decreased the extraction and processing of virgin raw materials, leading to reductions in abiotic depletion potential (ADP; elements, kg Sb eq.) together with the environmental impacts associated with upstream manufacturing processes. The agricultural application of compost further reduced AP and EP by decreasing the production and consumption of synthetic fertilizers. Additionally, lower fossil fuel consumption, reduced demand for primary resource extraction, and improved emission control during waste treatment contributed to a decline in human toxicity potential (HTP; kg DCB eq.). Overall, the findings indicate that integrating resource recovery into MSW management systems provides not only substantial reductions in greenhouse gas emissions but also broaden environmental improvements across multiple life cycle impact categories. Consequently, resource-efficient waste management strategies offer a more sustainable pathway for metropolitan regions such as Delhi, where increasing waste generation necessitates environmentally optimized treatment systems.

3.7 Case Study: Varanasi (Tier II city)

3.7.1 City Profile

Varanasi is a city of historical and cultural importance in Uttar Pradesh, India. It spread over an area of 1,535 square kilometres and has an estimated population of 16 lakh people. Varanasi is located on the banks of the sacred Ganges River at 25.3176° N latitude and 82.9739° E longitude. This city is around 80.71 meters (265 feet) above sea level having a unique climate and topography. Varanasi experiences a humid subtropical climate, defined mainly by three distinct seasons: summer, monsoon, and winter (https://www.thecivilindia.com). Summers span from March to June and are generally characterised by scorching heat and arid conditions, where temperature frequently surpassing 40°C (104°F). The city receives an average of approximately 1,100 millimetres (43 inches) of precipitation during the monsoon season, spans from July to September. Most of the annual rainfall occurs during this period, with elevated humidity and sometimes flooding. Winters are comfortable compared to the hot summers, lasting from December to February. The average temperature during the winter months is between 5°C (41°F) and 15°C (59°F).

The Varanasi Municipal Corporation, responsible for municipal administration and infrastructure development in Varanasi. The municipal corporation has divided the city into five zones, each with 14 sub-zones and 100 wards (Rai, 2017). The map of the different zone divided by Varanasi municipal corporation is given in (Fig. 3.19).

Fig. 3.19 Varanasi city map

3.7.2 Waste Generation and Composition

As per the estimate by the municipal corporation, waste generation rate at Varanasi is 1070 Tons per Day (TPD), out of which approximately 950 TPD waste is collected each day and processed through various pre-installed solid waste treatment facilities. Majority of fresh waste are biodegradable in nature (51%), and 15% are recyclable in nature other are categorized as 34% of the total waste. Food and kitchen waste are the major contributors in the fresh waste profile at Varanasi. The composition of the fresh waste are provided in the (Fig. 3.20).

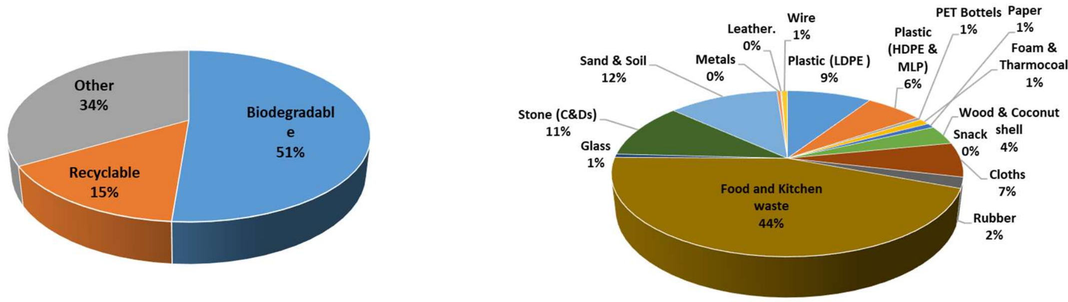


Fig. 3.20 Fresh waste profile at Varanasi

3.7.3 Waste Collection and Transportation

The waste is collected mainly door-to-door (D2D) collection. Sweeping & collection of wards and lifting of waste/garbage is done generally in two shifts: 06:00 AM to 02:00 PM. and 10:00 PM to 06:00 AM. The duty roster is designed in such a way that the D2D, sweeping & collection daily and swept twice every day. Waste/garbage, collected from the wards, from open points is transported by wheelbarrow and tricycle and unloaded into Auto Tippers (Tata Ace) to transfer station in each ward.

3.7.4 Waste Processing and Disposal Infrastructure

In Varanasi, solid waste processing infrastructure is an integration of centralized Waste-to-charcoal plants, composting and 3 bio-methanation facilities, 2 material recovery facilities, and one legacy landfill site that continues to receive both fresh and legacy waste. As of the most recent official assessment, the city's total installed processing capacity stands at approximately 1240 TPD against a generation load of approximately 950 TPD a processing gap of roughly 190 TPD that is currently absorbed largely through landfilling of untreated waste.

3.7.4.1 Material Recovery Facilities (MRFs)

Formal MRFs in Varanasi operate primarily at a decentralized, ward or zone level, together handling of ~25 TPD of recyclables (paper, plastics, metals, glass) waste recovered from the dry waste stream (Fig. 3.21). Waste pickers recover a substantial additional volume of recyclable material informally and the *kabadiwala* network at multiple points along the value chain at source, at community bins, at transfer stations, and at landfill faces before it is captured in formal municipal accounting. This informal recovery sector, while economically significant and environmentally beneficial in diverting recyclables but introduces uncertainty into formally reported composition and recovery-rate data. This addressed as a data-quality consideration in the LCA inventory in life cycle assessment study.

MRF facility

Fig. 3.21 MRF facility at Varanasi

3.7.4.2 Composting

Centralised composting capacity includes a compost plant at Karsara with a design capacity of approximately 900 TPD waste intake (Fig. 3.22). It produces about 25 TPD of compost at Karsara. Most of the RDF is sent to the various cement factories as well as waste to the charcoal plant.

Karsara composting plant

Fig. 3.22 Composting facility and RDF collection at Varanasi

3.7.4.3 Bio-methanation

Varanasi city have three Bio-methanation facilities, which convert segregated organic waste into biogas for energy recovery. Approximately, 10kwh/day electricity is generated from each plant in operating condition. This is a smaller (5 TPD each) but growing component of the organic-waste treatment portfolio producing small amount of compost (Fig. 3.23).

Biomethanization plant

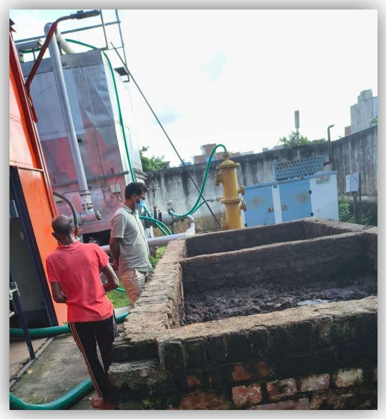


Fig. 3.23 Bio-methanization facility

3.7.4.4 Waste-to-charcoal (WTE) Plants

Waste to charcoal plant is currently the dominant processing route for Varanasi's mixed and residual waste stream. One waste-to-charcoal plant is presently operational Ramana, with an installed capacity of approximately 600 TPD, accounting for the majority of the city's formally processed waste to charcoal conversion (Fig. 3.24). Ultimately used as a fuel for power generation, co-fired in thermal power plants.

NTPC WtE plant

Fig. 3.24 WTE facility and RDF collection at Varanasi

3.7.4.5 Landfills and Legacy Waste

Varanasi’s major landfill sites are near Kasarda. This site has continued to receive waste due to the absence of adequate alternative processing capacity. Biomining operations involve mechanised excavation, screening, and segregation of aged waste into recoverable fractions (soil-like material, combustibles/RDF, recyclables, and inert reject). The principal legacy waste remediation strategy is being pursued at the sites, at the plant, and at the nearby site. The

Municipal Corporation has invited proposals for the redevelopment of reclaimed land into other activities. Nonetheless, considerable legacy volumes remain, and the sites continue to pose active environmental and public health risks, including landfill fires, leachate contamination of adjoining groundwater, fugitive methane emissions, and odour.

Leachate generation and management at these sites is a particular concern given Varanasi's monsoon-driven rainfall pattern and the high organic content of both fresh and legacy waste; uncontrolled leachate migration has been documented to affect groundwater quality in the vicinity of these landfills.

3.7.5 Material Flow analysis

Varanasi generates nearly 1070 TPD of MSW, of which ~90% is collected through formal collection system. Nearly 74% of total waste generated is processed through 4 major treatment route: WTE (38%), Composting (18%), MRF (<1%), Bio-methanation (<1%) and nearly 41% waste is landfilled (Fig. 3.25).

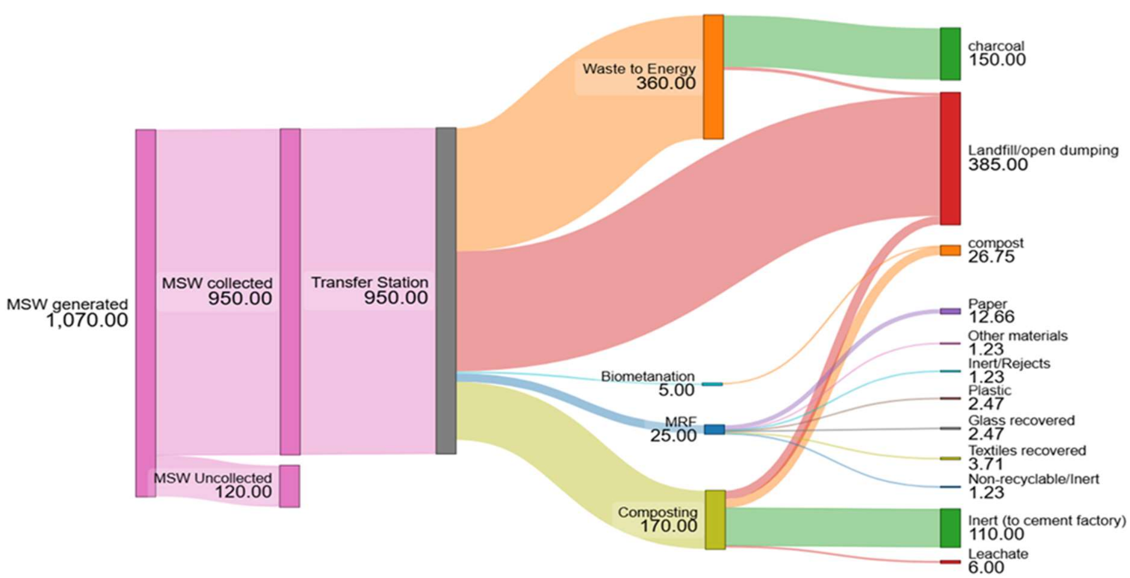


Fig. 3.25 Material Flow Analysis of current waste management practices in Varanasi

In the dry waste fraction approximately 360 TPD is sent to WTE plants and generating coal nealy 150 TPD. The total wet waste collected, approximately 170 TPD is processed through composting process. This treatment facility nearly generates ~26 TPD of compost which is further utilized as fertilizer. In addition, nearly 5 TPD of wet waste is sent to bio-methanation facility, with individual capacity of 5 TPD.

The material flow analysis highlights that nearly 41% of total generated waste continues to be sent to landfill facilities. Despite having various treatment routes and multiple recovery pathways nearly half of the generated waste is still sent to landfill. This highlights the urgent need for better segregation frameworks to prevent diversion of waste to landfill sites.

3.7.6 Life Cycle Assessment

The life cycle assessment of aggregated solid waste treatment facilities at Varanasi is being done. Which estimated that, the total global warming potential (GWP100) of the waste management system is approximately 5.2×10^5 kg CO_2-eq. for per day. In this result the cumulative climate change impact of all waste treatment and transportation processes considered in the LCA. Where the total impact is the sum of emissions generated throughout waste collection, transportation, treatment, and final disposal.

Landfilling is the largest contributor to the total GWP, contributing approximately 2.6×10^5 kg CO_2-eq., accounting for nearly 50% of the overall climate change impact. The waste-to-energy (including charcoal formation and burning) process represents the second highest contributor, with an estimated impact of approximately 1.9×10^5 kg CO_2-eq. Composting contributes a comparatively small fraction of the overall GWP (approximately 2–3 $\times 10^4$ kg CO_2-eq.). The impacts from truck-trailer transportation are relatively insignificant compared with treatment processes.

The total acidification potential (AP) of the MSWM system is approximately 84 kg SO_2-equivalent. This represents the cumulative contribution of all activities involved in waste collection, transportation, treatment, electricity consumption, and auxiliary operations.

The total eutrophication potential (EP) of the MSWM system is approximately 52 kg PO_4^{3-}-eq., representing the cumulative contribution of all processes involved in waste collection, transportation, treatment, and disposal. The landfilling process is the largest individual contributor, with an impact of EP approximately 20 kg PO_4^{3-}-eq., accounting for nearly 40% of the total eutrophication potential. Composting contributes approximately 12–13 kg PO_4^{3-}-eq., making it the second largest contributor.

The total Human Toxicity Potential (HTP) of the MSWM system is approximately 840 kg 1,4-DCB eq., representing the cumulative toxic burden associated with waste collection, transportation, electricity consumption, treatment, and other supporting operations.

Overall, the study suggests that the environmental performance of Varanasi's MSWM system can be significantly improved through enhanced source segregation, reduced landfill dependency, expansion of composting and anaerobic digestion facilities. The optimization of waste transportation logistics, improved landfill gas and leachate management, and increased utilization of renewable energy sources can also play a significant role in total emissions. Such integrated interventions would reduce environmental burdens across multiple impact categories while supporting the transition toward a circular economy and sustainable urban waste management.

3.8 Case study: Chennai (Tier I city)

3.8.1 City Profile

Chennai (formerly Madras) is the capital and largest city of Tamil Nadu, India, situated on the Coromandel Coast of the Bay of Bengal at approximately 13.08°N, 80.27°E on the predominantly flat Eastern Coastal Plains, with an expanded municipal area of 426 km^2 and mean elevation around 7 m above sea level. Its urban hydrology is organized around the Cooum and Adyar rivers traversing the core city, the Kosasthalaiyar along the northern fringe, and roughly 24.9 km of low-lying coastline that is highly exposed to cyclonic storm surges and monsoon-induced inundation. According to the 2011 Census, the expanded city area (426 km^2) contained 6.75 million inhabitants and an urban agglomeration of about 8.70 million, with recent projections indicating a metropolitan population exceeding 10 million by 2026. Meteorologically, Chennai exhibits a tropical savanna climate, with mean daily maximum temperatures on the order of 29–37 °C, minimum temperatures of 21–28 °C, historical extremes reaching 45 °C, and average annual rainfall of approximately 1,200–1,400 mm, predominantly received during the northeast monsoon (October–December) when cyclonic systems from the Bay of Bengal are frequent.

Administratively, Chennai is governed by the Greater Chennai Corporation (GCC), India's oldest municipal body, which currently manages an expanded urban area of about 426 km^2, subdivided into 15 zones (Thiruvottiyur to Sholinganallur) and 200 wards, grouped into three regional deputy commissioner jurisdictions: North, Central and South. At the metropolitan scale, spatial planning and development control are undertaken by the Chennai Metropolitan Development Authority (CMDA), which acts as the statutory planning authority for the wider Chennai metropolitan area beyond the corporation limits. Recent state-level policy decisions propose restructuring GCC into 20 zones and increasing the number of wards to around 250 through integration of additional suburban panchayats, although these changes remain in the implementation and notification phase as of mid-2026. (Fig. 3.26) shows zonal map of Chennai corporation locating few major solid waste management facilities.

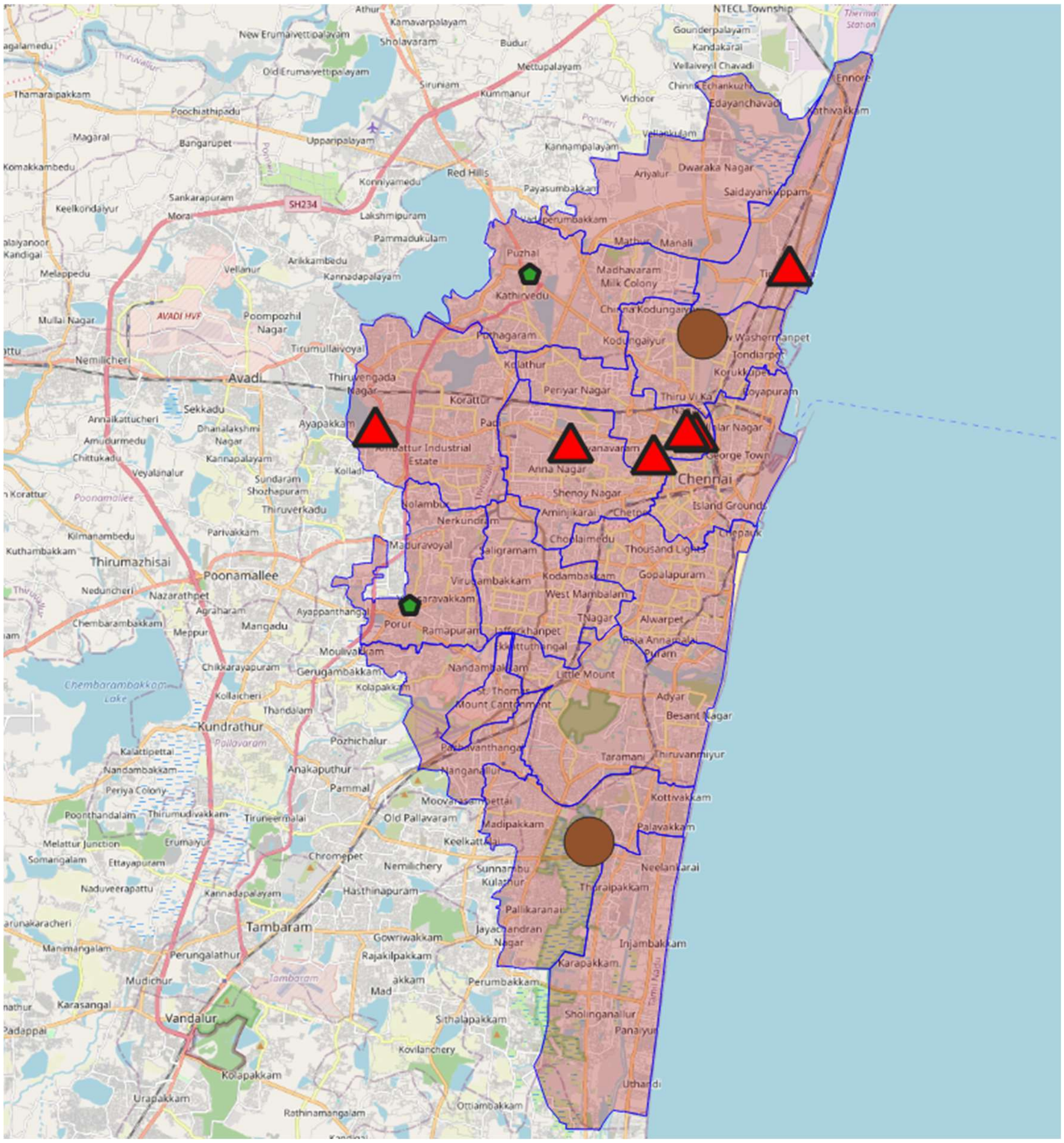
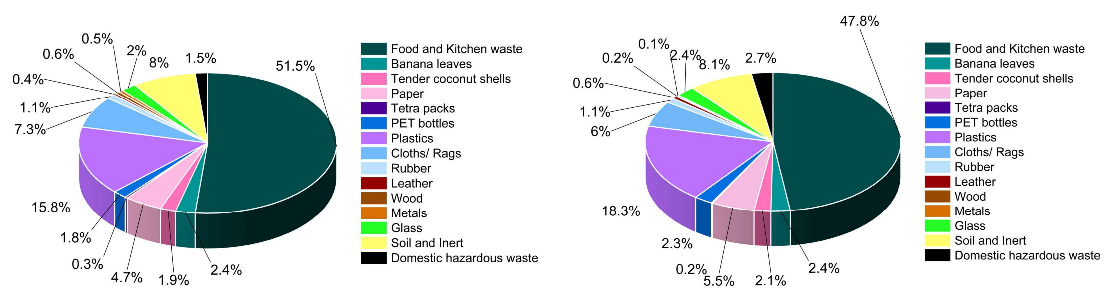


Fig. 3.26 Chennai city map

3.8.2 Waste Generation and Composition

Recent assessments indicate that the GCC generates on the order of 5,000–7,600 TPD of MSW, with official baselines around 6,000 TPD (Tamil Nadu Pollution Control Board) and more recent studies reporting 5,600–5,700 TPD and up to ~7,600 TPD when including all streams reaching disposal and processing facilities. This corresponds to a per capita MSW generation of approximately 0.6–0.7 kg/cap/day, yielding annual city-wide waste quantities of roughly 1.8–2.0 million tons. Physical and chemical characterization studies consistently show a waste composition dominated by biodegradable/organic (wet) fraction of about 50–55%, followed by recyclables (paper, plastics, metals, glass) at ~23%, inert and construction–demolition waste at ~20%, and sanitary/domestic hazardous waste at ~5%, with bulk waste moisture content around 45–55% and bulk density typically in the range 400–450 kg/m³ (Fig. 3.27).



a) Kodungaiyur b) Perungudi

Fig. 3.27 Composition of waste from sites a) Kodungaiyur and b) Perungudi

3.8.3 Waste Collection and Transportation

In Chennai's current waste management system, waste collection and transportation operates through distinct pathways based on waste type and source. Wet waste such as vegetable scraps and eggshells is collected using batter operated vehicles (BOVs) and deposited at MCC (Material Collection Centers) points, while rejected organic materials are transported to local segregation sites using the same vehicles for further processing at windrow facilities. Unsegregated waste from households is collected in RC (Resident Collection) bins distributed across service limits by BOV drivers and is routinely cleared daily using refuse compactors and sterilized with disinfection equipment before being directed to dump yards. Dry waste is processed through RRC (Resource Recovery Centers) where saleable materials are separated, while non-saleable plastic waste, RDF, and coconut waste are stored in temporary pits and subsequently transported to bailing plants, incinerators, and coconut waste processing centers respectively. Hazardous waste collected at RRC points is periodically transported to designated DHW (Domestic Hazardous Waste) centers on a weekly basis, while hazardous items like sanitary napkins and diapers are directed to incinerators. For commercial areas, waste collection employs a combination of LMVs (Light Motor Vehicles) and HMVs (Heavy Motor Vehicles), with large vegetable markets covered daily and smaller shops covered weekly; pure vegetable and food waste from commercial sources are directly transferred to bio-CNG plants, while bulk biodegradable and horticulture waste are directed to windrow facilities and briquetting plants respectively.

Despite reported collection efficiencies of ~90–95% and near-universal door-to-door collection, a substantial portion of this mixed and partially segregated waste stream continues to be transported to legacy dump sites at Kodungaiyur and Perungudi, while increasing fractions are diverted to micro-composting, biomethanation, dry-waste recovery, C&D recycling, and proposed waste-to-energy facilities

3.8.4 Waste Processing and Disposal Infrastructure

3.8.4.1 Windrow Composting

The windrow facility in Chennai is a government-owned facility located in the Madhavaram region with a design capacity of 100 tons per day (Fig. 3.28). Currently, the facility is operationally active and processing an average of 110.38 tons of organic waste daily which indicates it is operating beyond its design capacity. The facility is primarily utilized to manage bulk horticulture and vegetable waste from commercial markets and RRC.

Fig. 3.28 Windrow composting plant at Madhavaram

3.8.4.2 Biomethanation plant

Two centralized bio-CNG units are currently under operation in the Madhavaram and Chetpet areas of Chennai city (Fig. 3.29). These units are privately owned and each has a design capacity of 100 tons per day. Collectively, these two facilities are handling 132.13 tons of selected wet waste on a daily basis indicating efficient operational capacity utilization. Additionally, small-scale biogas plants in zones 5, 6, 7, 9, 10, and 12 are handling an average of 11.11 tons, and bio-methanation plants in zones 5, 6, and 8 are handling an average of 20.2 tons of wet waste daily.

Fig. 3.29 Biomethanation plant (SWMS Pvt. Ltd.), Chetpet

3.8.4.3 Horticulture waste briquetting plant

The private and government-owned briquetting plants located at two locations in Chennai city have a combined design capacity to handle 152 tons of garden waste per day. Currently, the city generates an average of 107.15 tons of garden waste daily indicating that the facilities are operating below full design capacity.

3.8.4.4 Tender coconut waste processing plant

The centralized tender coconut waste processing facility in Chennai is well-equipped with three interconnected shredders supported by automatic conveyors. On an average, these facilities (both centralized and decentralized combined) handle approximately 119 tons of coconut waste daily

3.8.4.5 Incineration plant

Chennai city has three incinerator plants located at different strategic locations Kodungaiyur (50 TPD), Manali (10 TPD), and Marina beach (5 TPD) (Fig. 3.30). These incinerators are currently operational and collectively handling an average of 16.48 tons of Refuse-Derived Fuel (RDF) and 3.99 tons of sanitary napkins and diapers on a daily basis. The largest incinerator (50tons capacity) is equipped with supplementary equipment including Trommel screen, shredder, heat recovery system, and stack emission monitoring systems. However, the other two plants lack some of these advanced systems but possess the necessary equipment to efficiently burn waste.

Fig. 3.30 Incineration plant at Koyambedu

3.8.4.6 Bailing plant

Specialized bailing plants are located near MCC and RRC centres at four locations (Madhavaram, Basinbridge, Pallikaranai, and Otteri) in Chennai city. These facilities have a combined capacity to handle 79.5 tons of plastic waste per day, with each unit handling approximately 1.5 to 8.5 tons of waste daily. Currently, an average of 50.15 tons of plastic waste is being processed daily showing that these facilities are operating well below their maximum capacity.

3.8.4.7 Pyrolysis plant

A privatized pyrolysis plant with a design capacity of 20 tons per day is currently undergoing testing in the Manali area of Chennai city. Although the plant has not yet commenced into full-fledged operations, the responsible team is working towards efficient optimization of the process. The plant aims to convert plastic waste into valuable products, particularly pyrolysis oil

3.8.4.8 Landfills and legacy waste

Perungudi and Kodungaiyur together originally held about 94 lakh tons of legacy waste, with roughly 27–30 lakh tons at Perungudi and 66.5 lakh tons at Kodungaiyur spread over about 477 acres of filled area. Between 2022 and late 2025 the GCC processed 48.41 lakh tons via biomining, reclaiming about 100.29 acres at the two dump yards for greening and future waste-management facilities. An updated February 2026 release reported 52.64 lakh tons cleared from both sites, with around 26.14–26.35 lakh tons removed at Perungudi and roughly

26.5 lakh tons at Kodungaiyur, and biomining of the remaining waste continuing in second-phase packages (Praveena S. A., 2026).

3.8.5 Material Flow Analysis

The Sankey diagram (Fig. 3.31) summarizes Chennai's municipal solid waste flows at around 6,100 TPD, of which approximately 5,700 tons are collected and about 400 tons remain uncollected or leak from the system. Of the collected stream, about one quarter (1,396 TPD) is segregated at source and three quarters (4,306 TPD) remain mixed, yielding a combined composition of roughly 2,916 TPD wet, 2,194.93 TPD dry, 520.48 TPD inert and 70.59 TPD domestic hazardous waste. Only modest fractions of the wet and dry streams are processed through resource-recovery routes (micro-composting, windrow composting, bio-CNG, coconut/garden waste treatment, RRCs, baling, incineration and pyrolysis), while the dominant pathway remains disposal, with around 2,329.85 TPD of wet residues and 1,904.31 TPD of dry residues sent to landfill, together with nearly all inert and hazardous fractions. In total, roughly 4,754.64 TPD of residual waste is landfilled, split between Kodungaiyur (≈2,204 TPD) and Perungudi (≈2,550.64 TPD), highlighting a system that is still strongly landfill-dependent despite the presence of multiple recovery and treatment options.

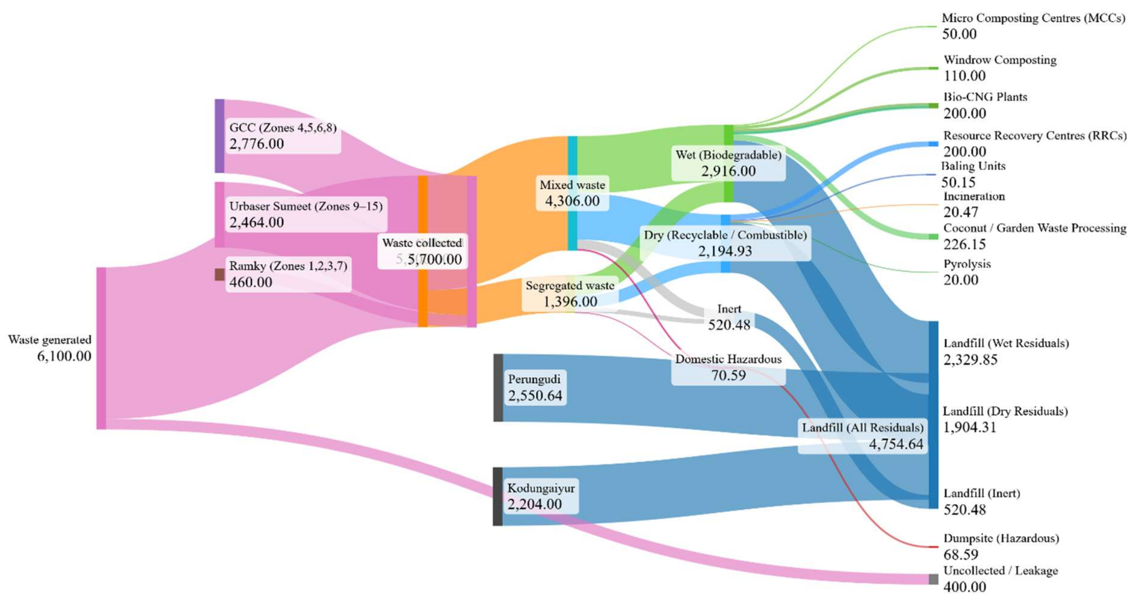


Fig. 3.31 Material flow analysis of current waste management practices in Chennai

3.8.6 Life Cycle Assessment

The LCA of the selected solid waste management facilities available in the city which includes 2 biomethanation plants of 100 TPD and a composting plant of 110 TPD. Table 3.7 reports the global warming contribution associated with selected solid waste management, expressed per ton of waste treated and as net daily emissions for the corresponding facility capacities. Composting of 110 TPD of organic waste exhibits a negative specific GWP of -5.62 kg CO_2-eq./ton, yielding a net climate benefit of -562 kg CO_2-eq., which reflects avoided emissions due to displacement of synthetic fertilizers and reduced methane generation compared to unmanaged decomposition. In contrast, biogas plants configured for transportation fuel and cooking fuel each treat 100 TPD, but show positive GWPs of 46.34 and 51.76 kg CO_2-eq./ton, respectively, corresponding to net burdens of 4,634 and 5,176 kg CO_2-eq.

However, the two open dump–type landfill sites at Kodungaiyur and Perungudi are major point sources of greenhouse gas emissions from the city's solid waste sector, primarily through methane generation from the large biodegradable fraction disposed there. GWP associated to landfill was taken 1110 kg CO_2 eq./ton (Madhavaraj and Karthikeyan, 2025). Landfill clearly dominates the city's waste-related global warming burden, contributing more than an order of magnitude higher emissions than any single alternative facility. This quantification underscores that continued reliance on Kodungaiyur and Perungudi for bulk disposal of mixed MSW is the principal driver of climate impacts in Chennai's waste management system and that meaningful mitigation requires substantial diversion of biodegradable waste away from these sites toward lower-GWP options such as well-managed composting and optimized biogas utilization.

Table 3.7 Global warming (GW) contribution of solid waste management processes in Chennai

Facility	Waste quantity (TPD)	GWP kg CO_2 eq./ton	Net GWP kg CO_2 eq.
Composting	110	-5.62	-562
Biogas plant (Transportation fuel)	100	46.34	4634
Biogas plant (Cooking fuel)	100	51.76	5176
Landfill	4700	1110	5217000

3.9 Discussion

Previous LCA studies on MSW management in Indian cities have consistently identified landfilling as the dominant contributor to GHG emissions, primarily due to uncontrolled methane release. Babu et al. (2014) conducted one of the early LCA-based assessments for Bangalore and demonstrated that extensive reliance on land disposal significantly increased the environmental burden of the city's waste management system. Similarly, Sughosh et al. (2019) highlighted that although recycling and composting practices in Bangalore contributed to emission reductions, the climate benefits were largely offset by the high fraction of waste disposed of in unmanaged landfills. At the national scale, Khandelwal et al. (2019) reported that increasing diversion of organic waste through composting, anaerobic digestion, and waste-to-energy systems could substantially reduce the carbon footprint of MSW management in India compared to conventional landfilling practices. Sharma and Chandel (2017), in their assessment of Mumbai, also observed that landfill disposal remained the largest source of emissions, while integrated systems incorporating recycling and energy recovery showed significantly improved environmental performance. Mehta et al. (2018) further emphasized that economically viable waste management systems should integrate resource recovery pathways to simultaneously reduce environmental impacts and improve sustainability outcomes. More recently, Pujara et al. (2023) demonstrated for Rajkot city that higher segregation efficiency and diversion toward composting and recycling resulted in considerable reductions in GHG emissions, reinforcing the importance of circular resource management strategies. Internationally, the waste hierarchy proposed by the European Commission and the integrated waste management framework described by Wilson et al. (2015) emphasize minimizing landfill disposal while maximizing recycling, biological treatment, and energy recovery. Moreover, the IPCC (2006) guidelines identify unmanaged landfills as significant anthropogenic methane sources, particularly in developing nations lacking landfill gas capture systems.

The findings of the present study are consistent with these earlier investigations. The results indicate that Bangalore exhibits the highest net emissions (795 kg CO_2 eq./t MSW) due to heavy dependence on landfilling without landfill gas capture, corroborating the observations of Babu et al. (2014) and Sughosh et al. (2019). Mysore showed moderate emissions (571 kg CO_2 eq./t MSW), reflecting partial diversion through composting but continued reliance on landfill disposal. In contrast, Tumkur demonstrated the lowest emissions (282 kg CO_2 eq./t MSW) owing to effective segregation and high diversion rates toward composting, recycling, and RDF utilization in cement industries. Similarly, Delhi exhibited the highest net greenhouse gas emissions under Scenario 1, with 1236 kg CO_2-eq per ton of MSW, where no material or energy recovery credits were considered. When the environmental benefits associated with material recovery and energy generation were incorporated through avoided burden credits, the net emissions decreased substantially to 530 kg CO_2-eq per ton of MSW. This reduction was mainly driven by three factors: (i) compost utilization, which displaced the production and application of synthetic fertilizers; (ii) electricity generation from WTE facilities, which offset carbon-intensive grid electricity; and (iii) landfill gas recovery, which prevented the direct release of methane while enabling energy recovery. Together, these measures significantly improved the overall environmental performance of the integrated MSW management system by reducing both direct process emissions and upstream emissions associated with conventional material and energy production. For Chennai, the GW burden from solid waste management is overwhelmingly driven by landfilling of mixed municipal solid waste at the two open dump sites, Kodungaiyur and Perungudi. Landfill is estimated to contribute around 5,217 t CO_2 eq. day^{-1}, which clearly dominates over modeled contributions from composting and biogas plants and is consistent with independent studies showing that biodegradable waste at these dumpyards alone has the potential to emit about 28,870 tons of methane per year, equal to roughly 52% of Tamil Nadu's landfill methane emissions. This dominance arises from two structural features of Chennai's current practice: (i) continued operation of Kodungaiyur and Perungudi as largely unmanaged open dumps receiving ~5,300–6,000 TPD of mixed waste including a very high organic fraction (50–55%), and (ii) limited diversion of biodegradable waste to low-GWP pathways, so that most wet waste undergoes anaerobic degradation in situ, producing methane that escapes to the atmosphere. The comparative analysis clearly indicates that cities adopting higher levels of material recovery and reduced landfill dependency achieve substantially lower climate impacts.

3.10 Summary

This chapter evaluated MSW management practices and their associated GHG emissions across three urban tiers in Karnataka, Bangalore (Tier 1), Mysore (Tier 2), Tumakur (Tier 3) Delhi (Tier 1), Varanasi (Tier 2) and Chennai (Tier 1) using a LCA framework. The analysis highlights substantial inter-city variability in environmental performance, driven primarily by differences in waste diversion rates and dependence on landfilling.

Among the three cities, Bangalore exhibits the highest climate impact, with net emissions of 795 kg CO_2 eq per ton of MSW, due to the significant proportion of waste (~60%) disposed of in landfills without landfill gas capture. Consequently, uncontrolled methane emissions dominate the overall footprint, offsetting the benefits achieved through recycling, composting, biogas recovery, and WTE processes.

Mysore demonstrates a moderate impact, with emissions of 571 kg CO_2 eq per ton, reflecting improved diversion of organic waste through composting. However, landfilling still accounts for a major share of emissions (~42% of waste), and the absence of methane capture systems limits the overall climate benefits of existing treatment practices.

In contrast, Tumakur shows the lowest emissions at 282 kg CO_2 eq per ton, primarily due to effective waste segregation and high diversion rates (~77%) toward composting, recycling, and RDF utilization in cement industries. The reduced reliance on landfilling significantly lowers methane emissions, illustrating the effectiveness of resource recovery-based waste management approaches.

Delhi exhibited the highest net GHG emissions under the baseline scenario (1236 kg CO_2-eq t^{-1} MSW); however, the incorporation of avoided burden credits reduced emissions to 530 kg CO_2-eq t^{-1} MSW. This finding highlights the critical role of resource recovery, particularly compost utilization, waste-to-energy electricity generation, and landfill gas capture, in enhancing the climate performance of integrated municipal solid waste management systems.

Across all cities, landfilling without gas capture emerges as the dominant contributor to GHG emissions, while resource recovery pathways consistently provide net emission reductions through material substitution and renewable energy generation. The findings demonstrate that increasing waste diversion, improving segregation efficiency, and integrating energy recovery systems are critical for reducing the climate footprint of MSW management. They further highlight the need for a systemic transition toward a circular waste management framework that prioritizes enhancing recycling and organic waste treatment, minimizing landfilling, and implementing landfill gas capture systems. These measures are essential for achieving substantial and sustained reductions in greenhouse gas emissions across urban waste management systems in India.

References

Annepu, R. K. (2012). Sustainable solid waste management in India. Columbia University, New York, NY, United States.

Babu, G. S., Lakshmikanthan, P., & Santhosh, L. G. (2014). Life cycle analysis of municipal solid waste (MSW) land disposal options in Bangalore City. In ICSI 2014: Creating infrastructure for a sustainable world (pp. 795–806).

Bruhat Bengaluru Mahanagara Palike. (accessed 15/04/2026). Official website of BBMP. https://bbmp.gov.in/home

European Commission. (2008). Directive 2008/98/EC on waste (Waste Framework Directive). European Commission.

Intergovernmental Panel on Climate Change (IPCC). (2006). 2006 IPCC guidelines for national greenhouse gas inventories: Volume 5 – Waste. IPCC.

Khandelwal, H., Thalla, A. K., Kumar, S., & Kumar, R. (2019). Life cycle assessment of municipal solid waste management options for India. Bioresource Technology, 288, 121515. https://doi.org/10.1016/j.biortech.2019.121515

Madhavaraj, M., & Karthikeyan, K. (2025). Assessment of waste-to-energy strategies for municipal solid waste landfills in Chennai: A case study using energy-economic-environmental (3E) approach. Cleaner Environmental Systems, 18, 100321. https://doi.org/10.1016/j.cesys.2025.100321

Mehta, Y. D., Shastri, Y., & Joseph, B. (2018). Economic analysis and life cycle impact assessment of municipal solid waste (MSW) disposal: A case study of Mumbai, India. Waste Management & Research, 36(12), 1177–1189. https://doi.org/10.1177/0734242X18790354

Mysuru City Corporation. (accessed 15/04/2026). Official website of Mysuru City Corporation. http://www.mysurucity.mrc.gov.in/

Praveena, S. A., "Tambaram WTE plant project moved to Keerapakkam, GCC floats tender," *The New Indian Express*, Mar. 7, 2026.

Pujara, Y., Govani, J., Patel, H. T., Pathak, P., Mashru, D., & Ganesh, P. S. (2023). Quantification of environmental impacts associated with municipal solid waste management in Rajkot city, India using life cycle assessment. Environmental Advances, 12, 100364. https://doi.org/10.1016/j.envadv.2023.100364

Rai PK. Problems of Sustainable Solid Waste Management in Urban Area: A Case Study of Varanasi City of India. European Geographical Studies. 2017 Dec 5;4(2). https://doi.org/10.13187/egs.2017.2.80

Sharma, B. K., & Chandel, M. K. (2017). Life cycle assessment of potential municipal solid waste management strategies for Mumbai, India. Waste Management & Research, 35(1), 79–91. https://doi.org/10.1177/0734242X16675684

Srivastava, A. K., & Nema, A. K. (2011). Life cycle assessment of integrated solid waste management system of Delhi. In Towards life cycle sustainability management (pp. 267–276). Springer, Dordrecht, Netherlands. https://doi.org/10.1007/978-94-007-1899-9_26

Sughosh, P., Anusree, N., & Babu, G. S. (2019). Life cycle analysis as a tool to assess the sustainability of waste management practices in Bangalore city. In Proceedings of the Eighth International Conference on Case Histories in Geotechnical Engineering (pp. 125–134). American Society of Civil Engineers.

Tumakuru City Corporation. (accessed 15/04/2026). Official website of Tumakuru City Corporation. http://www.tumakurucity.mrc.gov.in/

Wilson, D. C., Rodic, L., Scheinberg, A., Velis, C. A., & Alabaster, G. (2015). Comparative analysis of solid waste management in 20 cities. Waste Management & Research, 33(12), 1119–1133. https://doi.org/10.1177/0734242X15616099

Varanasi. The Civil India. 2025. https://www.thecivilindia.com/cityprofile/varanasi/

Chapter 4
Composting

4.1 Preamble

This chapter introduces an original hybrid "waste-to-value" framework that functionally integrates aerobic composting of organic fraction of municipal solid waste (OFMSW) with anaerobic digestion of the generated leachate for biogas recovery. To achieve this aim, the study will pursue the following specific objectives:

- establish an environmental baseline (Scenario 1) by quantifying the life-cycle impacts of a windrow composting facility for OFMSW where leachate is collected and managed as a liquid manure substitute (composting without energy recovery).
- evaluate the environmental performance of an integrated pathway (Scenario 2) where leachate is treated via anaerobic digestion, and the resulting biogas is converted into electricity in a genset, displacing India's coal-dominant grid electricity (composting with energy recovery, biogas-to-electricity).
- assess an alternative integrated pathway (Scenario 3) where leachate-derived biogas is purified, compressed, and upgraded to biomethane to be used as a vehicle fuel, displacing conventional fossil fuels (Composting with energy recovery, biogas-to-compressed biogas).
- identify environmental hotspots by performing contribution, uncertainty, and sensitivity analyses for each scenario, thereby pinpointing the most influential processes and parameters that should be targeted for future environmental improvement.

By comparing these three technically feasible scenarios using detailed, site-specific inventory data, this study will provide a quantitative basis for policymakers, plant operators, and investors to select the most environmentally sustainable pathway for OFMSW management (locally termed as segregated domestic wet waste), moving beyond simple containment to a true circular economy model of resource and energy recovery.

4.2 . Methodology

In this study, life-cycle assessment (LCA) was used as the analytical framework for comparison of OFMSW management alternatives. The LCA was performed in SimaPro (version 9.6.0.1).

The functional unit is taken as treatment of 1 ton of OFMSW (Colón et al., 2010; Serafini et al., 2025a). The LCA model includes the operation stage, the collection and transportation of OFMSW, the composting of waste, leachate handling, transportation of compost and liquid manure, and the substitution of synthetic fertilizer with compost and liquid manure (Fig. 4.1) (Nanlin et al., 2023; Tian et al., 2025). End-of-life processes, such as compost application and energy displacement, were included to ensure a cradle-to-grave perspective (Biancini et al., 2022; Khandelwal et al., 2019). For the assessment of environmental impacts, the ReCiPe 2016 (H) method was employed for both midpoint estimations (Singh et al., 2020).

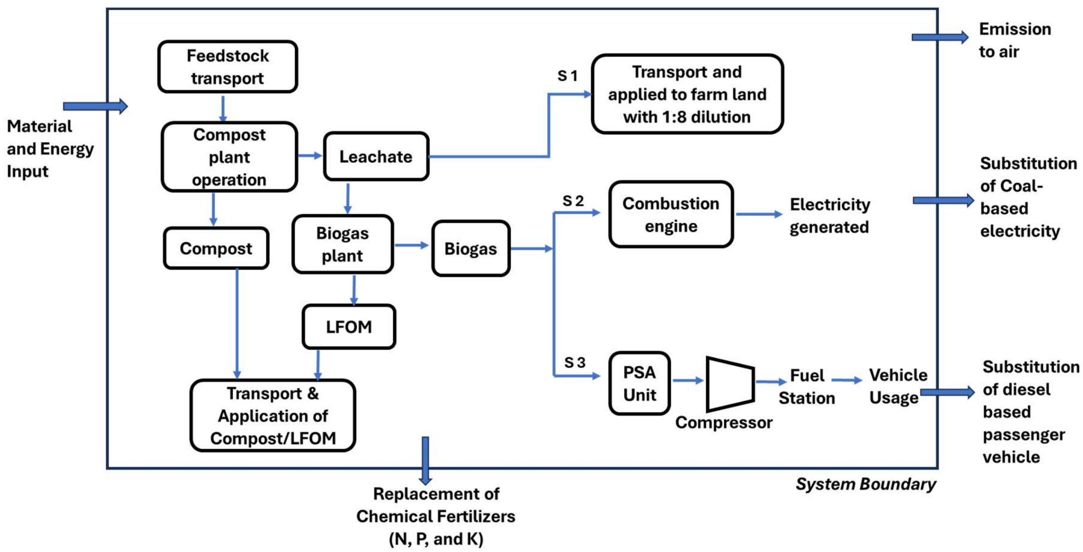


Fig. 4.1 System boundary of the compost plant life cycle assessment

4.2.1 System description and inventory data

4.2.1.1 Scenarios Studied

- *Composting without energy recovery from leachate*

In the first scenario, the OFMSW is collected and transported to the composting facility. The windrow is formed with the waste for 35-49 days (turned every 8th day for first 4 weeks). The digested windrow material is first passed through 35 mm trommel and then through 16 mm trommel. The 35 mm rejects are sent to WTE plant and 16 mm rejects are either given to farmer on a free of cost basis or mixed with fresh incoming waste to increase porosity. The remaining material passed through 16 mm trommel is kept in silos for 20 days for curing. It is then finally passed through 4 mm trommel. The rejects from 4 mm trommel are given to farmers for free of cost and <4mm passable material is sold as city (or town) compost. Mainly three components such as rejects, leachate, and compost are generated in such compost plants.

Table 4.1 Inventory data of various composting pathways for organic municipal solid waste (per functional unit) (S1: Composting without energy recovery from leachate; S2: Composting with energy recovery (in form of electricity generation) from leachate, S3: Composting with energy recovery (in form of bio-CNG production for vehicle fuel) from leachate)

	Units	S1	S2	S3	Comments/ References
<u>Inputs</u>					
Raw material	ton	1	1	1	
Transportation	km	25	25	25	
Electricity	kWh	1.9	3.5*	6**	*Includes electricity for biogas plant operation *(plant data)* **Includes purification and compression energy demand
Diesel	kg	1.2	1.2	1.2	
Freshwater	Litre	120	120	120	(Plant data for S1, S2, and S3 are assumed to be same)
<u>Outputs</u>					
Fermented organic manure (FOM)	kg	150	150	150	15% of input material *(plant data)*
Leachate	L	200	200	200	*(plant data)*
Biogas	m^3	-	10	10	Methane content: 60%
Emissions to air					
From compost plant					
Methane (CH_4)	kg	0.88	0.88	0.88	Nordahl et al., 2023
Dinitrogen monoxide (N_2O)	kg	0.07	0.07	0.07	Nordahl et al., 2023
Ammonia	kg	0.1	0.1	0.1	(Pujara et al., 2023)
Carbon dioxide (CO_2)	kg	244	244	244	(Pujara et al., 2023)
From biogas plant					
Methane (CH_4)	kg	-	0.08	0.08	Assuming 2% loss from plant (American Biogas Council, 2025)
From purification unit					
Methane (CH_4)	kg	-	-	0.27	Purification loss: 7% *(based on survey taken from experts working in the field);* and 0.075% loss from compression unit (Singh and Kalamdhad, 2022a)
From bio-CNG usage as a vehicle fuel (Tailpipe emission)					

Methane (CH_4)	kg	-	-	0.02	Assuming tailpipe emission to be 0.48% (Singh and Kalamdhad, 2022a)
From biogas combustion for electricity					
Methane (CH_4)	kg	-	0.17	-	CH_4 emission of 1.16 g/kWh (Kristensen et al., 2004)
Carbon dioxide (CO_2)	kg	-	22	-	Considered to be biogenic
Carbon monoxide (CO)	kg	-	0.015	-	CO emission of 1 g/kWh (Kristensen et al., 2004)
Dinitrogen monoxide (N_2O)	mg	-	0.0375	-	N_2O emission of 0.0025 g/kWh (Kristensen et al., 2004)
From digestate storage					
Methane (CH_4)	kg	-	0.02	0.02	0.5% emission is assumed from digestate tank (IEA Bioenergy, 2017)
From digestate preparation and application					
<u>Offset</u>					
Fuel Replacement					
Coal-based electricity	kWh	-	15	-	Emission loss is to taken as 2%, engine efficiency as 25%, LHV of biogas as 5.56 kWh/m^3 (Hakawati et al., 2017; Singh and Kalamdhad, 2022b)
Diesel	kg	-	-		Bio-CNG available: 3.8 kg *(calculated)*; Fuel efficiency - Bio-CNG: 24 km/kg. (Singh and Kalamdhad, 2022a)
Emission savings during diesel usage					
Methane (CH_4)	gm	-	-	0.46	CH_4 emission of 0.13 g/kg (Singh and Kalamdhad, 2022a)
Carbon dioxide (CO_2)	kg	-	-	11.5	CO_2 emission of 3186 g/kg (Singh and Kalamdhad, 2022a)
Dinitrogen monoxide (N_2O)	gm	-	-	0.09	N_2O emission of 0.26 g/kg (Singh and Kalamdhad, 2022a)
Fermented Organic Manure (FOM)					
N	kg	5.8	5.8	5.8	N – 1.8%, P – 1.9%, and K – 1.16% on the dry basis, Moisture content - 20% *(plant data)*. Portion of synthetic fertilizer wasted 40-90% (E. et al., 2024), efficiency: organic fertilizer 90% (Chmelíková et al., 2021)
P (as P_2O_5)	kg	6.2	6.2	6.2	
K (as K_2O)	kg	3.8	3.8	3.8	
Liquid Fermented Organic Manure (LFOM)					
N	kg	0.34	0.34	0.34	

P (as P_2O_5)	kg	0.19	0.19	0.19	N – 630, P – 350, and K – 1668 mg/L, Losses and efficiency are same as FOM
K (as K_2O)	kg	0.9	0.9	0.9	

Leachate emerging from the windrows during the early stages is collected through drains and stored in a collection tank. At the study location, this leachate was hitherto sent to sewage treatment plants for treatment but is now being discontinued in favour of on-site treatment options which are yet to be commissioned and performance data is not available and is therefore not considered. However, it is important to note that the study conducted by Indian Council of Agricultural Research-Indian Institute of Horticultural Research (ICAR-IIHR) in 2021-22 suggested that leachate generated from OFMSW composting plants could be used as potential liquid manure after 1:8 dilution with irrigation water. At all the composting plants, windrows are established on impervious concrete floor to avoid groundwater contamination

The extent of mineral fertilizer substituted was determined based on the content of nitrogen (N), phosphorus (P_2O_5), and potassium (K_2O) content of the solid residue (equated to fermented organic manure, FOM) and the liquid digestate (liquid fermented organic manure, LFOM) prepared, coupled with their respective substitution ratios (Singh et al., 2026). The relevant inventory data of this system is presented in Table 4.1.

- *Composting with energy recovery from leachate (biogas to electricity)*

In the second scenario, the biogas generated from the leachate is captured and converted into electricity using engines gensets (Singh et al., 2026; Singh and Kalamdhad, 2022c). The initial stages of this process namely the collection, transportation, and preparation of the OFMSW, as well as the composting method itself are identical to those in the baseline scenario. The relevant inventory data for this scenario is presented in Table 1. A key assumption for this model is that the generated electricity displaces an equivalent amount of power from the grid that would otherwise have been produced by coal-based power plants (Alengebawy et al., 2022). This substitution baseline is justified by two primary factors: it reflects India's operational reality, where coal comprises more than 60% of power generation and is the marginal source, and it aligns with the nation's climate policy to phase out the most carbon-intensive sources. This displacement of coal power provides the basis for the environmental credits, while credits for the compost and LFOM are treated similarly to the baseline case.

- *Composting with energy recovery from leachate (biogas to compressed biogas for vehicle fuel)*

A third alternative scenario examines the conversion of this leachate biogas into compressed biogas (CBG) for use as a vehicle fuel (Singh and Kalamdhad, 2022d). In this model, the generated biogas undergoes purification and compression to create upgraded biomethane, equivalent to CNG fuel stations for vehicular fuel. The upstream processes, from waste collection through composting and biogas generation, remain consistent with the electricity scenario. The crucial difference here is that the purified biomethane (termed CBG or sometimes bio-CNG) directly replaces fossil fuels like petrol or diesel for various types of transport vehicles (Ferreira et al., 2019a; Keogh et al., 2024). This substitution directly lowers fossil fuel dependency and the associated GHG emissions. For both the scenarios, the relevant inventory data is presented in Table 1, and the credits for compost and LFOM are calculated as in the first scenario.

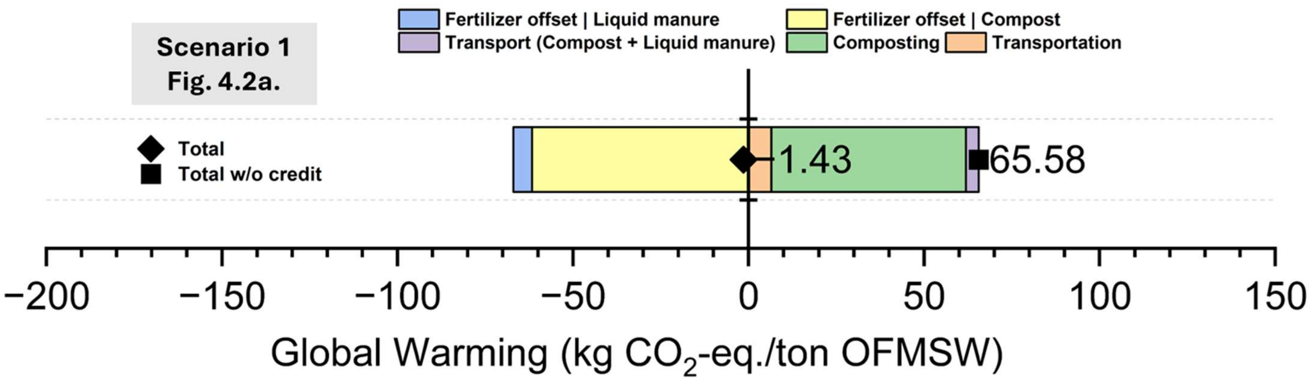
4.2.2 Sensitivity analysis

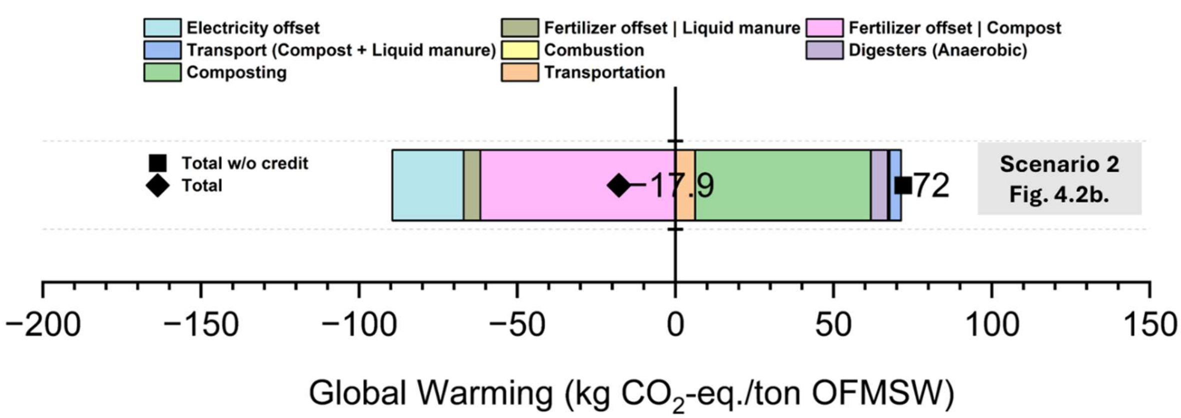
The sensitivity analysis was conducted by systematically varying key operational and substitution parameters within realistic ranges derived from literature and plant experience. The parameters evaluated included transport distance (25-100 km), compost production yield (10-25%), leachate production (5-25%), COD concentration of leachate (50,000-125,000 mg/L), compost substitution rate (0-100%), LFOM substitution (0-100%), and fossil substitution (0-100%). Each parameter was varied independently while keeping other parameters constant to isolate its individual effect. The break-even analysis extended this sensitivity assessment by identifying the specific parameter value at which the total global warming (GW) of each scenario equalled zero. In this context, "break-even" represents the operational or market threshold where the composting system transitions from a net source of GHG emissions to a net sink. These break-even points were determined through interpolation between the tested data points where the sign of the GW changed. For parameters where GW remained consistently positive or negative throughout the range, no break-even was recorded within the tested limits. The identified thresholds thus represent critical operational targets for climate neutrality, such as the transportation distance, minimum compost yield, energy recovery from leachate, or fossil substitution level needed to offset the system's inherent emissions.

4.3 Result and discussions

4.3.1 Global warming

The global warming (GW) of a compost plant per ton OFMSW is presented in Fig. 4.2. The result highlights individual contributions of various activities, the most significant contribution in gross emission (or total GW without credit) being associated with composting process. The credits in form of fertiliser offset (~67 kg CO_2 eq.), are also accounted which substantially reduces GW by avoiding emissions from synthetic fertiliser production through the beneficial use of FOM and LFOM (Bernstad and la Cour Jansen, 2012; Nordahl et al., 2020). Conversely, processes like feedstock transportation and plant operation contribute positively to GW (Nanlin et al., 2023). Ultimately, while the gross GW before credits (represented as total without credits in Fig. 4.2) stands at 65.58 kg CO_2 eq., and net GW at -1.43 kg CO_2 eq., representing a marginal GHG benefit (represented as total in Fig. 2.). The principal emissions arise from the composting process itself (55.5 kg CO_2 eq) and collection and transportation (6.46 kg CO_2 eq.), while large credits are gained from fertilizer replacement (-67 kg CO_2 eq.) and the avoided production of mineral fertilizers. Compost and leachate transport contributes 3.62 kg CO_2 eq. The net effect is a near-neutral carbon profile. This indicates the vital role of compost and leachate utilisation while replacing synthetic fertilizer in the overall environmental performance of the system.





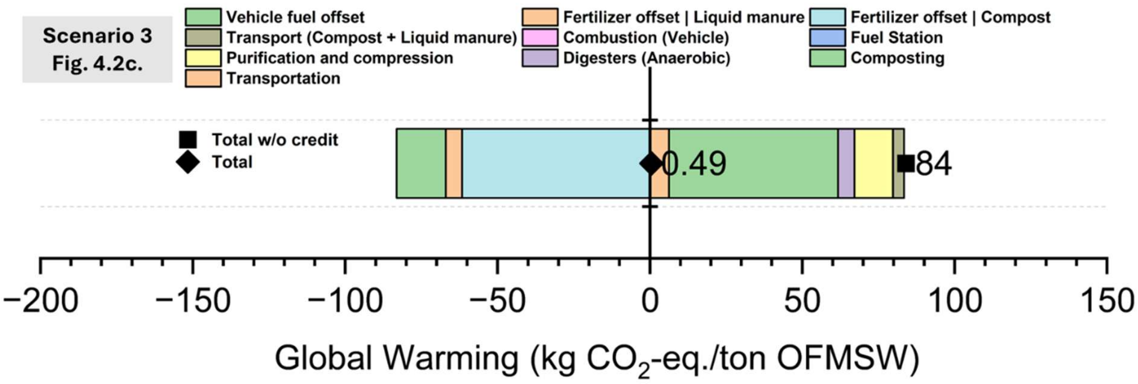


Fig. 4.2 Impact on global warming from compost plant based on organic fraction of municipal solid waste a) scenario 1 – composting without energy recovery from leachate b) scenario 2 - composting with energy recovery from leachate (biogas to electricity) c) scenario 3 - composting with energy recovery from leachate (upgraded biomethane used as vehicle fuel)

Scenario 2 (energy recovery from leachate for electricity generation has emerged as the most environmentally favourable option, demonstrating a net-negative carbon footprint of -17.9 kg CO_2 eq. While the composting and collection processes remain unchanged, the anaerobic digestion of leachate (5.39 kg CO_2 eq.) and subsequent electricity generation which deliver substantial credits by displacing coal-based power indicates the system acts as a net carbon sink, sequestering more greenhouse gas emissions than it produces. The strong environmental performance is attributed to two major credits: the displacement of synthetic fertilizer (a credit of -67 kg CO_2 eq.) which represents the largest contributions, and the second is the displacement of coal-based electricity (a credit of -22.5 kg CO_2 eq.).

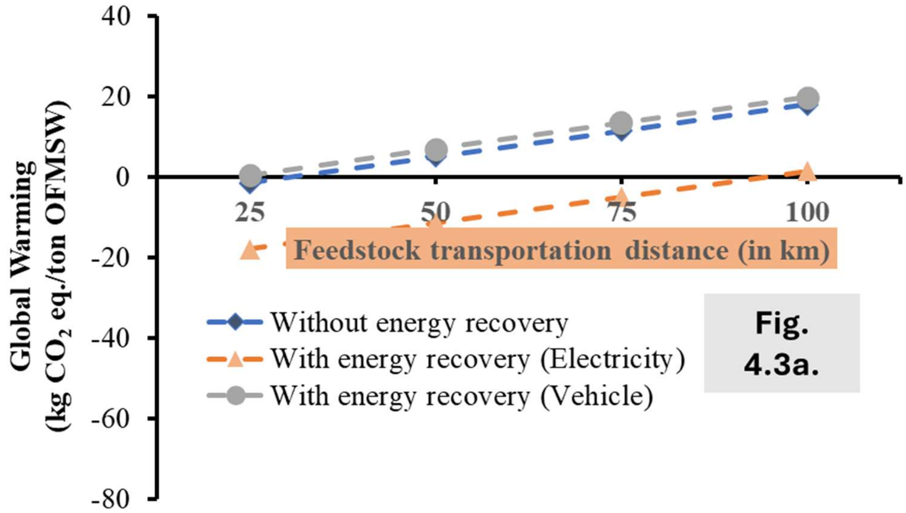
Scenario 3 (energy recovery from leachate for CBG production) resulted in a somewhat net-positive footprint of 0.491 kg CO_2 eq. indicating near climate neutrality. The difference arises from the energy-intensive purification and compression steps to produce CBG (12.6 kg CO_2 eq.), which partly offset the credit gained from diesel substitution (-16.2 kg CO_2 eq.). Despite this penalty, Scenario-3's performance approaches net zero, confirming that renewable transport fuel pathways can also achieve parity with electricity pathways if upgradation efficiencies and conversion efficiencies improves to even higher levels (Singh et al., 2026). The ranking of scenarios in terms of GW is S2 > S1 > S3, with S2 providing the highest benefit from GHG perspective.

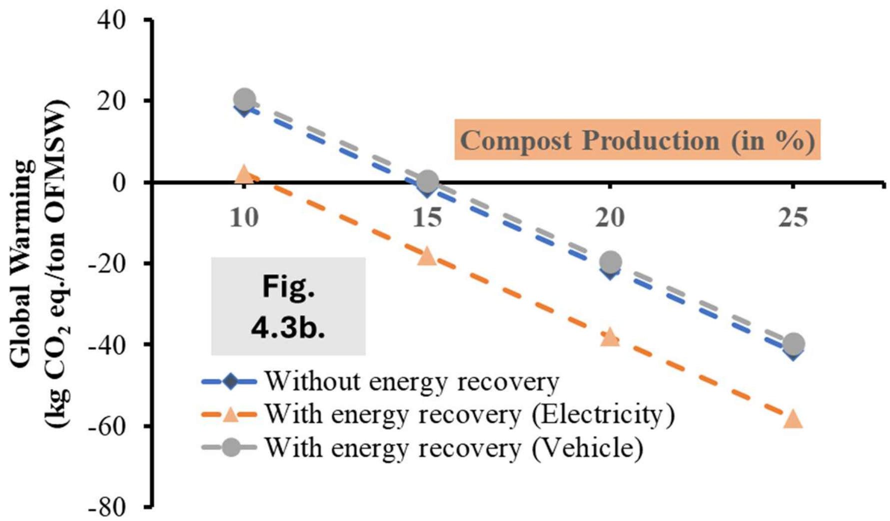
4.3.2 Sensitivity and break-even analysis

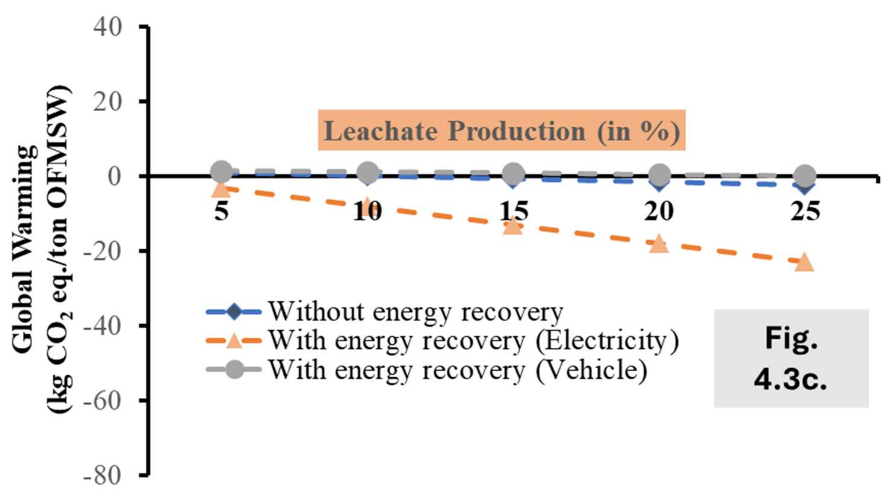
The sensitivity analysis reveals that the global warming (GW) of all three composting scenarios such as S1 (composting without energy recovery), S2 (composting with biogas-to-electricity recovery), and S3 (composting with biogas-to-compressed biogas, CBG) is shaped by a small number of highly influential parameters. These parameters fall into three interconnected domains: logistics (feedstock collection and transportation distance), circular economy performance (compost utilization and substitution), and energy recovery efficiency (Fig. 4.3a – 4.3g). Collectively, these determine whether the system behaves as a net GHG sink (negative GW) or a net source (positive GW). The negative values represent net GHG savings (environmental benefit), while positive values indicate increased emissions (environmental burden). The overall ranking under baseline conditions remains S2 > S1 > S3, but the sensitivity and break-even analysis show that under certain operational or market constraints, these rankings can reverse.

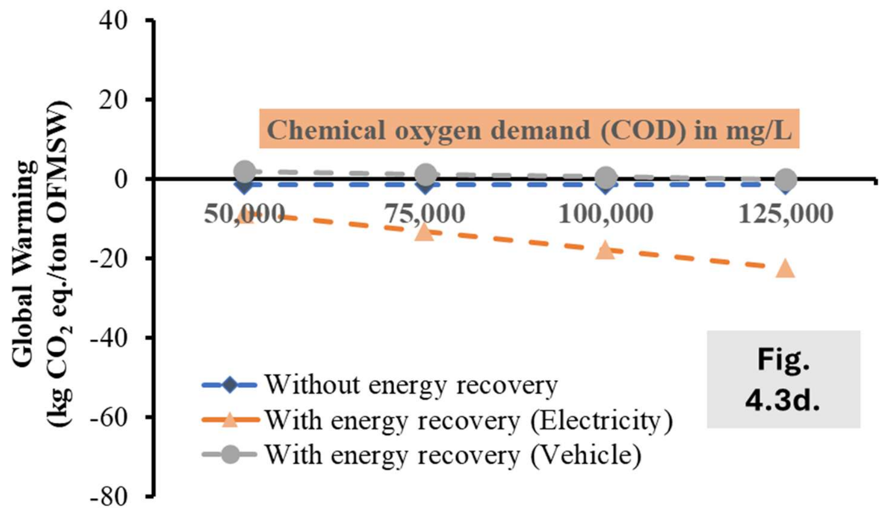
Logistics, represented by transport distance, imposes a linear and unavoidable GHG burden across all systems. As distance increases from 25 km to 100 km, total GW rises by about 18-20 kg CO_2 eq. ton^{-1} in all scenarios. The break-even points occur at approximately 30.5 km for S1 and 94.2 km for S2 (Fig. 4.3a). Beyond these distances, the additional diesel combustion during waste transport negates the benefits of composting and energy recovery. S3 remains slightly positive throughout the range and would only become net-negative at distances shorter than 25 km, implying that decentralized, locally-sited CBG facilities are essential for achieving GHG neutrality. These results provide a clear directive for urban planners.

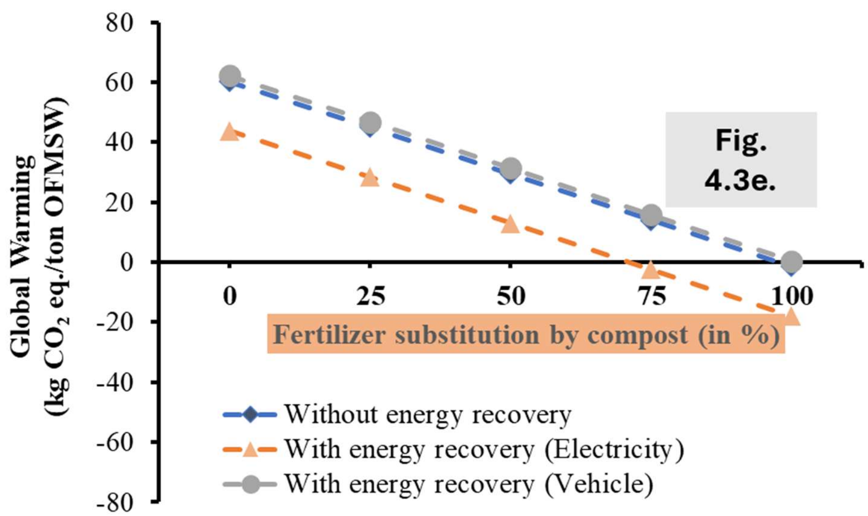
A related variable is compost production efficiency, which strongly affects the GW by determining how much OFMSW is converted into usable compost. Increasing yield from 10% to 25% reduces GW by more than 59 kg CO_2 eq. ton^{-1} across all scenarios. The break-even yields, where GW crosses zero, occur at roughly 14.6% for S1, 10.5% for S2, and 15.1% for S3 (Fig. 4.3b). This means that if the composting process consistently converts more than these fractions of waste into finished compost, the systems become net-negative in climate terms. Below these thresholds, the additional aeration, curing, and handling energy outweighs the fertilizer substitution credit. These results emphasize that process engineering such as moisture control, aeration cycles, and screening optimization is an emissions-critical operation, not merely a matter of product quality.

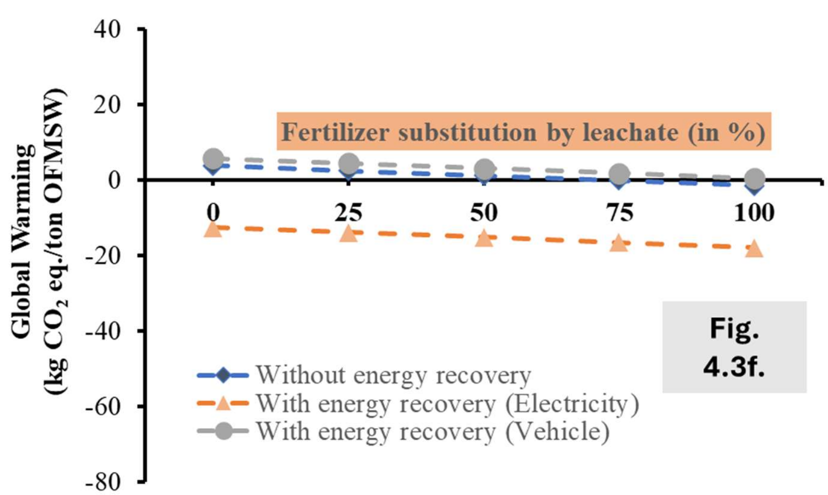

Global Warming
(kg CO_2 eq./ton OFMSW)
40
20
0
-20
-40
-60
-80
25
50
75
100
Feedstock transportation distance (in km)
Without energy recovery
With energy recovery (Electricity)
With energy recovery (Vehicle)
Fig. 4.3a.


Global Warming
(kg CO_2 eq./ton OFMSW)
40
20
0
-20
-40
-60
-80
10
15
20
25
Compost Production (in %)
Fig. 4.3b.
Without energy recovery
With energy recovery (Electricity)
With energy recovery (Vehicle)


Global Warming
(kg CO_2 eq./ton OFMSW)
40
20
0
-20
-40
-60
-80
5
10
15
20
25
Leachate Production (in %)
Without energy recovery
With energy recovery (Electricity)
With energy recovery (Vehicle)
Fig. 4.3c.


Global Warming
(kg CO_2 eq./ton OFMSW)
40
20
0
-20
-40
-60
-80
Chemical oxygen demand (COD) in mg/L
50,000
75,000
100,000
125,000
Without energy recovery
With energy recovery (Electricity)
With energy recovery (Vehicle)
Fig. 4.3d.


Global Warming
(kg CO_2 eq./ton OFMSW)
80
60
40
20
0
-20
-40
-60
-80
0
25
50
75
100
Fertilizer substitution by compost (in %)
Without energy recovery
With energy recovery (Electricity)
With energy recovery (Vehicle)
Fig. 4.3e.


Global Warming
(kg CO_2 eq./ton OFMSW)
40
20
0
-20
-40
-60
-80
Fertilizer substitution by leachate (in %)
0
25
50
75
100
Without energy recovery
With energy recovery (Electricity)
With energy recovery (Vehicle)
Fig. 4.3f.

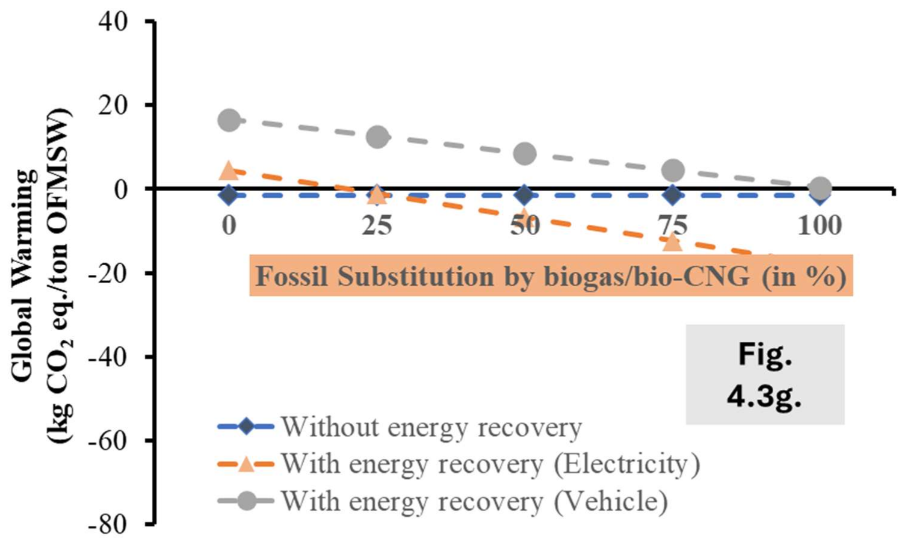


Fig. 4.3 Influence of variation in different parameters on global warming of compost plant based on organic fraction of municipal solid waste a) feedstock transportation distance b) compost production c) leachate production d) chemical oxygen demand (COD) of leachate e) fertilizer substitution by compost f) fertilizer substitution by leachate/liquid fermented organic manure (LFOM) g) fossils substitution by biogas/bio-CNG

The leachate and energy recovery parameters reveal fundamental operational differences among the scenarios. In S1, which lacks any energy recovery, increased leachate production marginally worsens performance, with GW changing from 0.97 to -2.23 kg CO_2 eq. ton^{-1} as leachate rises from 5% to 25% (Fig. 4.3c). The modest shift toward neutrality arises from dilution rather than energy gain, and the break-even point occurs near 11% leachate production, above which the treatment energy and fugitive methane emissions begin to dominate. Conversely, in S2 and S3, leachate becomes a beneficial feedstock. In S2, higher leachate generation enhances GW performance, reducing it from -8.05 to -22.8 kg CO_2 eq. ton^{-1}, while in S3 it improves from 1.5 to 0.15 kg CO_2 eq. ton^{-1}. Similar improvements appear with rising COD and biogas yield, reflecting the conversion of organic matter to renewable energy. The COD break-even for S3 occurs near 118,000 mg L^{-1}, while S2 remains net-negative over the full tested range (Fig. 4.3d). In terms of biogas production, S3 crosses zero around 11.8 m^3 ton^{-1} OFMSW, becoming net-negative at higher yields (reaching -0.21 kg CO_2 eq. ton^{-1} at 12.5 m^3). This threshold marks the minimum digestion performance required for CBG systems to offset their own purification and compression energy demand (Kalita et al., 2023; Ravindran et al., 2025). Below this point, S3 becomes a net emitter; above it, it functions as a climate-positive technology.

The result of compost substitution rate, which directly represents the circular economy benefit of displacing synthetic fertilizers shows that when compost is not used at all (0% substitution), all systems become large GHG emitters (Bernstad and la Cour Jansen, 2012; Nordahl et al., 2020), with GW values of 60.3, 43.8, and 62.2 kg CO_2 eq. ton^{-1} for S1, S2, and S3 respectively (Fig. 4.3e). This clearly demonstrates that the climate advantage of municipal composting arises overwhelmingly from nutrient recycling rather than from waste stabilization alone. Energy recovery from leachate, although valuable, is secondary in magnitude. The break-even substitution levels where GW is zero occur at approximately 98% for S1 and 71% for S2, while S3 remains slightly positive across the entire 0-100% range, approaching neutrality at full substitution. These thresholds mean that S1 can only achieve climate neutrality if almost all fertilizer demand is met through compost, a challenging condition to satisfy in practice. S2, in contrast, can reach net-negative emissions at much more achievable market penetration levels. Thus, the single most decisive policy condition for composting viability is securing a stable and guaranteed end-market for compost. Without active utilization, the composting system becomes a net emitter regardless of its technical sophistication. The LFOM substitution variable supports these conclusions. For S1, a break-even occurs around 73% LFOM substitution while S2 remains net-negative throughout the tested range and S3 remains marginally positive (Fig. 4.3f).

The fossil substitution parameter further highlights this trade-off between recovery pathway efficiency and internal energy consumption. S3 exhibits a heavy energy burden at 0% substitution, with GW of 16.7 kg CO_2 eq. ton^{-1}, representing the parasitic energy load of gas upgrading (Fig. 4.3g). It approaches neutrality only near full substitution (100%), emphasizing that high biogas yield and effective CBG utilization are non-negotiable for its success (Singh et al., 2026). S2, on the other hand, achieves break-even at a much lower fossil substitution rate of approximately 20%, due to the simplicity of converting biogas directly into electricity and its low parasitic losses. Even with modest fossil displacement, S2 remains net-negative (-4.6 kg CO_2 eq. ton^{-1} at 0% substitution), making it the most resilient configuration in terms of energy pathway sensitivity.

Integrating all parameters, the analysis shows that the break-even points serve as practical operational thresholds. They define the minimum performance or infrastructure conditions needed for each system to deliver climate neutrality. For S1, these thresholds are tight: compost yield > 14.6%, compost substitution > 97%, and transport < 30 km. S2 requires compost substitution above 71%, fossil substitution above 20%, and can tolerate longer transport distances up to ~94 km; hence, it remains the most robust option. S3 offers the highest theoretical upside a true net-negative GW of 0.21 kg CO_2 eq. ton^{-1} at optimum yield but only if biogas yield exceeds 11.8 m^3 ton^{-1} and fossil substitution approaches 100%. Below these break-even values, the energy cost of upgrading and compression outweighs the environmental benefit.

The broader interpretation is that break-even represents the tipping point of climate viability: the minimum operational or market condition at which the composting system ceases to be a net GHG emitter and becomes a contributor to mitigation (Singh et al., 2026). Because several of these break-even thresholds lie close to realistic operating ranges, small deviations in process performance or market conditions can move a facility from climate-positive to climate-negative. Therefore, design and policy should aim not merely to reach, but to exceed these break-even values by a comfortable margin, for example, targeting 20 % compost yields, >50 % biogas substitution, and siting distances under 25 km to ensure robustness against uncertainty.

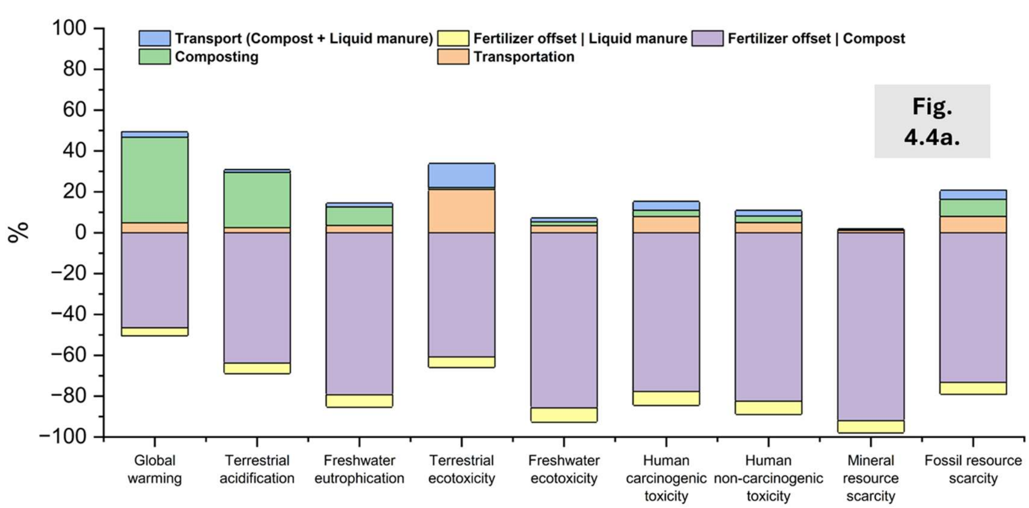
In summary, the integrated sensitivity and break-even analysis confirms that the climate performance of composting systems depends on three decisive factors. First, circular-economy performance, particularly compost substitution and production efficiency is the dominant determinant of total GW. Second, energy recovery efficiency defines the system's resilience: electricity generation (S2) is the most stable configuration, while CBG upgrading (S3) offers greater potential but at higher technical risk. Third, logistical design is an inflexible boundary condition; long transport distances can nullify all other environmental benefits. Among the configurations, S2 (biogas-to-electricity) is the most robust and environmentally beneficial across a wide range of conditions, maintaining net-negative GW under most plausible operational scenarios. However, the long-term climate success of any composting strategy ultimately depends on consistently staying beyond these break-even thresholds by ensuring a guaranteed compost market, optimizing biogas yield, and minimizing transport distances to transform waste management from an emissions liability into a climate-mitigation opportunity.

4.3.3 Mid-point results

Terrestrial acidification reflects emissions of sulfur oxides and nitrogen oxides from combustion and biological processes (Tisserant et al., 2022). Across all scenarios, the values are relatively small but consistently negative, indicating net mitigation potential. S1 exhibits -0.148 kg SO_2 eq., S2 achieves -0.214 kg SO_2 eq., and S3 shows -0.145 kg SO_2 eq. Acidifying burdens arise mainly from composting operations, including diesel and electricity use and associated N_2O emissions (Slorach et al., 2019), while avoided mineral fertilizer production provides the dominant offset (Fig. 4.4). The superior performance of S2 is attributable to coal-based electricity displacement (Singh et al., 2020), whereas S3 shows slightly higher impacts due to additional energy demand for biogas purification and compression. Overall, fertilizer substitution remains the primary controlling factor for acidification regardless of the energy recovery route.

Freshwater eutrophication potential (FEP) across all scenarios is minimal, with values of -0.0204 kg P eq. for S1, -0.0339 kg P eq. for S2, and -0.0155 kg P eq. for S3. Small indirect phosphorus releases from energy use during composting are outweighed by credits from avoided fertilizer production. S2 shows marginal improvement due to indirect upstream benefits from electricity displacement, while S3 incurs slightly higher impacts because of additional processing energy (Singh et al., 2020; Whiting and Azapagic, 2014). These results confirm that compost application as a soil conditioner substantially reduces eutrophication potential compared with disposal.

The ecotoxicity categories capture heavy metal and persistent organic compound impacts in terrestrial and aquatic environments. Ecotoxicity indicators show large net environmental credits across all scenarios. Terrestrial and freshwater ecotoxicity are dominated by avoided fertilizer production (Singh et al., 2020), which far outweighs moderate contributions from feedstock handling and composting operations. S2 achieves the lowest ecotoxicity impacts due to combined fertilizer and electricity substitution benefits, while S3 exhibits minor penalties associated with biogas upgrading (Fig. 4.4).



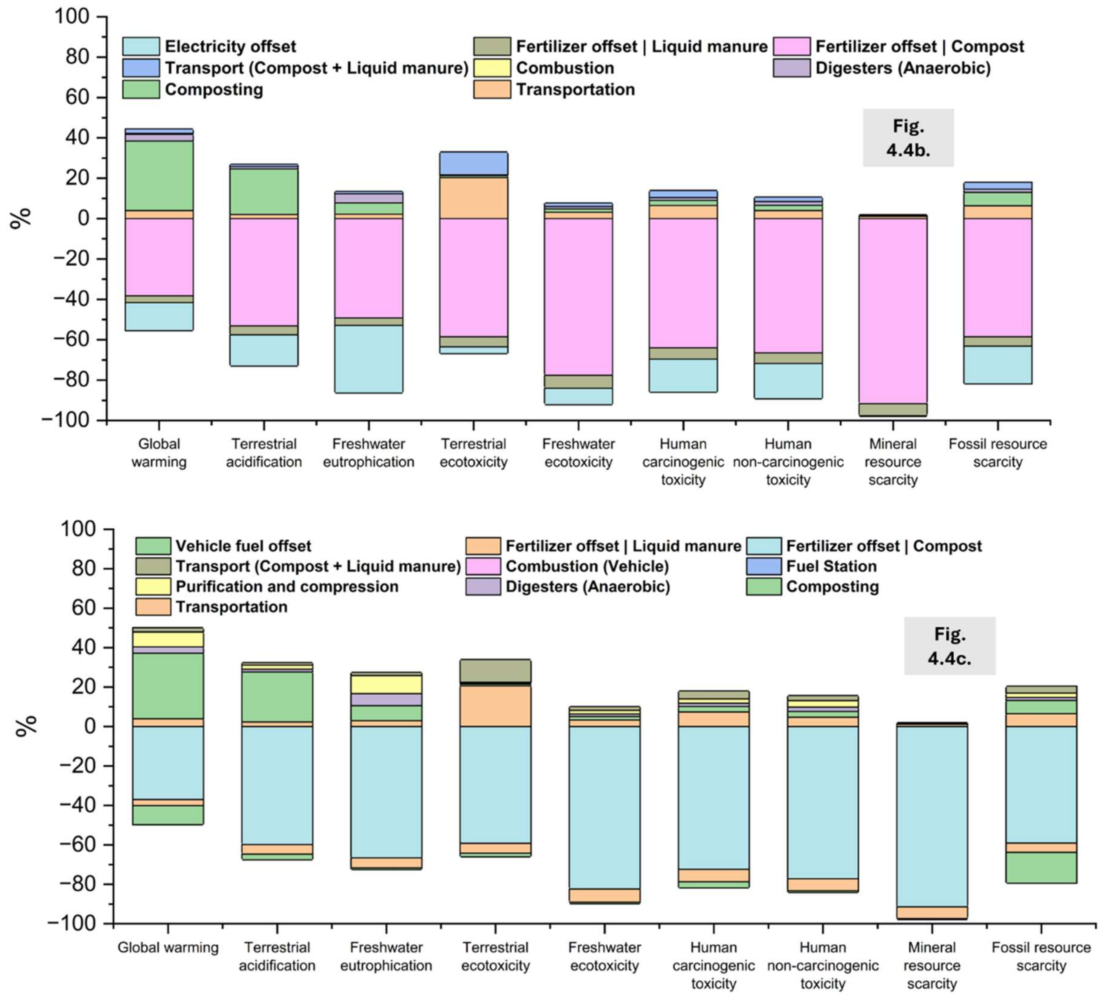


Fig. 4.4 Contribution of different impact categories from compost plant based on organic fraction of municipal solid waste a) scenario 1 – composting without energy recovery from leachate b) scenario 2 - composting with energy recovery from leachate (biogas to electricity) c) scenario 3 - composting with energy recovery from leachate (upgraded biomethane used as vehicle fuel)

Human toxicity impacts follow similar trends. Both carcinogenic and non-carcinogenic toxicity categories are dominated by fertilizer substitution credits, with composting and transport contributing minor burdens. S2 consistently delivers the greatest human health benefits due to additional avoided emissions from coal-based electricity, whereas S3's benefits are slightly reduced by purification-related energy use.

Mineral resource scarcity shows little variation across scenarios and is driven primarily by reduced demand for fertilizer-related mineral extraction. Fossil resource scarcity, however, differs markedly: S2 performs best due to coal displacement, followed closely by S3 through diesel substitution in transport. Energy use during biogas upgrading slightly reduces S3's net benefit.

Across all midpoint indicators, the overall environmental ranking is S2 > S3 > S1. Integrating leachate-based energy recovery substantially enhances environmental performance compared with composting alone. While fertilizer substitution drives the majority of benefits across impact categories, energy recovery provides critical additional gains in climate change and fossil resource depletion. These results demonstrate that integrated composting systems combining nutrient recycling with energy valorization represent the most sustainable pathway for OFMSW management, particularly when internal energy demands are minimized and compost utilization is ensured.

Process-level analysis shows that composting and treated MSW stages dominate gross impacts, particularly for global warming, acidification, and toxicity, while fertilizer substitution provides the primary environmental offsets across nearly all midpoint categories (Nordahl et al., 2020; Oviedo-Ocaña et al., 2023; Slorach et al., 2019). Energy recovery from leachate biogas contributes additional benefits mainly in climate change and fossil resource scarcity, but has limited influence on toxicity-related indicators, where fertilizer avoidance remains decisive. Transportation contributes a consistent but comparatively minor burden, indicating that local siting is a secondary factor relative to nutrient and energy recovery

Across midpoint indicators, energy recovery and material substitution act synergistically to enhance environmental performance. Scenario 2 (biogas-to-electricity) achieves the most balanced and highest overall benefits, while Scenario 3 (biogas-to-CBG) performs similarly but is constrained by the energy intensity of gas upgrading. Scenario 1 relies entirely on nutrient recycling and is therefore sensitive to compost utilization rates and transport distances.

Overall, the results confirm that integrated composting systems combining fertilizer substitution with leachate-based energy recovery represent the most sustainable OFMSW management pathway. Strengthening compost markets, improving biogas recovery efficiency, and minimizing internal energy demand are key levers for maximizing environmental benefits across all midpoint impact categories.

4.4 Practical implications

The findings of this study carry several important implications for municipal solid waste management, energy policy, and climate mitigation strategies, particularly in countries with high organic waste generation and carbon-intensive energy systems such as India. Following recommendations are suggested based on this work:

- The results demonstrate that composting facilities should be recognized not merely as waste treatment infrastructure but as integrated resource recovery systems. Policies that focus only on waste diversion or landfill avoidance risk overlooking significant climate mitigation opportunities. Explicitly incentivizing the valorization of composting leachate, rather than treating it as a residual liability, can substantially improve the environmental performance of composting systems. Regulatory frameworks and design guidelines for composting plants should therefore mandate or encourage leachate collection and its productive utilization, including anaerobic digestion.

- The study highlights the dominant role of fertilizer substitution in determining environmental benefits across most impact categories. This implies that the climate and environmental success of composting depend heavily on secure and sustained end-markets for compost and liquid fermented organic manure (LFOM). Policymakers should strengthen demand-side measures, such as quality standards, certification schemes, public procurement mandates, and extension services for farmers, to ensure consistent uptake of organic fertilizers. Without such market assurance, even technically advanced composting systems risk becoming net greenhouse gas emitters.

- Among the evaluated energy recovery pathways, biogas-to-electricity emerged as the most robust and resilient option under a wide range of operational conditions. Given India's coal-dominated electricity grid, policies that support grid integration of biogas-based electricity-such as preferential feed-in tariffs, net metering, or recognition under renewable purchase obligations-can deliver immediate and reliable climate benefits. While compressed biomethane (CBG) for transport offers long-term decarbonization potential, its higher sensitivity to upgrading efficiency suggests that it should be promoted selectively, where high biogas yields and reliable fuel substitution can be ensured.

- The sensitivity and break-even analyses underscore the importance of spatial planning and decentralization. Transport distance was shown to be a critical boundary condition beyond which environmental benefits rapidly erode. Urban and regional planning policies should therefore prioritize decentralized or peri-urban composting and digestion facilities located close to waste generation centres to minimize logistics-related emissions.

4.5 Summary

This study shows that the environmental sustainability of OFMSW composting systems is governed not only by waste stabilization but also by the effective valorization of all outputs, particularly compost leachate. By integrating leachate-based energy recovery into the life cycle boundary, the analysis highlights a major opportunity to enhance the climate performance of composting facilities.

Among the evaluated scenarios, composting combined with anaerobic digestion of leachate and biogas-to-electricity generation emerged as the most robust and environmentally favorable option, consistently achieving net-negative global warming impacts. The biogas-to-CBG pathway approached climate neutrality but was more sensitive to biogas yield and the energy demand of upgrading and compression. Across midpoint impact categories, fertilizer substitution from compost and liquid fermented organic manure dominated environmental benefits, while energy recovery provided important additional gains, particularly for climate change and fossil resource depletion.

Sensitivity and break-even analyses revealed that compost utilization rates, transport distances, and energy recovery efficiency are decisive factors determining climate viability. These findings indicate that composting systems must be designed as integrated circular economy infrastructures rather than standalone treatment units. Ensuring secure compost markets, minimizing transport distances, and valorizing leachate through energy recovery are essential to transform OFMSW management from an emissions source into a reliable climate mitigation pathway.

Reference

Aereon, 2022. Retrofitting Air-Assisted Flares to Attain 99.5% Destruction Efficiency [WWW Document]. URL https://aereon.com/retrofitting-air-assisted-flares-to-attain-99-5-destruction-efficiency/?utm_source=chatgpt.com

Alengebawy, A., Mohamed, B.A., Ghimire, N., Jin, K., Liu, T., Samer, M., Ai, P., 2022. Understanding the environmental impacts of biogas utilization for energy production through life cycle assessment: An action towards reducing emissions. Environ. Res. 213, 113632. https://doi.org/10.1016/j.envres.2022.113632

American Biogas Council, 2025. FAQs [WWW Document]. URL https://americanbiogascouncil.org/resources/biogas-faqs-american-biogas-council/#leakage

Arias, A., Rama, M., González-García, S., Feijoo, G., Moreira, M.T., 2020. Environmental analysis of servicing centralised and decentralised wastewater treatment for population living in neighbourhoods. Journal of Water Process Engineering 37, 101469. https://doi.org/10.1016/j.jwpe.2020.101469

Ayyad, A., Abbas, A., Elminshawy, N., 2021. A simulation study of the effect of post-combustion amine-based carbon-capturing integrated with solar thermal collectors for combined cycle gas power plant. Discover Sustainability 2, 9. https://doi.org/10.1007/s43621-021-00018-x

Bernstad, A., la Cour Jansen, J., 2012. Review of comparative LCAs of food waste management systems – Current status and potential improvements. Waste Management 32, 2439–2455. https://doi.org/10.1016/j.wasman.2012.07.023

Biancini, G., Marchetti, B., Cioccolanti, L., Moglie, M., 2022. Comprehensive Life Cycle Assessment Analysis of an Italian Composting Facility concerning Environmental Footprint Minimization and Renewable Energy Integration. Sustainability 14, 14961. https://doi.org/10.3390/su142214961

Bisinella, V., Hulgaard, T., Riber, C., Damgaard, A., Christensen, T.H., 2021. Environmental assessment of carbon capture and storage (CCS) as a post-treatment technology in waste incineration. Waste Management 128, 99–113. https://doi.org/10.1016/j.wasman.2021.04.046

Buffi, M., Hurtig, O., Scarlat, N., 2024. Methane emissions in the biogas and biomethane supply chains in the EU An analysis to update the greenhouse gas emissions accounting. https://doi.org/10.2760/7927411

Cañote, S.J.B., Barros, R.M., Lora, E.E.S., del Olmo, O.A., dos Santos, I.F.S., Piñas, J.A.V., Ribeiro, E.M., de Freitas, J.V.R., de Castro e Silva, H.L., 2021. Energy and Economic Evaluation of the Production of Biogas from Anaerobic and Aerobic Sludge in Brazil. Waste Biomass Valorization 12, 947–969. https://doi.org/10.1007/s12649-020-01046-w

Chandel, M.K., Kwok, G., Jackson, R.B., Pratson, L.F., 2012. The potential of waste-to-energy in reducing GHG emissions. Carbon Manag. 3, 133–144. https://doi.org/10.4155/cmt.12.11

Cheela, V.R.S., John, M., Biswas, W., Dubey, B., 2023. Environmental impact evaluation of landfill mining of legacy waste with on-site sorting using life cycle assessment. Environmental Science and Pollution Research 30, 30033–30047. https://doi.org/10.1007/S11356-022-24210-2/TABLES/3

Cherubini, F., Strømman, A.H., 2011. Life cycle assessment of bioenergy systems: State of the art and future challenges. Bioresour. Technol. 102, 437–451. https://doi.org/10.1016/j.biortech.2010.08.010

Chicaiza-Ortiz, C., Peñafiel-Arcos, P., Herrera-Feijoo, R.J., Ma, W., Logroño, W., Tian, H., Yuan, W., 2024. Waste-to-Energy technologies for municipal solid waste management: Bibliometric review, life cycle assessment, and energy potential case study. J. Clean. Prod. 480, 143993. https://doi.org/10.1016/j.jclepro.2024.143993

Chmelíková, L., Schmid, H., Anke, S., Hülsbergen, K.-J., 2021. Nitrogen-use efficiency of organic and conventional arable and dairy farming systems in Germany. Nutr. Cycl. Agroecosyst. 119, 337–354. https://doi.org/10.1007/s10705-021-10126-9

Christensen, T.H., Bisinella, V., 2021. Climate change impacts of introducing carbon capture and utilisation (CCU) in waste incineration. Waste Management 126, 754–770. https://doi.org/10.1016/j.wasman.2021.03.046

Clasen, A.P., Agostinho, F., Almeida, C.M.V.B., Liu, G., Giannetti, B.F., 2024. Advancing towards circular economy: Environmental benefits of an innovative biorefinery for municipal solid waste management. Sustain. Prod. Consum. 46, 571–581. https://doi.org/10.1016/j.spc.2024.03.015

Colón, J., Martínez-Blanco, J., Gabarrell, X., Artola, A., Sánchez, A., Rieradevall, J., Font, X., 2010. Environmental assessment of home composting. Resour. Conserv. Recycl. 54, 893–904. https://doi.org/10.1016/j.resconrec.2010.01.008

E., P., Sarkar, S., Maji, P.K., 2024. A review on slow-release fertilizer: Nutrient release mechanism and agricultural sustainability. J. Environ. Chem. Eng. 12, 113211. https://doi.org/10.1016/j.jece.2024.113211

Elgas, 2023. LPG Gas Composition: LPG Gas Mixture of Propane & Butane [WWW Document]. URL https://www.elgas.com.au/elgas-knowledge-hub/residential-lpg/lpg-composition/

Esteves, E.M.M., Herrera, A.M.N., Esteves, V.P.P., Morgado, C. do R.V., 2019. Life cycle assessment of manure biogas production: A review. J. Clean. Prod. 219, 411–423. https://doi.org/10.1016/j.jclepro.2019.02.091

Evangelisti, S., Clift, R., Tagliaferri, C., Lettieri, P., 2017. A life cycle assessment of distributed energy production from organic waste: Two case studies in Europe. Waste Management 64, 371–385. https://doi.org/10.1016/j.wasman.2017.03.028

Ferreira, S.F., Buller, L.S., Berni, M., Forster-Carneiro, T., 2019a. Environmental impact assessment of end-uses of biomethane. J. Clean. Prod. 230, 613–621. https://doi.org/10.1016/j.jclepro.2019.05.034

Ferreira, S.F., Buller, L.S., Berni, M., Forster-Carneiro, T., 2019b. Environmental impact assessment of end-uses of biomethane. J. Clean. Prod. 230, 613–621. https://doi.org/10.1016/j.jclepro.2019.05.034

Fuchsz, M., Kohlheb, N., 2015. Comparison of the environmental effects of manure- and crop-based agricultural biogas plants using life cycle analysis. J. Clean. Prod. 86, 60–66. https://doi.org/10.1016/j.jclepro.2014.08.058

Gao, C., Bian, R., Li, P., Yin, C., Teng, X., Zhang, J., Gao, S., Niu, Y., Sun, Y., Wang, Y., Wang, H., 2025. Analysis of carbon reduction potential from typical municipal solid waste incineration plants under MSW classification. J. Environ. Manage. 373, 123844. https://doi.org/10.1016/j.jenvman.2024.123844

González, R., Rosas, J.G., Blanco, D., Smith, R., Martínez, E.J., Pastor-Bueis, R., Gómez, X., 2020. Anaerobic digestion of fourth range fruit and vegetable products: comparison of three different scenarios for its valorisation by life cycle assessment and life cycle costing. Environ. Monit. Assess. 192, 551. https://doi.org/10.1007/s10661-020-08521-w

Guo, H., Zhao, Y., Damgaard, A., Wang, Q., Wang, H., Christensen, T.H., Lu, W., 2021. Quantifying global warming potential of alternative biorefinery systems for producing fuels from Chinese food waste. Waste Management 130, 38–47. https://doi.org/10.1016/j.wasman.2021.05.004

Guo, Y., Hatton, T.A., 2025. Enhancing continuous-flow CO2 capture and release from aqueous carbonates via thermal pH regulation. Nature Chemical Engineering. https://doi.org/10.1038/s44286-025-00313-8

Hakawati, R., Smyth, B.M., McCullough, G., De Rosa, F., Rooney, D., 2017a. What is the most energy efficient route for biogas utilization: Heat, electricity or transport? Appl. Energy 206, 1076–1087. https://doi.org/10.1016/j.apenergy.2017.08.068

Hakawati, R., Smyth, B.M., McCullough, G., De Rosa, F., Rooney, D., 2017b. What is the most energy efficient route for biogas utilization: Heat, electricity or transport? Appl. Energy 206, 1076–1087. https://doi.org/10.1016/j.apenergy.2017.08.068

Havukainen, J., Zhan, M., Dong, J., Liikanen, M., Deviatkin, I., Li, X., Horttanainen, M., 2017. Environmental impact assessment of municipal solid waste management incorporating mechanical treatment of waste and incineration in Hangzhou, China. J. Clean. Prod. 141, 453–461. https://doi.org/10.1016/j.jclepro.2016.09.146

Henderson, C., 2015. Power plant CO2 capture heat integration. IEA Clean Coal Centre.

IEA Bioenergy, 2017. Methane emissions from biogas plants, IEA Bioenergy - Task 37.

IPCC, 2005. IPCC Special report on Carbon dioxide capture and storage. Prepared by Working Group III of the Intergovernmental Panel on Climate Change, Cambridge University Press. Cambridge, United Kingdom and New York, NY, USA.

Jayawickrama, K., Ruparathna, R., Seth, R., Biswas, N., Hafez, H., Tam, E., 2024. Challenges and Issues of Life Cycle Assessment of Anaerobic Digestion of Organic Waste. Environments 11, 217. https://doi.org/10.3390/environments11100217

Jin, Q., Yang, L., Poe, N., Huang, H., 2018. Integrated processing of plant-derived waste to produce value-added products based on the biorefinery concept. Trends Food Sci. Technol. 74, 119–131. https://doi.org/10.1016/j.tifs.2018.02.014

Kalita, S., Ohlsson, J.A., Karlsson Potter, H., Nordberg, Å., Sandgren, M., Hansson, P.-A., 2023. Energy performance of compressed biomethane gas production from co-digestion of Salix and dairy manure: factoring differences between Salix varieties. Biotechnology for Biofuels and Bioproducts 16, 165. https://doi.org/10.1186/s13068-023-02412-1

Keogh, N., Corr, D., Monaghan, R.F.D., 2024. An environmental and economic assessment for biomethane injection and natural gas heavy goods vehicles. Appl. Energy 360, 122800. https://doi.org/10.1016/j.apenergy.2024.122800

Khandelwal, H., Dhar, H., Thalla, A.K., Kumar, S., 2019. Application of life cycle assessment in municipal solid waste management: A worldwide critical review. J. Clean. Prod. 209, 630–654. https://doi.org/10.1016/j.jclepro.2018.10.233

Koornneef, J., van Keulen, T., Faaij, A., Turkenburg, W., 2008. Life cycle assessment of a pulverized coal power plant with post-combustion capture, transport and storage of CO2. International Journal of Greenhouse Gas Control 2, 448–467. https://doi.org/10.1016/j.ijggc.2008.06.008

Kristensen, P.G., Jensen, J.K., Nielsen, M., Illerup, J.B., 2004. Emission factors for gas fired CHP units < 25 Mw, in: International Gas Research Conference Proceedings.

Kumar, A., Agrawal, A., 2020. Recent trends in solid waste management status, challenges, and potential for the future Indian cities – A review. Current Research in Environmental Sustainability 2, 100011. https://doi.org/10.1016/j.crsust.2020.100011

Kumar, M., 2023. Lack of market support for bio-manure hindering growth of compressed biogas plants [WWW Document]. URL https://india.mongabay.com/2023/01/lack-of-market-support-for-bio-manure-hindering-growth-of-compressed-biogas-plants/

Lausselet, C., Cherubini, F., Oreggioni, G.D., del Alamo Serrano, G., Becidan, M., Hu, X., Rørstad, P.Kr., Strømman, A.H., 2017. Norwegian Waste-to-Energy: Climate change, circular economy and carbon capture and storage. Resour. Conserv. Recycl. 126, 50–61. https://doi.org/10.1016/j.resconrec.2017.07.025

Liu, W., Zhang, Z., Xie, X., Yu, Z., von Gadow, K., Xu, J., Zhao, S., Yang, Y., 2017. Analysis of the Global Warming Potential of Biogenic CO2 Emission in Life Cycle Assessments. Sci. Rep. 7, 39857. https://doi.org/10.1038/srep39857

López González, L.M., Pereda Reyes, I., Pedraza Garciga, J., Barrera, E.L., Romero Romero, O., 2020. Energetic, economic and environmental assessment for the anaerobic digestion of pretreated and codigested press mud. Waste Management 102, 249–259. https://doi.org/10.1016/j.wasman.2019.10.053

Martínez-Arce, A., Kargupta, W., Domínguez, C.G., Odey, E.A., McMahon, H., Huerta, J.D., Zimmermann, J., Bishop, G., Gaffey, J., Styles, D., 2025. An integrated technoeconomic and environmental assessment of biomethane production via anaerobic digestion of food waste in Ireland: Updated insights under market volatility. Sustainable Energy Technologies and Assessments 82, 104563. https://doi.org/10.1016/j.seta.2025.104563

Masson-Delmotte, V., Zhai, P., Pirani, A., Connors, S., Péan, C., Berger, S., Caud, N., Chen, Y., Goldfarb, L., Gomis, M., Huang, M., 2021. Climate change 2021: the physical science basis. Contribution of working group I to the sixth assessment report of the intergovernmental panel on climate change.

Materazzi, M., Chari, S., Sebastiani, A., Lettieri, P., Paulillo, A., 2024. Waste-to-energy and waste-to-hydrogen with CCS: Methodological assessment of pathways to carbon-negative waste treatment from an LCA perspective. Waste Management 173, 184–199. https://doi.org/10.1016/j.wasman.2023.11.020

Mendieta, O., Castro, L., Rodríguez, J., Escalante, H., 2020. Management and valorization of waste from a non-centrifugal cane sugar mill via anaerobic co-digestion: Technical and economic potential. Bioresour. Technol. 316, 123962. https://doi.org/10.1016/j.biortech.2020.123962

MoHUA, 2021. Circular Economy in Municipal solid and liquid waste. Ministry of Housing and Urban Affairs, GOI 1–112.

Montejo, C., Tonini, D., Márquez, M. del C., Fruergaard Astrup, T., 2013. Mechanical–biological treatment: Performance and potentials. An LCA of 8 MBT plants including waste characterization. J. Environ. Manage. 128, 661–673. https://doi.org/10.1016/j.jenvman.2013.05.063

MoPNG, 2025. SATAT.

Mukherjee, A., Chatterjee, S., 2022. Carbon Capture Utilization and Storage (CCUS) – Policy Framework and Deployment Mechanism in India (NITI Aayog).

Naaz, I., Thengane, S.K., Arora, P., Thirumoorthy, G., Singal, S.K., 2025. Waste-to-energy pathways for fresh and legacy waste management: A case study in India. Energy Nexus 19, 100472. https://doi.org/10.1016/j.nexus.2025.100472

Nanlin, L., Fan, L., Hua, Z., Liming, S., Pinjing, H., 2023. Environmental and economic assessment of the construction, operation, and demolition of a decentralized composting facility. Science of The Total Environment 884, 163724. https://doi.org/10.1016/j.scitotenv.2023.163724

Nordahl, S.L., Devkota, J.P., Amirebrahimi, J., Smith, S.J., Breunig, H.M., Preble, C. V., Satchwell, A.J., Jin, L., Brown, N.J., Kirchstetter, T.W., Scown, C.D., 2020. Life-Cycle Greenhouse Gas Emissions and Human Health Trade-Offs of Organic Waste Management Strategies. Environ. Sci. Technol. 54, 9200–9209. https://doi.org/10.1021/acs.est.0c00364

Oviedo-Ocaña, E.R., Abendroth, C., Domínguez, I.C., Sánchez, A., Dornack, C., 2023. Life cycle assessment of biowaste and green waste composting systems: A review of applications and implementation challenges. Waste Management 171, 350–364. https://doi.org/10.1016/j.wasman.2023.09.004

Pasciucco, F., Francini, G., Pecorini, I., Baccioli, A., Lombardi, L., Ferrari, L., 2023. Valorization of biogas from the anaerobic co-treatment of sewage sludge and organic waste: Life cycle assessment and life cycle costing of different recovery strategies. J. Clean. Prod. 401, 136762. https://doi.org/10.1016/j.jclepro.2023.136762

Paulillo, A., Sebastiani, A., Lettieri, P., Materazzi, M., 2024. Decarbonising waste-to-energy: A life cycle assessment study. Resour. Conserv. Recycl. 209, 107812. https://doi.org/10.1016/j.resconrec.2024.107812

Poeschl, M., Ward, S., Owende, P., 2012. Environmental impacts of biogas deployment – Part II: life cycle assessment of multiple production and utilization pathways. J. Clean. Prod. 24, 184–201. https://doi.org/10.1016/j.jclepro.2011.10.030

Pujara, Y., Govani, J., Patel, H.T., Pathak, P., Mashru, D., Ganesh, P.S., 2023. Quantification of environmental impacts associated with municipal solid waste management in Rajkot city, India using Life Cycle Assessment. Environmental Advances 12, 100364. https://doi.org/10.1016/j.envadv.2023.100364

Ravindran, J.K., Fagg, D.P., Coelho, M.C., 2025. Current production routes and life cycle analysis of "Green Energy-Dense Fuels" from biogas: A comprehensive review. Appl. Energy 402, 126832. https://doi.org/10.1016/j.apenergy.2025.126832

Rosa Aon Cardoso Fernandes, A., Eduardo Lobo Baêta, B., Damgaard, A., 2023. Life-cycle assessment as a prospection stage for the biochemical methane potential of pretreated lignocellulosic biomass. Bioresour. Technol. 386, 129584. https://doi.org/10.1016/j.biortech.2023.129584

Sadiq, M., Sharma, R., Kalita, H.J., Pandey, P., 2025. CCUS in India: A Techno-Economic and Policy Roadmap to Net-Zero Amid Climate and Environmental Challenges. Journal Of The Geological Society Of India 101, 1663–1673. https://doi.org/10.17491/jgsi/2025/174290

Sandström, J., Van Heusden, R., Morrison, H., Puleo, M., Murray, L., 2020. Aluminium for Climate: Exploring pathways to decarbonize the aluminium industry. WEF, Cologny/Geneva, Switzerland.

Serafini, L.F., Praça, P.J.G.M., González-Andrés, F., Gonçalves, A., 2025a. Life cycle approach as a tool for assessing municipal biowaste treatment units: A systematic review. Waste Management & Research: The Journal for a Sustainable Circular Economy 43, 1509–1524. https://doi.org/10.1177/0734242X251326866

Serafini, L.F., Praça, P.J.G.M., González-Andrés, F., Gonçalves, A., 2025b. Life cycle approach as a tool for assessing municipal biowaste treatment units: A systematic review. Waste Management & Research: The Journal for a Sustainable Circular Economy. https://doi.org/10.1177/0734242X251326866

Shi, Z., He, P., Guo, J., Zou, J., Peng, W., Zhang, H., Lü, F., 2024. Carbon reduction trade-off between pretreatment and anaerobic digestion: A field study of an industrial-scale biogas plant. Environ. Res. 246, 118139. https://doi.org/10.1016/j.envres.2024.118139

Shinde, A.M., Dikshit, A.K., Odlare, M., Thorin, E., Schwede, S., 2021. Life cycle assessment of bio-methane and biogas-based electricity production from organic waste for utilization as a vehicle fuel. Clean Technol. Environ. Policy 23, 1715–1725. https://doi.org/10.1007/s10098-021-02054-7

Singh, A.D., Upadhyay, A., Shrivastava, S., Vivekanand, V., 2020. Life-cycle assessment of sewage sludge-based large-scale biogas plant. Bioresour. Technol. 309, 123373. https://doi.org/10.1016/j.biortech.2020.123373

Singh, P., Babu, G.L.S., Hoysall, C., Rao, L., 2026. Assessing biogas valorization from municipal organic waste in India: Integrated environmental-economic analysis. Bioresour. Technol. 442, 133675. https://doi.org/10.1016/j.biortech.2025.133675

Singh, P., Kalamdhad, A.S., 2024. Unravelling barriers associated with dissemination of large-scale biogas plant with analytical hierarchical process and fuzzy analytical hierarchical process approach: Case study of India. Bioresour. Technol. 413, 131543. https://doi.org/10.1016/j.biortech.2024.131543

Singh, P., Kalamdhad, A.S., 2022a. Biomethane plants based on municipal solid waste and wastewater and its impact on vehicle sector in India — An Environmental-economic-resource assessment. Environ. Technol. Innov. 26, 102330. https://doi.org/10.1016/j.eti.2022.102330

Singh, P., Kalamdhad, A.S., 2022b. Assessment of agricultural residue-based electricity production from biogas in India: Resource-environment-economic analysis. Sustainable Energy Technologies and Assessments 54, 102843. https://doi.org/10.1016/j.seta.2022.102843

Singh, P., Kalamdhad, A.S., 2022c. Assessment of agricultural residue-based electricity production from biogas in India: Resource-environment-economic analysis. Sustainable Energy Technologies and Assessments 54, 102843. https://doi.org/10.1016/j.seta.2022.102843

Singh, P., Kalamdhad, A.S., 2022d. Biomethane plants based on municipal solid waste and wastewater and its impact on vehicle sector in India — An Environmental-economic-resource assessment. Environ. Technol. Innov. 26, 102330. https://doi.org/10.1016/j.eti.2022.102330

Slorach, P.C., Jeswani, H.K., Cuéllar-Franca, R., Azapagic, A., 2019. Environmental and economic implications of recovering resources from food waste in a circular economy. Science of The Total Environment 693, 133516. https://doi.org/10.1016/j.scitotenv.2019.07.322

Soni, A., Gupta, S.K., Rajamohan, N., Yusuf, M., 2025. Waste-to-energy technologies: a sustainable pathway for resource recovery and materials management. Mater. Adv. 6, 4598–4622. https://doi.org/10.1039/D5MA00449G

Su, D., Herraiz, L., Lucquiaud, M., Thomson, C., Chalmers, H., 2023. Thermal integration of waste to energy plants with Post-combustion CO2 capture. Fuel 332, 126004. https://doi.org/10.1016/j.fuel.2022.126004

TERI, 2023. Financing Decarbonization of the Secondary Steel Sector in India: Towards an Enabling Environment. New Delhi, India: The Energy and Resources Institute.

Tian, P., Wu, Y., Shang, B., Qi, C., Xu, Z., Li, G., Luo, W., Zhang, W., Li, Y., 2025. LCA as a decision support tool for the environmental improvement of organic fraction of municipal solid waste composting in China. J. Clean. Prod. 495, 145068. https://doi.org/10.1016/j.jclepro.2025.145068

Tisserant, A., Morales, M., Cavalett, O., O'Toole, A., Weldon, S., Rasse, D.P., Cherubini, F., 2022. Life-cycle assessment to unravel co-benefits and trade-offs of large-scale biochar deployment in Norwegian agriculture. Resour. Conserv. Recycl. 179, 106030. https://doi.org/10.1016/j.resconrec.2021.106030

Vinayak, A.K., Chauhan, G., 2026. Circularity in polyethylene waste management through multidimensional integration. Next Sustainability 7, 100247. https://doi.org/10.1016/J.NXSUST.2026.100247

Whiting, A., Azapagic, A., 2014. Life cycle environmental impacts of generating electricity and heat from biogas produced by anaerobic digestion. Energy 70, 181–193. https://doi.org/10.1016/j.energy.2014.03.103

Woon, K.S., Lo, I.M.C., Chiu, S.L.H., Yan, D.Y.S., 2016. Environmental assessment of food waste valorization in producing biogas for various types of energy use based on LCA approach. Waste Management 50, 290–299. https://doi.org/10.1016/j.wasman.2016.02.022

Chapter 5
Biogas/Bio-methanation Plants

5.1 Preamble

This study conducted a detailed LCA and economic analysis of OFMSW treatment through biogas plants in Bengaluru and Chennai. The primary objectives were

- to assess and compare the environmental impacts of five distinct utilization scenarios (flaring, electricity production, direct cooking, cooking with direct biogas and also with purified CBG, and CBG vehicle fuel),
- to identify critical parameters influencing their performance,
- to evaluate the economic feasibility of plants across scales (25 – 500 TPD), and
- to recommend strategies for optimizing both environmental and financial outcomes.

5.2 Methodology

This research employed a dual approach of combining environmental and economic analysis and assessments. A LCA study was carried out to evaluate the environmental performance. A financial analysis was carried out by evaluating economic indicators such as net present value (NPV), internal rate of return (IRR) and payback period.

5.2.1 Life cycle assessment (LCA)

The LCA is a standardized, data-driven methodology, guided by ISO 14040/14044, for compiling and evaluating a product system's inputs, outputs, and potential environmental impacts throughout its entire life. It involves four key phases: goal and scope definition, inventory analysis, impact assessment, and interpretation.

5.2.1.1 Goal and Scope

The goal of this study was to estimate the environmental impact of various scenarios for biogas utilization and byproducts produced during the anaerobic digestion of OFMSW. This study also identifies the hotspot along the biogas system for various scenario where most environmental loads are associated. Specifically, five scenarios were considered based on the most common end-uses of biogas pertaining to India:

- **Scenario 1:** Biogas flaring
- **Scenario 2:** Electricity generation from biogas

- **Scenario 3:** Biogas directly used as cooking fuel in nearby areas
- **Scenario 4:** Upgraded biomethane (CBG) used as cooking fuel
- **Scenario 5:** Upgraded biomethane (CBG) used as vehicle fuel

The defined functional unit for this analysis was the treatment of 1000 kg of OFMSW (Clasen et al., 2024; Serafini et al., 2025b). An LCA model usually includes the operation of the treatment facility and the construction and decommissioning of the biogas facility is not considered here, since it has been established that these two phases have negligible environmental impact as compared to operation phase (Arias et al., 2020). The environmental burden of the construction phase (e.g., steel, concrete, site preparation, heavy machinery use) is spread out over the plant's long operational lifespan, which is typically 20 years. A previous study by (Fuchsz and Kohlheb, 2015) reported that these stages typically contributes between 0.9- 7.7% of the total impact compared to the operational phase.

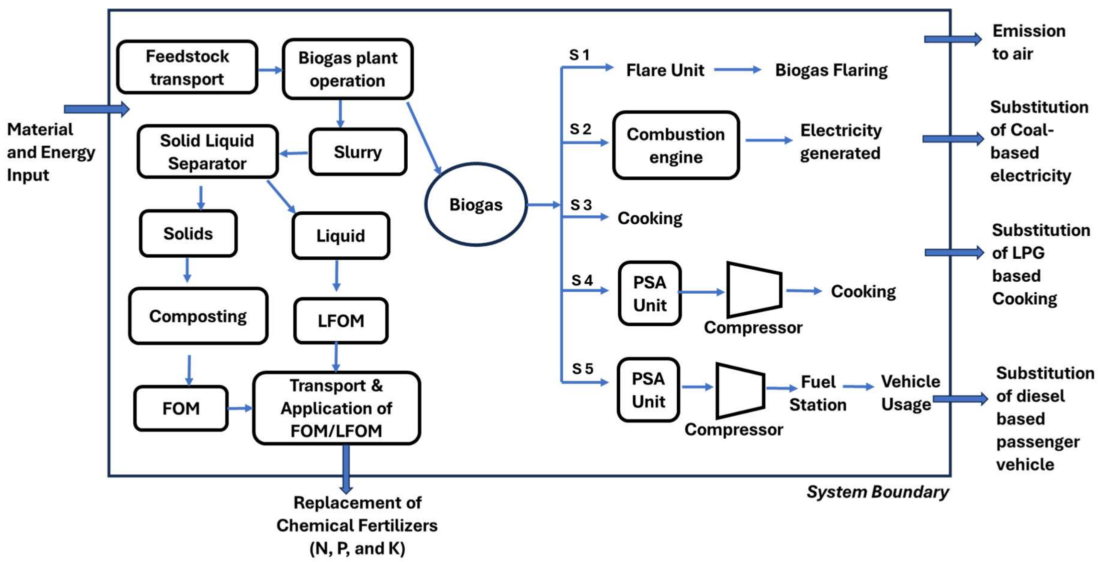


Fig. 5.1 System boundary of the biogas plant life cycle assessment

The system boundary of treatment of OFMSW in biogas plant in this study follows cradle to grave approach (Fig. 5.1) which includes all major operational processes of the biogas plant, namely:

- collection and transportation of OFMSW,
- feed preparation phase (specifically grinding and feeding),
- the digesters (both pre-digesters and main digesters),
- digestate storage, and

- fermented organic manure (FOM) and liquid fermented organic manure (LFOM) preparation and transportation
- Furthermore, biogas upgrading was included where applicable to a given scenario, along with the subsequent usage of the byproducts (biogas and manure).

Credits were applied to account for the substitution of conventional resources by the byproducts of biogas system. These relevant substitutions included generation of coal-based electricity, the use of liquefied petroleum gas (LPG) as cooking fuel, diesel-based vehicle fuel, and the production and application of mineral fertilizer.

5.2.1.2 Life cycle inventory (LCI)

For the inventory analysis, all material and energy inputs and outputs within the system boundary were quantified relative to the functional unit. Wherever possible, foreground data was sourced directly from the field visit and communication with the companies operating the biogas plant, with supplementary data drawn from academic literature. Background data for processes were obtained from the ecoinvent 3.11 database.

5.2.1.3 Scenarios studied

- *Flaring of biogas (Scenario 1)*

The supply chain begins with the collection and transportation of organic waste to the facility. The feedstock undergoes preparation, specifically grinding, before being introduced into the anaerobic digesters. Within these digesters, anaerobic microorganisms break down the organic matter in the absence of oxygen to biogas, primarily a mixture of methane and carbon dioxide. The CO_2 released from biogas plants (through plant leakage, biogas combustion, or during biogas upgradation) is biogenic in nature and hence does not account to global warming (Buffi et al., 2024; Evangelisti et al., 2017). The biogas generated is collected locally and transported via a basic piping system to a flaring unit. Following digestion of OFMSW, the digested organic called fermented organic manure (FOM) and the liquid purveying this organic matter after fermentation is termed fermented organic manure (LFOM) which is prepared by separating the solid and liquid from the digestate slurry (output) generated from biogas plants.

This fermented material in solid and liquid forms (FOM/LFOM), carry a lot of plant and crop nutrients; these are valuable for recycling at a crop to local level to ensure material and resource sustainability. The extent of mineral fertilizers substituted was determined based on the content of nitrogen (N), phosphorus (P_2O_5), and potassium (K_2O) content of the prepared FOM and LFOM, coupled with their respective substitution ratios. The conventional mineral fertilizers often experience nutrient losses of 40-90% in field applications due to leaching, runoff, and volatilization (E. et al., 2024), with an average loss of around 65% used in this study. In contrast, studies have reported that digestate-derived fertilizers (such as FOM and LFOM) can achieve nutrient uptake efficiencies of approximately 90% (Chmelíková et al., 2021), primarily because of their gradual nutrient release and enhanced soil organic matter content.

While this approach builds upon the energy potential of the biogas, it serves as a method for reducing the volumes of waste, controlling mal-odors, and mitigating the environmental impact of methane emissions by converting it to carbon dioxide. The relevant inventory data of this system is presented in Table 1. This list did not include all the materials used. Minor auxiliary materials such as cleaning agents, and small quantities of lubricants used in routine maintenance were excluded from the inventory due to lack of data or information. Given their very low consumption their exclusion is not expected to materially affect the overall LCA results.

- *Electricity production from biogas (Scenario 2)*

In this scenario, biogas produced from OFMSW is converted into electricity using genset engines. The initial stages of this process namely, collection and transportation of OFMSW, feedstock preparation, biogas generation, and manure generation remain consistent with those described in scenario 1. The relevant inventory data for this scenario are presented in Table 5.1. A key assumption for scenario 2 is that the electricity generated from biogas and supplied to the grid will displace an equivalent amount of electricity that would otherwise be produced from coal-based power plants. The use of coal-based electricity as the substitution baseline is justified by two key factors. First, it reflects the operational reality in India, where coal accounts for 70-75% of generation and is often the marginal source displaced by new capacity. Second, this approach aligns with India's strategic climate policy to prioritize phasing out the most carbon-intensive source. This substitution forms the basis for the environmental credits applied in this scenario. Credits related to FOM and LFOM are similar to scenario 1.

- *Biogas directly used as a cooking fuel (Scenario 3)*

In this scenario, the generated biogas is directly utilized as a cooking fuel, serving as a renewable alternative to conventional energy sources. The initial stages of the system, including feedstock preparation, biogas generation, and manure generation, are consistent with those outlined in scenario 1. A key distinguishing feature of this scenario is that it focuses on the direct utilization of biogas at or near the source of waste generation. This implies that the collection and transportation of OFMSW occur over significantly shorter distances, often within the confines of large residential complexes, institutional kitchens, or other facilities where a substantial amount of food waste is generated locally. Consequently, the biogas is typically channeled through a basic piping system to adjacent households or community kitchens, where it is combusted in specially designed biogas stoves for cooking purposes. The primary environmental benefit of this scenario lies in the displacement of conventional cooking fuels, predominantly liquefied petroleum gas (LPG). Environmental credits are applied for the avoided emissions associated with the extraction, processing, and combustion of these displaced fuels. Credits related to FOM and LFOM are similar to scenario 1. The relevant inventory data for this scenario are detailed in Table 5.1

- *Upgraded biomethane used as cooking fuel (Scenario 4)*

In this scenario, the generated biogas undergoes purification and compression to produce upgraded biomethane, which is then used as a cooking fuel. The initial, upstream stages of this process namely, the collection and transportation of OFMSW, feedstock preparation, biogas generation, and manure generation are consistent with those detailed in Scenario 1 and 2. A crucial aspect of this scenario is that the purified and compressed biomethane directly replaces liquefied petroleum gas (LPG) as a cooking fuel. This substitution forms the basis for the environmental credits applied, accounting for the avoided impacts associated with LPG production, transport, and combustion. Credits related to FOM and LFOM are similar to scenario 1. The relevant inventory data for this scenario are presented in Table 5.1.

- *Upgraded biomethane used as vehicle fuel (Scenario 5)*

In this final scenario, OFMSW is anaerobically treated to produce biogas, which then undergoes purification and compression to generate bio-compressed natural gas (bio-CNG) or CBG. This CBG is subsequently utilized as a vehicle fuel. A key environmental advantage of this scenario is the replacement of diesel fuel-based passenger vehicles with those powered by CBG. This substitution directly contributes to reduced reliance on fossil fuels and lower associated emissions. The remainder of the supply chain, encompassing the collection and transportation of OFMSW, feedstock preparation, biogas generation, and manure generation, is consistent with the processes outlined in scenario 1, 2 and 4. The relevant inventory data for this scenario are presented in Table 5.1.

Table 5.1 Inventory data of various utilisation pathway of biogas based on organic fraction of municipal solid waste (per functional unit) (S1: Flaring; S2: Electricity, S3: Direct Cooking, S4: purified and bottled cooking fuel, S5: bio-CNG production for vehicle fuel)

	Units	S1	S2	S3	S4	S5	Comments
Inputs							
Raw material	ton	1	1	1	1	1	
Transportation	km	25	25	-	25	25	
Electricity	kWh	20	20	20	35*	35*	electricity for biogas plant operation (plant data) *Includes purification and compression energy demand
Freshwater	Litre	600	600	600	600	600	300 - 400 L of recycled water is used (plant data)
Outputs							
Biogas	m^3	60	60	60	60	60	Methane content: 60%) (plant data)
Fermented organic manure (FOM)	kg	150	150	150	150	150	15% of input material (plant data)
Liquid fermented organic manure (LFOM)	L	300	300	300	300	300	(plant data)
Emissions to air							
From Plant							
Methane (CH_4)	kg	0.47	0.47	0.47	0.47	0.47	Assuming 2% loss from plant (American Biogas Council, 2025)
From Purification and compression unit							
Methane (CH_4)	kg	-	-	-	1.6	1.6	Purification loss: 7% (based on survey taken from experts working in the field); and 0.075% loss from compression unit (Singh and Kalamdhad, 2022a)
From Fuel station							
Methane (CH_4)	kg	-	-	-	-	0.002	Assuming 0.01% loss from Fuel station (Singh and Kalamdhad, 2022a)
From bio-CNG usage as a vehicle fuel (Tailpipe emission)							
Methane (CH_4)	kg	-	-	-	-	0.102	Assuming tailpipe emission to be 0.48% (Singh and Kalamdhad, 2022a)
From biogas flaring							
Methane (CH_4)	kg	0.114	-	-	-	-	Flare efficiency to be 99.5% (Aereon, 2022)
Carbon dioxide (CO_2)	kg	66	-	-	-	-	This CO_2 emission is considered to be biogenic
From biogas combustion for electricity							
Methane (CH_4)	kg	-	0.102	-	-	-	CH_4 emission of 1.16 g/kWh (Kristensen et al., 2004)
Carbon dioxide (CO_2)	kg	-	90	-	-	-	Considered to be biogenic
Carbon monoxide (CO)	kg	-	0.09	-	-	-	CO emission of 1 g/kWh (Kristensen et al., 2004)
Dinitrogen monoxide (N_2O)	mg	-	0.15	-	-	-	N_2O emission of 0.0025 g/kWh (Kristensen et al., 2004)
From biogas/bio-CNG combustion for cooking							
Methane (CH_4)	kg	-	-	0.072	0.07	-	Combustion efficiency 99.5%; considered to be biogenic

Carbon dioxide (CO_2)	kg	-	-	66	58.8	-	
From digestate storage							
Methane (CH_4)	kg	0.12	0.12	0.12	0.12	0.12	0.5% emission is assumed from digestate tank (IEA Bioenergy, 2017)
From digestate preparation and application							
	-	Negligible					Slurry is assumed to be stabilized
<u>Offset</u>							
Fuel Replacement							
Coal-based electricity	kWh	-	88	-	-	-	Emission loss is to taken as 2%, engine efficiency as 25%, LHV of biogas as 5.56 kWh/m^3 (Hakawati et al., 2017; Singh and Kalamdhad, 2022b)
Cooking Fuel (LPG)	kg	-	-	26.46	23	-	Assuming 1 m^3 of biogas is equivalent to 0.45 kg of LPG (Cañote et al., 2021). LPG is 35% propane and 65% butane (Elgas, 2023)
Diesel	L	-	-	-	-	26.2	Bio-CNG available: 22 kg (calculated); Fuel efficiency - Bio-CNG: 24 km/kg. (Singh and Kalamdhad, 2022a)
Emission savings during LPG usage							
Propane	kg	-	-	0.03	0.02	-	Assuming unburnt propane during use is 0.03% (calculated)
Butane	kg	-	-	0.05	0.05	-	Assuming unburnt butane during use is 0.03% (calculated)
Carbon dioxide (CO_2)	kg	-	-	79.11	68.77	-	1 kg of LPG combustion releases 2.99 kg of CO_2 (calculated)
Emission savings during diesel usage							
Methane (CH_4)	gm	-	-	-	-	2.84	CH_4 emission of 0.13 g/kg (Singh and Kalamdhad, 2022a)
Carbon dioxide (CO_2)	kg	-	-	-	-	70	CO_2 emission of 3186 g/kg (Singh and Kalamdhad, 2022a)
Dinitrogen monoxide (N_2O)	gm	-	-	-	-	0.57	N_2O emission of 0.26 g/kg (Singh and Kalamdhad, 2022a)
Fermented Organic Manure (FOM)							
N	kg	4.4	4.4	4.4	4.4	4.4	N – 1.8%, P – 1.2%, and K – 1.2% on the dry basis, Moisture content - 40% (plant data). Portion of synthetic fertilizer wasted 40-90% (E. et al., 2024), efficiency: organic fertilizer 90% (Chmelíková et al., 2021)
P (as P_2O_5)	kg	2.9	2.9	2.9	2.9	2.9	
K (as K_2O)	kg	2.9	2.9	2.9	2.9	2.9	
Liquid Fermented Organic Manure (LFOM)							
N	kg	0.73	0.73	0.73	0.73	0.73	N – 1.8%, P – 1.2%, and K – 1.2% on the dry basis, Moisture content - 95%. Losses and efficiency are same as FOM
P (as P_2O_5)	kg	0.49	0.49	0.49	0.49	0.49	
K (as K_2O)	kg	0.49	0.49	0.49	0.49	0.49	

5.2.1.4 Life cycle impact assessment (LCIA)

The LCA for this study was performed using SimaPro (version 10.2.0.2). For the assessment of environmental impacts, the ReCiPe 2016 (H) method was employed for both midpoint and endpoint estimations (Poeschl et al., 2012; Singh et al., 2020). The mid-point impact categories considered in this study are global warming (GW), terrestrial acidification (TA), freshwater eutrophication (FE), terrestrial ecotoxicity (TE), freshwater ecotoxicity (FET), human carcinogenic toxicity (HCT), human non-carcinogenic toxicity (HNCT), mineral resource scarcity (MRS), and fossil resource scarcity (FRS). The endpoint impact assessment was conducted using the ReCiPe 2016 Endpoint (H) v1.11 / World (2010) H/A method. The method aggregates results across three areas of protection: human health, ecosystem quality, and resource scarcity. Using ReCiPe 2016 Endpoint (H) v1.11 / World (2010) H/A, normalization expresses each damage type as a share of the 2010 global per-capita environmental load, and weighting applies the average perspective weights (400, 400, 200) to combine them into a single score in Pt.

5.2.1.5 Sensitivity analysis

To ensure the reliability of our findings, a one-at-a-time sensitivity analysis was performed by systematically varying critical input parameters across established ranges. This approach directly measures the normalized impact of each parameter's uncertainty on the global warming (GW). Five key influencing factors were selected based on the utilization pathways.

- Logistics (Transportation distance): The effect of centralized versus decentralized plants by varying the average transportation distance of OFMSW from the minimum feasible distance (approximated at 25 km) up to 100 km. This establishes the break-even point where logistical emissions negated the environmental benefits of the biogas utilization pathways.
- Performance (Biogas yield): To account for variations in feedstock quality and operational stability, GW sensitivity to the total biogas yield is analyzed, spanning a typical range from 40 m^3 to 100 m^3/ton OFMSW. This range encompasses low-performing and optimized-yield scenarios, highlighting the critical nature of front-end process stability.
- Process efficiency (Purification losses/methane slip): This is the most crucial environmental parameter. We investigated the effect of methane slip during the upgrading process (for CBG/Vehicle fuel and purified cooking gas) by varying purification losses from 2% (ideal scenario) up to 10% (poorly managed system). This analysis directly

quantifies how fugitive methane emissions erode the climate mitigation benefits, which is particularly relevant for the high-end utilization pathways.

- Market dynamics (Fossil substitution rate): The environmental credit derived from substituting fossil fuels (coal for electricity, LPG for cooking, or diesel for vehicle fuel) is assessed by varying the rate of fossil substitution from 0% to 100% to identify the substitution rate required to cross the GW break-even point.
- Co-product value (Fertilizer substitution rate): The rate at which the separated FOM and LFOM fractions substitute commercial mineral fertilizers was varied from 0% (no credit) to 100% (full credit) substitution to gauge the impact of local agricultural market acceptance on environmental impact.

These scenario ranges provide a robust framework for isolating the high-leverage parameters and demonstrating where operational control and policy intervention will yield the highest returns in both climate mitigation and financial performance.

5.2.2 Economic assessment

The economic analysis evaluated bio-CNG plants (with or without subsidy) at scales of 25, 50, 100, 200, and 500 TPD. The key indicators included net present value (NPV) (eqn. 5.1), internal rate of return (IRR) (eqn. 5.2), and payback period (eqn. 5.3), calculated over a 20-year lifespan with a 15% discount rate (Pasciucco et al., 2023; Singh and Kalamdhad, 2022a). Revenue streams included CBG, fermented organic manure (FOM), and liquid fermented organic manure (LFOM). The capital expenditure (CaPex) and operational expenditure (OPex) data for various scales of bio-CNG plant is obtained from official documents published by the Ministry of Housing and Urban Affairs (MoHUA, 2021), Government of India, which provide standardized cost benchmarks for waste-to-energy and bio-CNG facilities across various scales. The data for economic analysis is presented in Table 2. For the purpose of this analysis, it is assumed that each ton of municipal solid waste (MSW) generates 60 m^3 of biogas with a methane content of 60%. A conversion ratio of 0.36 is used to model the production of compressed biogas (CBG) from raw biogas, indicating that 1 m^3 of biogas yields 0.36 kg of CBG. This factor accounts for cumulative losses during the production (2%), purification (7%), compression, and fueling stages. The plant's operational schedule is set at 350 days per year with a total lifespan of 20 years (Singh and Kalamdhad, 2022a). In addition to CBG, the process yields fermented organic manure at a rate of 15% of the input material and liquid fermented organic manure (LFOM) at a rate of 0.3 kL/t of OFMSW input. A key market assumption is that all CBG, FOM, and LFOM produced are sold. Financially, the procurement cost of CBG (purified to IS 16087:2016 standards and compressed at 250 bars) is assumed to be ₹66.01/kg ($0.74/kg) (excluding GST), corresponding to a retail slab of ₹80.01 - ₹85/kg (MoPNG, 2025). The model incorporates an annual escalation of 2% for operating expenses (OPex), while the selling prices for CBG and solid manure are projected to increase by 1% per annum (Singh and Kalamdhad, 2022a). It is important to note that this analysis does not account for subsidies, salvage value, insurance, or interest on loans.

$$NPV = -initial\ cost + \sum_{i=1}^{n} \frac{Net\ cash\ flow}{(1+r)^i} \tag{5.1}$$

$$NPV = 0 = -initial\ cost + \sum_{i=1}^{n} \frac{Net\ cash\ flow}{(1+\text{IRR})^i} \tag{5.2}$$

$$\text{Payback period} = \frac{Total\ Initial\ investment}{Yearly\ cash\ flow} \tag{5.3}$$

Where r, is discount rate (taken as 15%), n the lifespan in years (taken as 20 years), and IRR is internal rate of return

The GoI has standardized digestate products like FOM and LFOM under FCO (FCO 2025), which provides essential quality benchmarks to ensure their safe agricultural application and integration into the circular economy. Furthermore, schemes like SATAT and GOBAR-Dhan create assured market linkages through financial incentives and mandates for fertilizer companies to offtake FOM from biogas plants, thereby transforming the digestate into a standardized, marketable commodity. In a general context, the marketability and economic value of anaerobic digestate can still be uncertain. To account for this, in this study three distinct revenue scenarios are modelled to reflect the dynamic market and assess the economic viability under different business models:

- Scenario 1 (CBG only): This conservative baseline reflects a situation where a plant owner focuses solely on the energy-selling aspect, treating digestate as a cost (for disposal) or a zero-value product.
- Scenario 2 (CBG and FOM sold): This represents the most common emerging business model, where the solid digestate is processed into standardized FOM and sold as a valuable biofertilizer, leveraging the new FCO standards.
- Scenario 3 (CBG, FOM, and LFOM sold): This reflects a full-resource valorization model where both the solid and liquid fractions of the digestate are monetized, maximizing the plant's circular economy potential.

Table 5.2 Data for economic analysis of different scales (from 25-500 TPD) bio-CNG plants

Quantity of waste (TPD)	**25**	**50**	**100**	**200**	**500**
Cost					
CAPEX, ₹ in lakhs	₹1200	₹2000	₹3500	₹6000	₹12000
	($1,352,813)	($2,254,690)	($3,945,707)	($6,764,069)	($13,528,138)
OPEX, ₹ lakhs/year	75	120	189	300	600
	($84,568)	($135,308)	($213,111)	($338,272)	($676,544)
Revenue Details					
Compressed biogas (CBG), kg/day	540	1080	2160	4320	10800
Fermented organic manure (FOM), TPD	3.75	7.5	15	30	75
Liquid fermented organic manure (LFOM), TPD	7.5	15	30	60	150
CBG Price, ₹/kg	66.01	66.01	66.01	66.01	66.01
	($0.74)	($0.74)	($0.74)	($0.74)	($0.74)
Fermented organic manure (FOM), ₹ /Ton	2000	2000	2000	2000	2000
	($22.55)	($22.55)	($22.55)	($22.55)	($22.55)
Liquid fermented organic manure (FOM), ₹ /Ton	1000	1000	1000	1000	1000
	($11.27)	($11.27)	($11.27)	($11.27)	($11.27)
Revenue per year					
CBG, ₹ lakhs	124.7	249.5	499.1	998.1	2495.2
	($140,537)	($281,186)	($562,373)	($1,124,746)	($2,811,864)
FOM, ₹ lakhs	26.25	52.5	105	210	525
	($29,588)	($59,177)	($118,353)	($236,706)	($591,765)
LFOM, ₹ lakhs	26.25	52.5	105	210	525
	($29,588)	($59,177)	($118,353)	($236,706)	($591,765)

5.3 Results and Discussion: Part I Bangalore

5.3.1 Life cycle impact assessment

5.3.1.1 Global warming

The global warming (GW) of an anaerobic digestion plant employing biogas flaring per ton OFMSW (Scenario 1) is presented in Fig. 5.2a. The results highlight individual contributions of various activities, the most significant contribution in gross emission (or total without credit) being associated in with digesters unit (pre-digesters and main digesters). The credits in form of fertilizer offset (48 kg CO_2 eq.), are also accounted which substantially reduces GW by avoiding emissions arising through the substitution of synthetic fertilizers production by the use of FOM and LFOM (Mendieta et al., 2020). Conversely, processes like feedstock transportation, plant operation and OFMSW pre-processing such as griding and feeding, digestate handling, etc contribute positively to GW. Ultimately, while the gross GW before credits (represented as total without credits in Fig. 2a.) stands at 61 kg CO_2 eq., and net GW at 13 kg CO_2 eq. (represented as total in Fig. 2a.) this indicates the vital role of digestate utilization while replacing synthetic fertilizer in the overall environmental performance of the system.

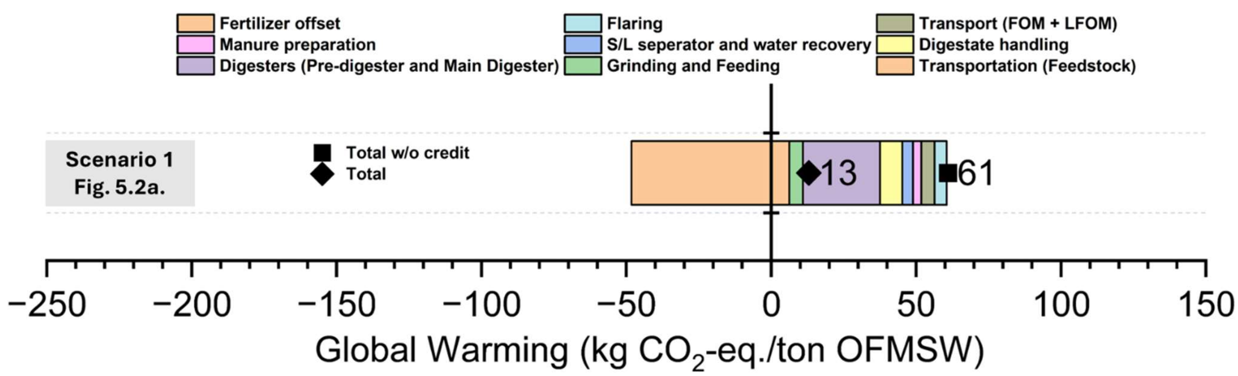
The option of biogas-to-electricity conversion (Scenario 2) has an almost similar extent of GW of 61 kg CO_2-eq as scenario 1 without accounting for related benefits (Fig. 5.2b.). The GW is reduced by 302% after considering the offset. The overall GW becomes negative, indicating a net environmental benefit where more emissions are avoided than generated. This substantial environmental advantage is primarily driven by the "electricity offset," where renewable electricity generation displaces emissions from conventional power sources (88 kWh coal-based electricity), followed by the "fertilizer offset" from utilizing FOM and LFOM. While operational aspects like feedstock transportation and the combustion process itself contribute positively to GW, the overall system functions as a net reducer of GHG emissions, highlighting the superior climate mitigation potential of energy recovery from biogas compared to simple flaring.

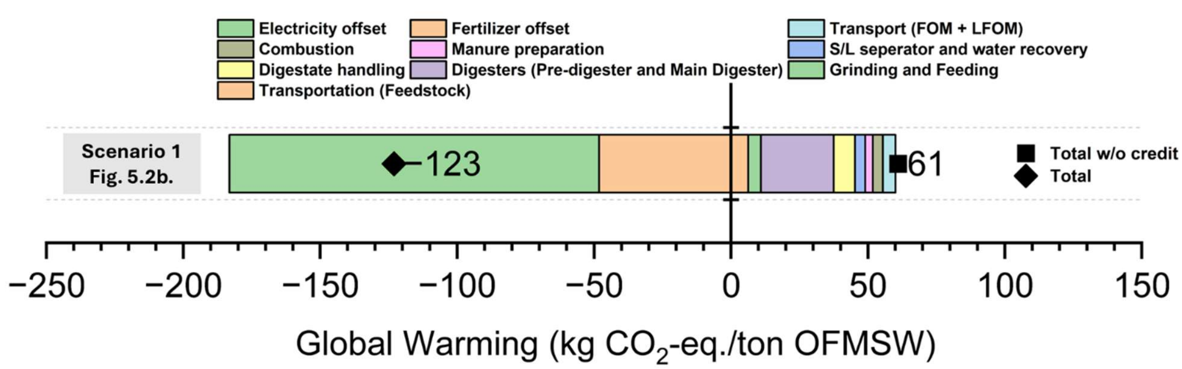
In Scenario 3, the biogas produced is utilized as a cooking fuel, acting as a renewable substitute for conventional sources of energy, namely LPG. This has a significant 52 kg CO_2-eq GW before benefits are taken into consideration (Fig. 5.2c.). The reduction in gross GW compared to Scenario 1 and 2 is mainly because of elimination of feedstock transportation activity. This achieves a notable net negative GW of -108 kg CO_2-eq. The combined offsets lead to a remarkable 308% reduction in GW. This substantial environmental benefit is primarily driven by the "cooking fuel offset," which represents the avoided emissions from displacing conventional cooking fuels (26 kg LPG in this case) and is further enhanced by the "fertilizer offset" from utilizing nutrient-rich FOM and LFOM as a sustainable alternative to synthetic fertilizers. Despite positive GW contributions from operational aspects like feedstock transportation, biogas combustion, and digester processes, the combined offsets render the system a net reducer of greenhouse gas emissions, showcasing the significant climate mitigation potential of such integrated waste-to-energy and resource recovery systems.

In Scenario 4, the biogas produced is compressed and purified to generate upgraded biomethane (locally called compressed biogas, CBG (MoPNG, 2025)), which is subsequently utilized as a cooking fuel. The result shows that Scenario 4, achieves a gross GW of 133 kg CO_2-eq (Fig. 5.2d). After offsetting through the use as cooking fuel and fertilizer use, the GW gets reduced by 91%. In this outcome, although the GW is higher than scenarios involving direct biogas use or electricity generation, it still signifies an overall environmental benefit, as a higher level of emissions is avoided than generation. The primary driver for this GW reduction is the substantial "cooking fuel offset," attributed to the displacement of 23 kg LPG with CBG. However, this benefit is partially counteracted by the significant positive GW contribution from the "purification and compression" process (74 kg CO_2-eq), highlighting the emissions losses (7%) and energy intensity (0.21 kWh/m^3 of raw biogas) for upgrading biogas. Coupled with the "fertilizer offset" from digestate utilization and other operational emissions like feedstock transportation, the result indicates that while beneficial, the GW mitigation potential is somewhat diminished by the energy demands of advanced biogas processing. Here economic viability conflicts with sustainability potential to a small extent.

The results shown in (Fig. 5.2e) is the GW of an anaerobic digestion plant when biogas is upgraded to CBG for use as vehicular fuel (Scenario 5). The gross GW from this Scenario is approximately 134 kg CO_2-eq. This is similar to Scenario 4. In this scenario too the major GHG footprint contribution is from "purification and compression" stages (mainly due to 7% methane loss and electricity consumption as discussed before). Should new processes reduce this 'sacrificial /fugitive methane emissions' by a larger extent, the overall GHG footprint can become even smaller and results in a "negative footprint". It is found that 92% GW is reduced through vehicular fuel and fertilizer offset. This near-neutral GW is primarily driven by the substantial "vehicle fuel offset" which represents avoided emissions from displacing diesel fuel-based vehicles with CBG (resulting in savings of 26 L diesel per ton of OFMSW). The considerable offsets from replacing fossil fuels ensure that the overall system is almost carbon-neutral, highlighting its potential for sustainable waste management and transport decarbonization.

The comparative analysis of the GW for various treatment scenarios of organic fraction of municipal solid waste (OFMSW) in a biogas plant clearly shows that while flaring of biogas results in a net positive GW of 13 kg CO_2-eq., all other scenarios demonstrate a net negative GW, indicating increasing overall environmental benefits. The most significant level of GW reduction is achieved when biogas is converted to electricity while also displacing coal-based electricity, leading to a net GW of -123 kg CO_2-eq. Directly utilizing biogas for cooking (unpurified) also yields a substantial net GW of -108 kg CO_2-eq. Even after purification and bottling, using biogas for cooking (purified) still results in a negative GW of -12 kg CO_2-eq, less impactful than direct use. Lastly, utilizing biogas as vehicle fuel also provides a net negative GW of -11 kg CO_2-eq. while being the most economic option so far.





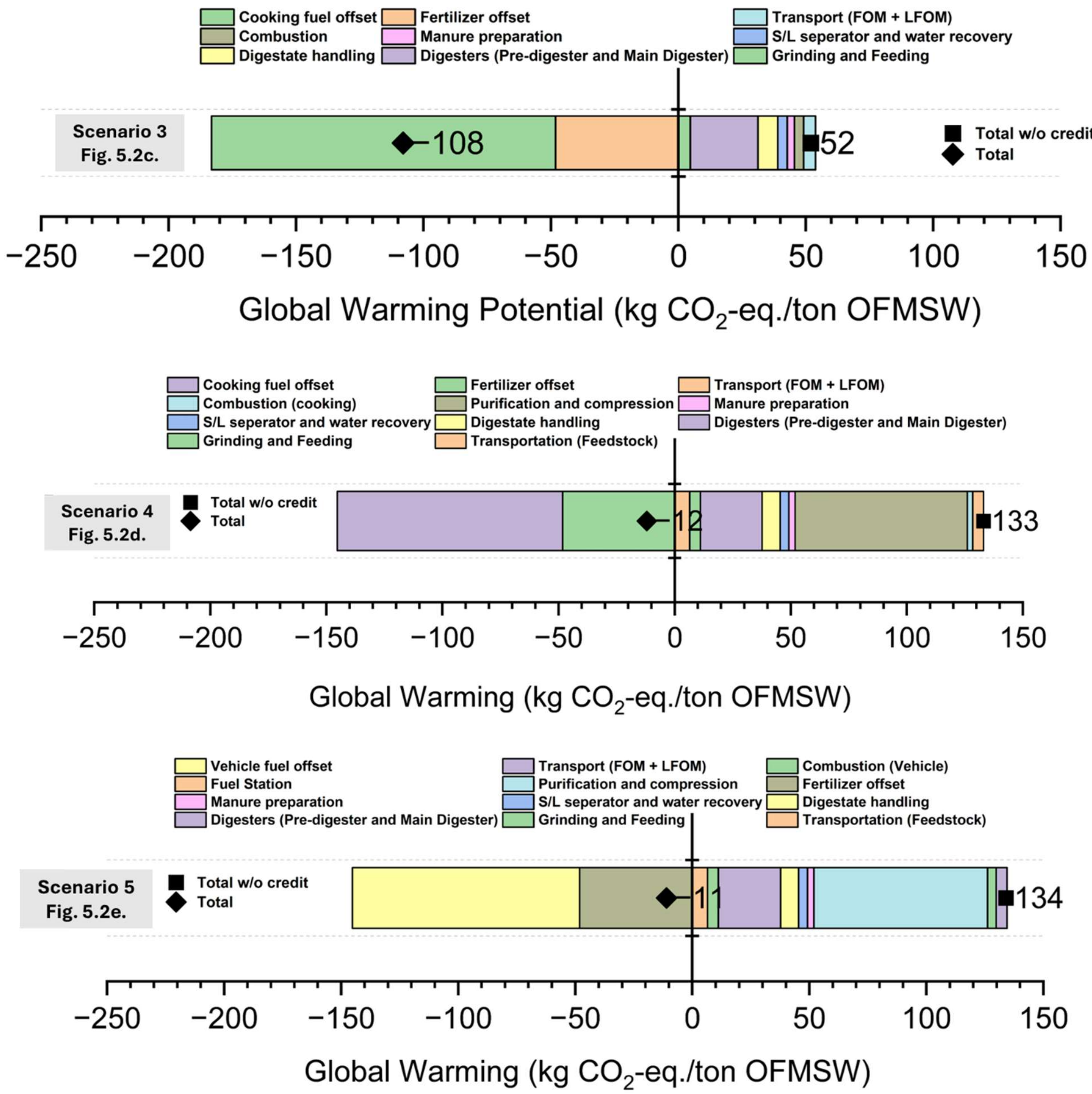


Fig. 5.2 Impact on global warming from biogas plant based on organic fraction of municipal solid waste a) scenario 1 - flaring of biogas b) scenario 2 - biogas to electricity c) scenario 3 - biogas directly used as cooking fuel d) scenario 4 - upgraded biomethane used as cooking fuel and e) scenario 5 - upgraded biomethane used as vehicle fuel

To contextualize these findings, a comparison with previous LCA studies indicates that the GW outcomes reported here fall within the broad range observed internationally for biogas systems. The study by (Montejo et al., 2013) reported gross impacts of 50 to 90 kg CO_2-eq/ton (without accounting for credits) in comparison to our finding of 60-123 kg CO_2-eq/ton. For electricity generation, our estimate of -123 kg CO_2-eq/ton is higher in magnitude than values reported for brewer spent grain in Brazil (-54 kg CO_2-eq/ton) (Rosa Aon Cardoso Fernandes et al., 2023) and combined heat and power systems in China (-61.2 kg CO_2-eq/ton) (Shi et al., 2024), but lower than the -190 kg CO_2-eq/ton reported for organic MSW in China (Havukainen et al., 2017). The upgraded biogas scenarios (-12 to -11 kg CO_2-eq/ton) show lower benefits relative to grid-injected biomethane in Ireland (-46 kg CO_2-eq/ton) (Martínez-Arce et al., 2025), compressed natural gas replacement in China (-134 kg CO_2-eq/ton) (Guo et al., 2021), or petrol displacement in Hong Kong -104 kg CO_2-eq/ton (Woon et al., 2016) reflecting the influence of biogas yield and higher methane losses. Overall, this comparison reinforces the robustness of the present findings while underscoring the sensitivity of biogas LCA results to regional, technical, and methodological factors.

It should be noted that a direct, one-to-one comparison of final impact values between different LCA studies is not only challenging but can be fundamentally misleading. The results of an LCA are not universal truths but are instead the product of a specific set of assumptions, boundaries, and contextual factors unique to each study (Ferreira et al., 2019b). The core challenge lies in the fact that no two LCA studies are identical (Jayawickrama et al., 2024). Their comparability is fundamentally limited by a wide array of methodological choices made by researchers, including the definition of the functional unit, the delineation of the system boundary, the selection of specific inventory databases and software, and the choice of a life cycle impact assessment method. A variation in any one of these foundational elements means the studies are essentially modeling different systems or asking different questions, making a simple comparison of their final results invalid (Jayawickrama et al., 2024).

Furthermore, LCA results, particularly for bioenergy, are highly sensitive to regional and case-specific variables. As highlighted by (Cherubini and Strømman, 2011), outcomes are strongly dependent on regional factors. This includes the local energy grid mix, prevailing environmental and political conditions, and the availability or scarcity of accurate, updated local data, all of which can significantly alter the results (Jin et al., 2018).

In spite of aforementioned, previous studies indicated that environmental benefits of biogas plants depend on the end use of biogas (Esteves et al., 2019). Comparing the utilization options, this study aligns with study by (González et al., 2020; Shinde et al., 2021), which identified electricity generation as a more environmentally friendly option than upgrading biogas to vehicle fuel. Research by (Hakawati et al., 2017b) indicates that the most energy-efficient pathways are those where biogas is used directly, though the decision should also consider economic and logistical aspect as well.

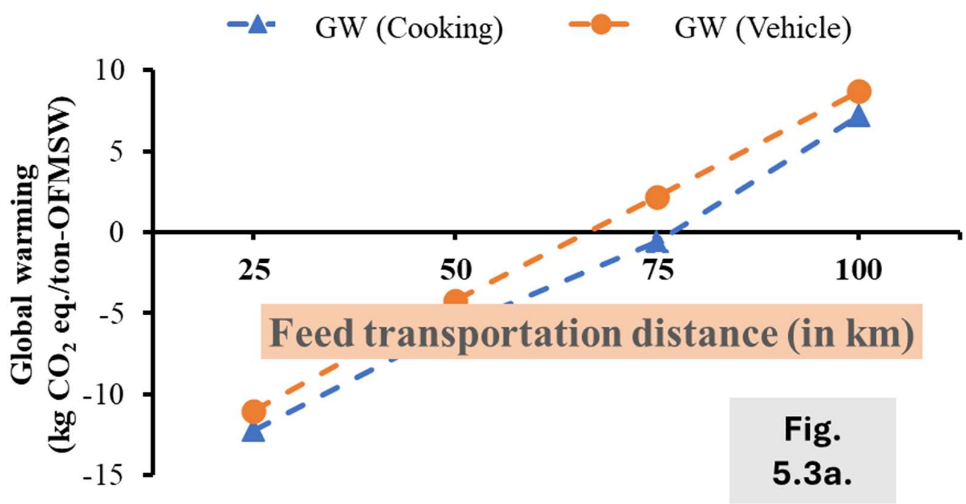
Using biogas to generate electricity presents significant economic hurdles. A critical barrier is the marginal economic return (price of biogas-based electricity 5-7 Rs. /kWh) would often leads to very low profitability. This financial strain is compounded by direct competition from cheaper electricity generated by large, established power plants. Without significant government subsidies or guaranteed high feed-in tariffs, these biogas-to-electricity projects frequently struggle to be economically viable. When used as a direct cooking fuel, biogas faces a different set of logistical challenges. The limitation is that biogas plants for cooking must be installed exactly where the fuel will be consumed, such as in a household's backyard or a community kitchen, making large, centralized production plants for widespread distribution impractical. It should be noted that the ability to purify and compress the biogas as CBG opens avenues for commercial distribution to areas creating a high value marketable product that improves energy access. Furthermore, this comparison underscores that energy recovery and fossil fuel displacement are crucial for maximizing the climate change mitigation potential of anaerobic digestion plants, with electricity generation offering the highest GW reduction.

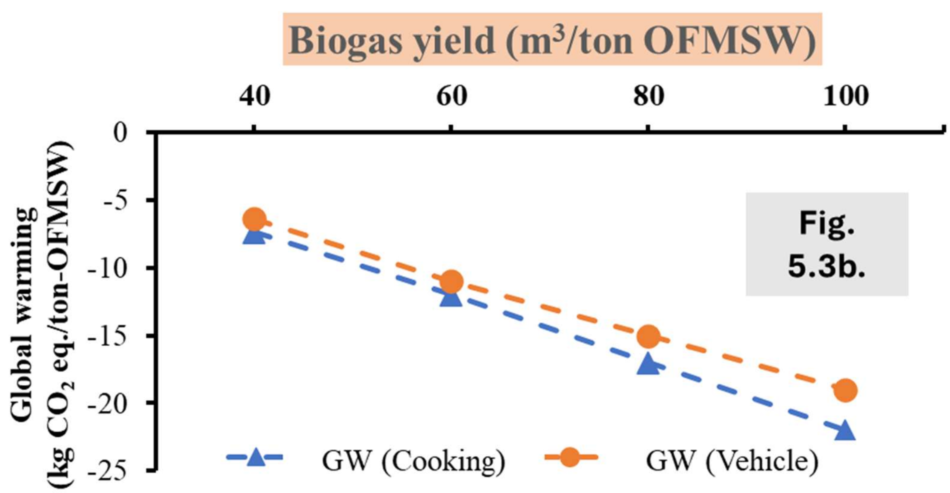
5.3.1.2 Influence of various parameters on global warming of biogas plants

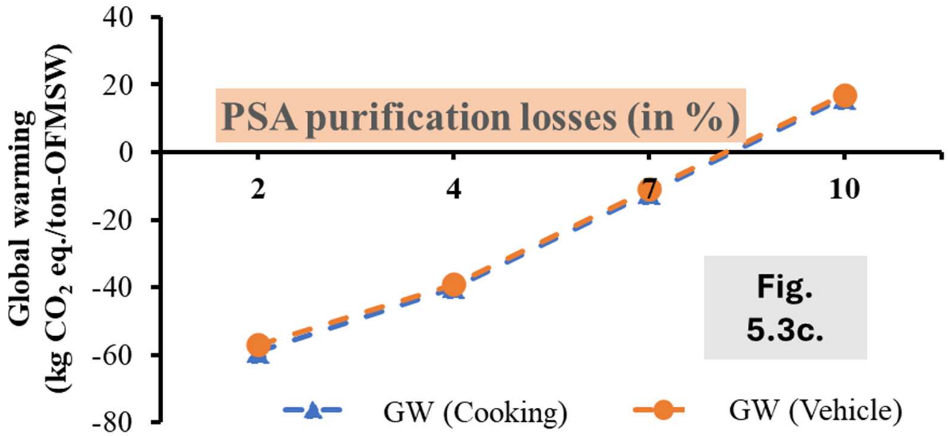
The GW is furthermore assessed at different values of various parameters such as feedstock transportation distance, biogas yield, methane losses in purification, credits associated with byproducts, specifically fermented organic manure (FOM), liquid fermented organic manure (LFOM), and biogas utilization under different scenarios (Fig. 5.3.).

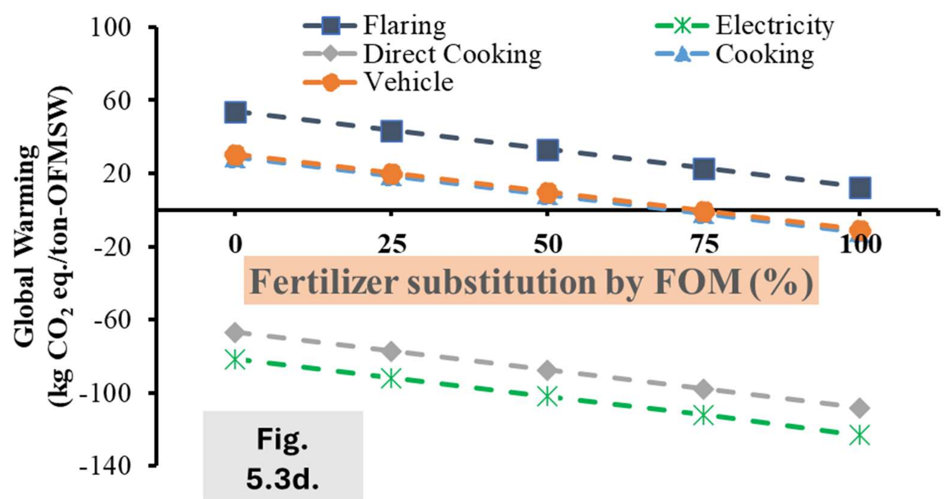
- *Feedstock transportation distance*

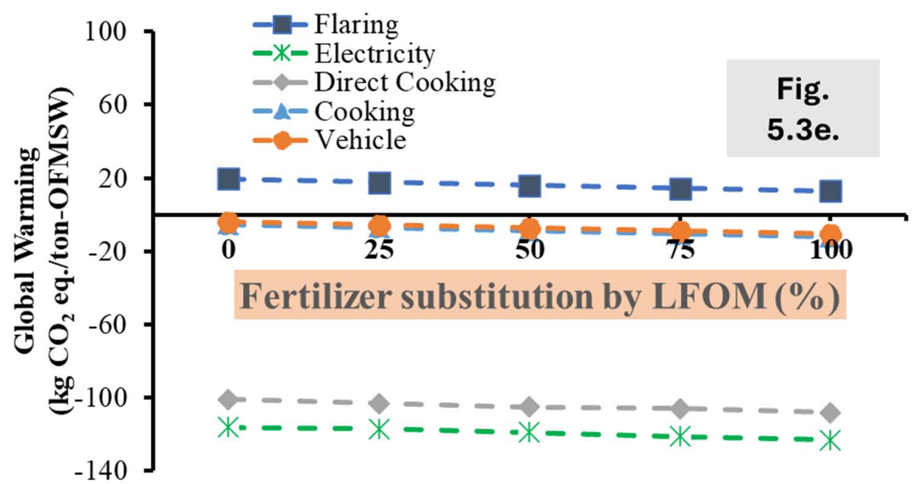
The result shown in Fig. 5.3a. illustrates the influence of feedstock transportation distance on the GW for anaerobic digestion scenarios where biogas is used after purification and compression for cooking or as vehicle fuel. As the transportation distance of feedstock increases, the net GW for both applications also increases, moving from a net negative to a net positive impact. The cross-section at the X-axis (where GW is 0) represents the critical transportation distance at which the environmental benefits of the anaerobic digestion system are entirely offset by the emissions from feedstock transport, resulting in a neutral global warming impact. This break-even crossover point occurs at approximately 75 km for the cooking scenario, and 60-65 km for the vehicle scenario, meaning beyond this distance, the system becomes a net emitter of greenhouse gases. It should be noted that this break-even distance will change based on the type of the vehicle. This highlights the crucial importance of minimizing feedstock transportation distances to ensure the overall climate benefits of these biogas utilization pathways are maintained.






PSA purification losses (in %)
Global warming
(kg CO_2 eq./ton-OFMSW)
GW (Cooking)
GW (Vehicle)
Fig. 5.3c.


Flaring
Electricity
Direct Cooking
Cooking
Vehicle
Global Warming
(kg CO_2 eq./ton-OFMSW)
Fertilizer substitution by FOM (%)
Fig. 5.3d.


Flaring
Electricity
Direct Cooking
Cooking
Vehicle
Fig. 5.3e.
Global Warming
(kg CO_2 eq./ton-OFMSW)
Fertilizer substitution by LFOM (%)

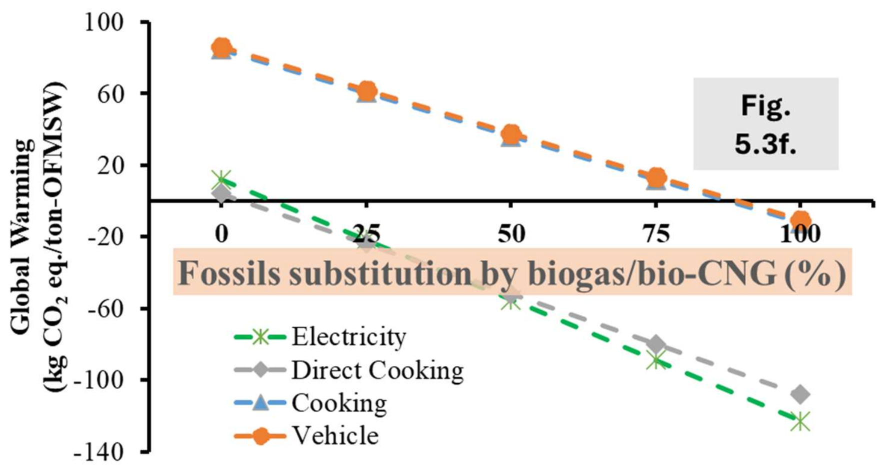


Fig. 5.3 Influence of variation in different parameters on global warming from biogas plant based on organic fraction of municipal solid waste a) feedstock transportation distance b) biogas yield and c) purification losses d) fertilizer substitution by fermented organic manure (FOM) e) fertilizer substitution by liquid fermented organic manure (LFOM) f) fossils substitution by biogas/bio-CNG in respective scenarios

- *Biogas yield*

Fig. 5.3b. illustrates the strong inverse relationship between biogas yield and GW for scenarios utilizing biogas for cooking or vehicle fuel: as biogas yield increases from 40 to 100 m^3/ton of OFMSW the GW for both applications becomes more negative, signifying enhanced climate benefits. This is evident as GW (cooking) drops from around -7 kg CO_2-eq to -22 kg CO_2-eq, and GW (vehicle) decreases from approximately -6 kg CO_2-eq to -19 kg CO_2-eq. This downward trend underscores that higher biogas production translates directly into greater displacement of fossil fuels and associated emissions. This result highlights the critical importance of maximizing biogas yield and, crucially, of valorizing the produced biogas through energy recovery pathways (cooking, vehicle fuel) rather than merely flaring it, to significantly reduce overall greenhouse gas emissions.

- *Purification losses*

Fig. 5.3c illustrates the critical impact of biogas purification losses on the GW for scenarios where the upgraded biogas is used for cooking or as vehicle fuel. As purification losses increase from approximately 2% to 10%, the GW for both applications experiences a substantial rise, transitioning from a desirable net negative value to an undesirable net positive one. The crossover points on the X-axis (where GW equals zero) is particularly important: for both cooking and vehicle fuel applications, this occurs at approximately 8% purification losses. This signifies the threshold beyond which the emissions associated with uncaptured methane during purification negate all environmental benefits of the anaerobic digestion system, turning it into a net contributor to global warming. Beyond this point, the system moves into positive GW territory, reaching nearly 20 kg CO_2-eq at 10% losses. This strong positive correlation underscores that minimizing methane or energy losses during the biogas purification process is paramount; otherwise, the environmental benefits of converting biogas into higher-value fuels can be significantly undermined, potentially negating the climate advantages of anaerobic digestion.

- *Substitution of fertilizer by fermented organic manure and liquid fermented organic manure*

The substitution of inorganic fertilizer with FOM provides a significant and necessary secondary GW credit across all utilization pathways (Fig. 5.3d). The GW impact improves linearly as FOM substitution increases from 0% to 100%, indicating a reliable environmental benefit from displacing fossil-fuel-intensive conventional fertilizer. For the cooking and vehicle scenarios (when considered with 100% fossil fuel substitution), FOM is essential, as these pathways require approximately at least 75% FOM replacement to reach the break-even GW point. This highlights that achieving viability relies on a dual-strategy of both fuel and fertilizer displacement. In contrast, the credit from LFOM substitution shows minimal sensitivity across all scenarios (Fig. 3e), playing a minor role in determining the overall GW outcome.

- *Substitution of fossil fuel substitution by biogas/CBG*

The credit gained from substituting fossil fuels with biogas or CBG is the dominant factor determining GW viability. Scenarios utilizing unpurified biogas for electricity and direct cooking become environmentally beneficial GW (negative CO_2) footprint at a fossil energy replacement rate of less than 10% (Fig. 5.3e). These pathways avoid the energy-intensive purification step, allowing the GW credit to be realized almost immediately. Conversely, scenarios using upgraded fuel for cooking or vehicle applications are heavily penalized by initial methane leakage losses during the biogas purification process. They require a much higher minimum displacement, needing just over 85% fossil fuel replacement to break even (GW = 0). This confirms that leakage mitigation is the critical sustainability pillar for the CBG value chain. Flaring, which offers no useful energy substitution credit, remains a net emitter of GW even under the most favorable fertilizer substitution rates.

Table 5.3 Mid impact categories scores of different bio-methanation Scenarios

Impact category	**Unit**	**Flaring (S1)**	**Electricity (S2)**	**Cooking (S3)**	**CBG Cooking (S4)**	**Vehicle fuel (S5)**
Global warming	kg CO2 eq	12.6	-123	-108	-12.2	-10.7
Terrestrial acidification	kg SO2 eq	0.14	-0.53	-0.225	-0.153	-0.125
Freshwater eutrophication	kg P eq	0.0114	-0.0822	0.0084	0.027	0.0265
Terrestrial ecotoxicity	kg 1,4-DCB	-22.6	-101	-169	-71.6	-52.4
Freshwater ecotoxicity	kg 1,4-DCB	-2.07	-4.75	-2.52	-1.8	-1.79
Human carcinogenic toxicity	kg 1,4-DCB	-3.74	-21.2	-8.59	-4.98	-4.77
Human non-carcinogenic toxicity	kg 1,4-DCB	-26.4	-173	-39.8	-11.6	-11.4
Mineral resource scarcity	kg Cu eq	-0.886	-0.913	-0.951	-0.922	-0.919
Fossil resource scarcity	kg oil eq	-5.11	-40	-44.1	-33.4	-30.4

5.3.1.3 Midpoint scores

The different mid-point categories (or problem oriented) performance of different treatment scenarios for the OFMSW in a biogas plant is presented in (Table 5.3). A consistent trend observed across most impact categories is that energy recovery from biogas significantly outperforms simple flaring, often leading to net environmental benefits rather than burdens. The displacement of conventional energy sources (coal-based electricity, LPG, or diesel-based vehicle fuels) and the beneficial use of digestate (FOM and LFOM) as fertilizer are critical drivers of these benefits.

Regarding GW, flaring biogas (scenario 1) results in a net positive impact of 12.6 kg CO_2- eq., making it the least environmentally favorable option. In contrast, all other energy recovery scenarios yield substantial net negative GW values, indicating a significant climate change mitigation benefit. Biogas conversion to electricity, displacing coal-based electricity (scenario 2), demonstrates the most profound reduction with a remarkable net GW of -123 kg CO_2- eq. This is primarily due to the high carbon intensity of coal-based electricity it replaces. Directly utilizing unpurified biogas for cooking (scenario 3) also offers a considerable benefit at -108 kg CO_2- eq. While still beneficial, upgrading biogas for purified cooking (scenario 4, -12.2 kg CO_2- eq.) and vehicle fuel (scenario 5, -11 kg CO_2- eq.) leads to less significant GW reductions compared to electricity generation or direct cooking. This reduction in benefit is likely attributable to the methane losses, and additional energy required for purification and compression processes.

Similar patterns are evident for terrestrial acidification and freshwater eutrophication. Flaring remains the only scenario with a net positive contribution to terrestrial acidification (0.14 kg SO_2-eq), whereas all energy recovery options result in net benefits, with electricity generation showing the largest reduction (-0.53 kg SO_2-eq.). For freshwater eutrophication, biogas to electricity again exhibits a significant net benefit (-0.08 kg P eq.), while flaring, direct cooking, purified cooking, and vehicle fuel scenarios all show small net positive impacts. This suggests that while energy recovery is broadly beneficial, the specific method and displaced product determine the magnitude of these benefits across different environmental concerns.

For toxicity categories (terrestrial ecotoxicity, freshwater ecotoxicity, human carcinogenic toxicity, human non-carcinogenic toxicity), as well as mineral resource scarcity and fossil resource scarcity, all five scenarios, including flaring, yield net negative impacts (environmental benefits). This widespread benefit across toxicity and resource scarcity indicators is largely driven by the significant negative contributions from "fertilizer offset (FOM/LFOM)" categories across all scenarios. This underscores the paramount importance of the digestate's use as a fertilizer, which displaces the production and transportation of conventional chemical fertilizers, thereby avoiding a broad range of associated environmental burdens. Among the energy recovery options, electricity generation consistently demonstrates the largest net benefits across most of these categories, followed by direct cooking, purified cooking, and vehicle fuel, reinforcing its overall environmental superiority.

In conclusion, the analysis clearly demonstrates that maximizing the environmental benefits of organic fraction of MSW treatment in biogas plants hinges on effective energy recovery and the full utilization of digestate as a fertilizer. While all energy recovery scenarios significantly mitigate GW compared to flaring, the conversion of biogas to electricity offers the most comprehensive environmental benefits across a broad spectrum of mid-point impact categories due to the high environmental burden of the displaced coal-based electricity. Even with additional processing, utilizing biogas as a purified cooking fuel or vehicle fuel still provides substantial environmental advantages by displacing fossil-based alternatives, albeit sometimes with slightly reduced benefits compared to direct utilization or electricity generation.

5.3.1.4 Endpoint scores

This endpoint category analysis provides a crucial perspective on the environmental damages associated with different biogas utilization scenarios, expressed in points (Pt). Unlike mid-point indicators that quantify problem-oriented impact such as (GW, acidification, toxicity, and others), endpoint categories translate these into tangible impacts on human health, ecosystems, and resources (Fig. 5.4.) (López González et al., 2020).

The results highlight that biogas flaring (scenario 1) is the only treatment option that consistently leads to a net environmental damage across all aggregated categories, with a total impact of 4.5 Pt. This damage is predominantly driven by its substantial positive impact on human health indicating direct adverse effects on human well-being. A small positive impact on ecosystems is also observed. Interestingly, flaring shows a slight net benefit for resources (-0.02 Pt), likely due to resource savings from the digestate's use as fertilizer. Negative Pt values indicate that the process yields net environmental benefits through avoided impacts or resource credits.

In contrast, all scenarios involving energy recovery from biogas yield significant net environmental benefits, as indicated by their negative point scores. Biogas to electricity generation (scenario 2) emerges as the most environmentally beneficial option, demonstrating the largest overall damage reduction with a total score of -7.6 Pt. This benefit is consistently observed across all three damage categories: it provides the most substantial benefits for human health (-7.4 Pt) and ecosystems (-0.2 Pt), largely due to the avoidance of high-impact emissions from displaced coal-based electricity.

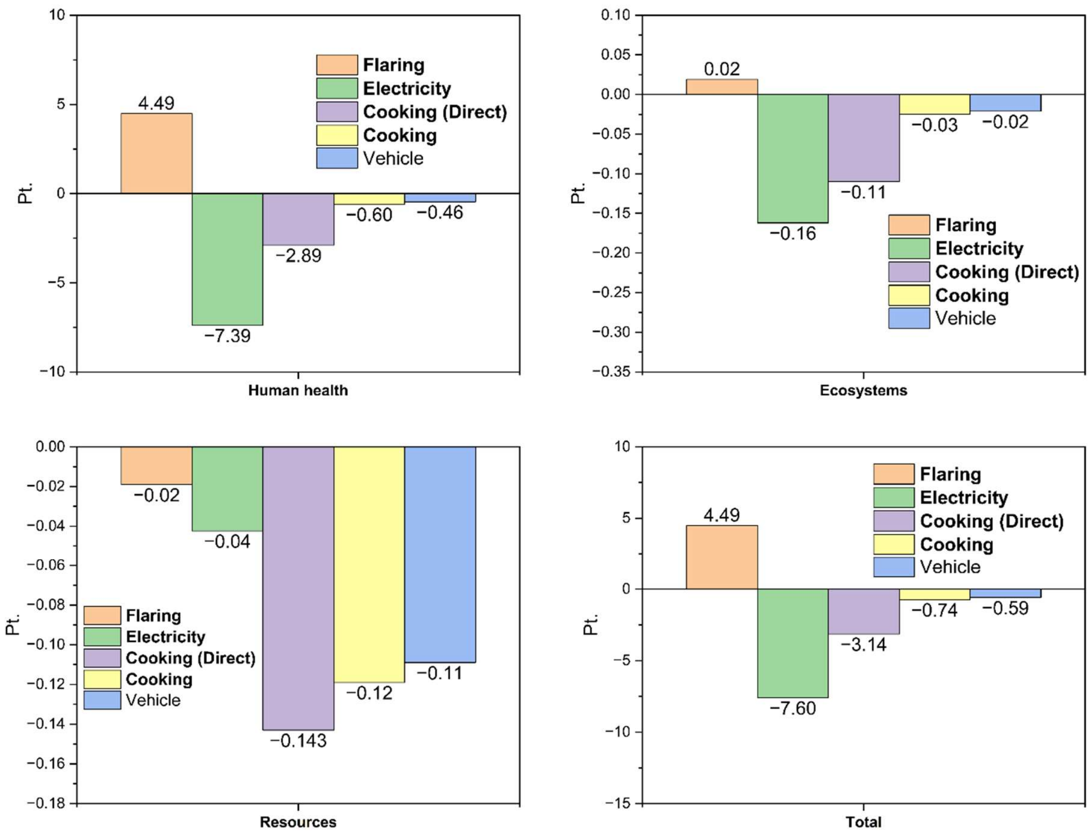


Fig. 5.4 Damage category and single point score of different scenarios of biogas plant based on organic fraction of municipal solid waste

Between the two cooking scenarios, direct unpurified biogas for cooking (scenario 3), provides a greater total damage reduction of -3.1 Pt compared to purified biogas for cooking, which yields -0.7 Pt. This suggests that the additional purification and compression steps, adding process burdens at the mid-point (as seen in previous GW analysis), ultimately resulting in lesser benefits for human health (-2.9 Pt for direct vs. -0.60 Pt for purified) and ecosystems (-0.11 Pt vs. -0.03 Pt).

Utilizing biogas as vehicle fuel (scenario 5) also results in a net environmental benefit (-0.593 Pt total), offering reductions in human health (-0.46 Pt) and ecosystems (-0.021 Pt) impacts.

While beneficial, its overall performance is less impactful than electricity generation or purified biogas for cooking in terms of total damage reduction.

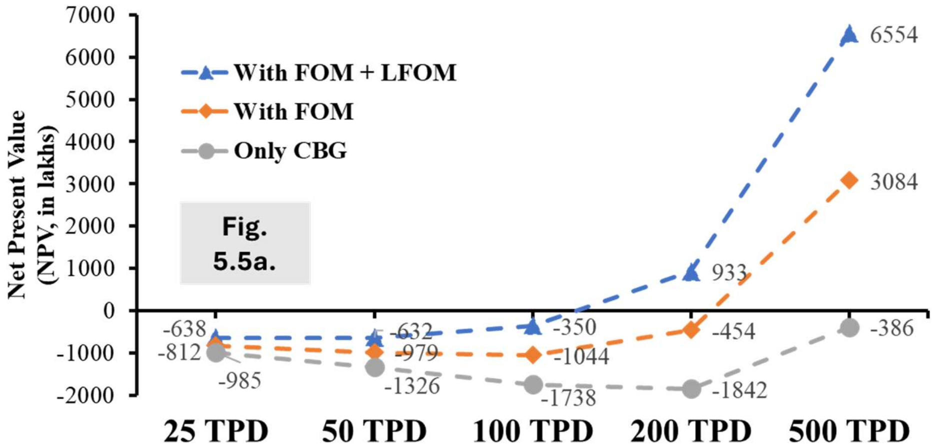
For the resources category, all energy recovery scenarios demonstrate net benefits, with direct biogas for cooking (Scenario 4, -0.14 Pt) showing the highest resource savings, marginally outperforming purified cooking (-0.12 Pt) and vehicle fuel (-0.109 Pt). Electricity generation (-0.04 Pt) also contributes to resource savings, though not as significantly as the cooking or vehicle fuel applications in this specific category. This divergence from other categories where electricity was dominant might reflect the specific resource intensity of the displaced fuels (e.g., LPG vs. coal).

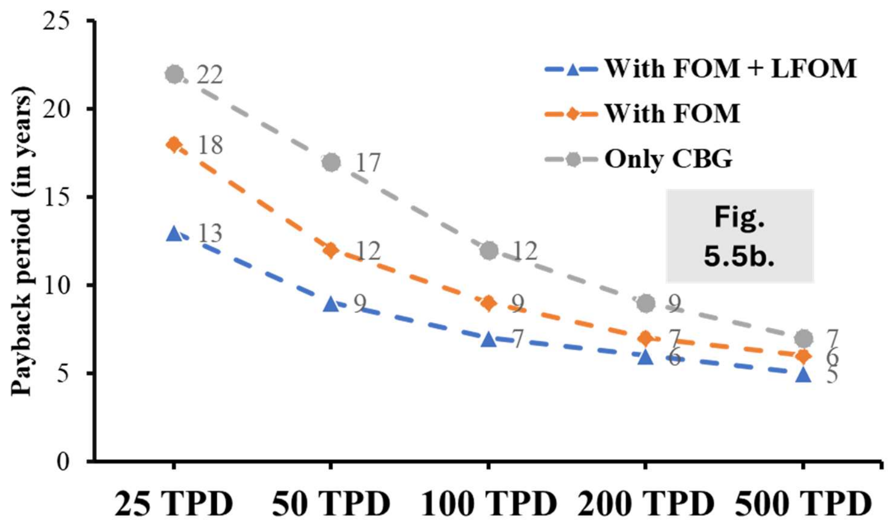
In summary, the endpoint analysis clearly illustrates the critical role of energy recovery from OFMSW in avoiding significant environmental damages, particularly to human health. While all energy recovery pathways offer benefits, electricity generation emerges as the most effective strategy for overall environmental mitigation, followed by the use of purified biogas for cooking, highlighting that the choice of end-use greatly influences the ultimate environmental outcome. The benefits derived from the displacement of conventional energy sources and the recycling of nutrients through digestate use are fundamental to these positive environmental outcomes.

5.3.2 Economic analysis

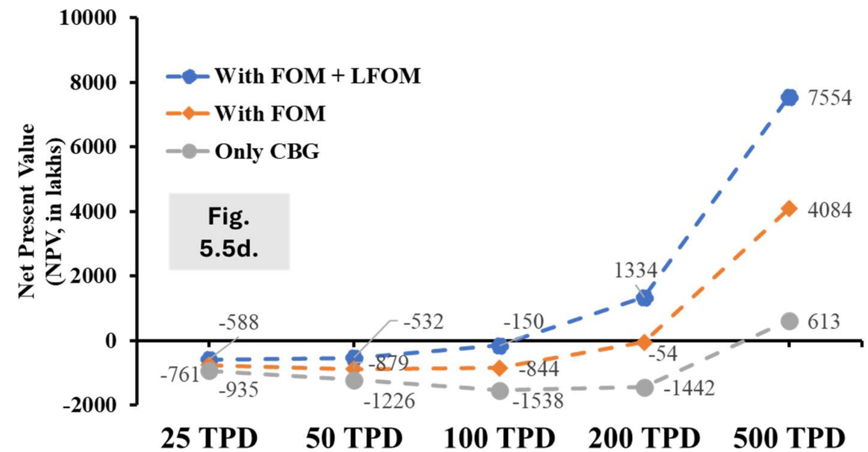
The analysis clearly demonstrates significant economies of scale inherent in biogas projects. Regardless of the revenue strategy, larger plant capacities consistently exhibit improved financial performance. As the quantity of waste processed increases from 25 TPD to 500 TPD, the NPV shifts from substantial negative figures to highly positive ones (Fig. 5.5a.), the IRR steadily rises (Fig. 5.5b.), and the payback period shortens (Fig. 5.5c). For instance, a 25 TPD plant generating revenue from all streams (CBG, FOM, LFOM) has a negative NPV of -₹638 lakhs (- $727,375) and a lengthy payback period of 13 years, with an IRR below the assumed 15% discount rate. In comparison, a 500 TPD plant under the same revenue model boasts a highly attractive NPV of ₹6554 lakhs ($7,388,618), a robust IRR of 23.6%, and a swift payback period of just 5 years, making it highly financially viable.

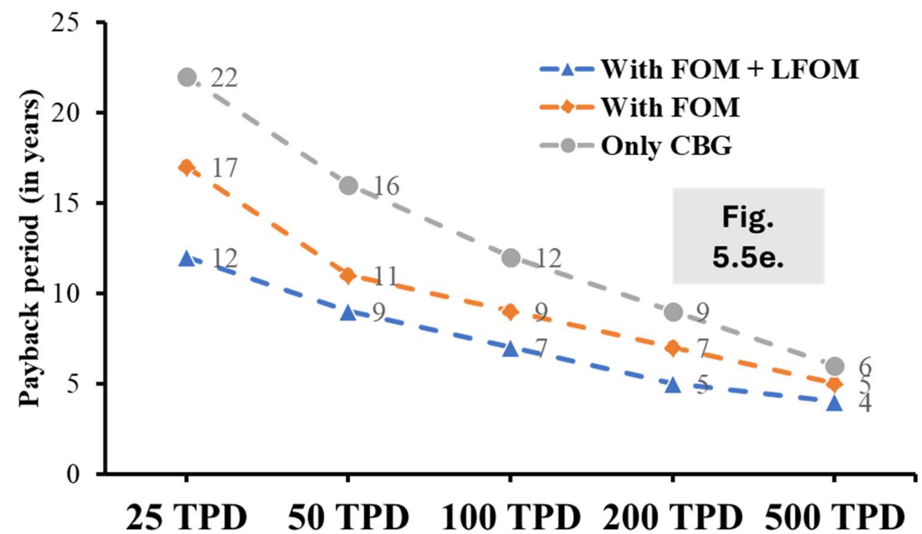
Without Subsidy





With Subsidy





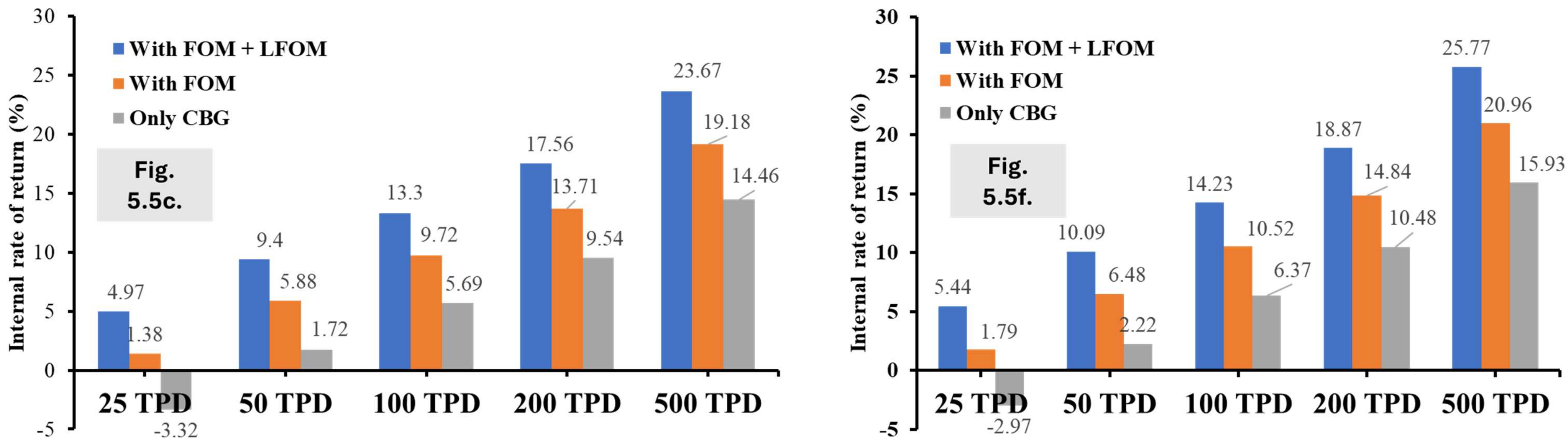


Fig. 5.5 Economic indicators of different scales of bio-CNG plants A) Without subsidy - a) Net present value b) Payback period and c) Internal rate of return B) With subsidy – d) Net present value e) Payback period and f) Internal rate of return

5.3.2.1 Critical role of manure sales (FOM and LFOM)

The inclusion of revenue from both solid (fermented organic manure - FOM) and liquid (liquid fermented organic manure - LFOM) is paramount to the financial success of these biogas plants. Across all plant sizes, scenarios that include manure sales (either "With FOM + LFOM" or "With FOM") consistently outperform the "Without Manure" scenario. For example, at 200 TPD, including both FOM and LFOM results in a positive NPV of ₹933 lakhs ($1,051,825) and an IRR of 17.6%, while excluding all manure (FOM + LFOM) sales leads to a significantly negative NPV of -₹1842 lakhs (-$2,076,569) and an unviable IRR of 9.5%. Even at the largest scale (500 TPD), while CBG revenue alone leads to a negative NPV of -₹386 lakhs (-$440,073), incorporating both FOM and LFOM drastically increases the NPV to ₹6554 lakhs ($7,388,618), underscoring the vital contribution of these co-products to profitability. This highlights that CBG alone, while being the primary revenue source, often falls short of ensuring project viability; the additional income from nutrient-rich manure streams provides the necessary financial margin (Kumar, 2023).

5.3.2.2 Effect of government subsidy

When government subsidies (₹4 crore per 4800 kg CBG/day; for this study it is converted to ₹25 lakhs ($28,183) per 300 kg CBG/day) are incorporated, the overall economic outlook improves markedly across all plant sizes. As shown in Fig. 5 (d-f), the 25 TPD plant, which earlier showed an NPV of –₹638 lakhs ($719,246), improves slightly to –₹588 lakhs (-$662,878) under the "With FOM + LFOM" scenario, with an IRR rising from below 5% to 5.44% and the payback period reducing from 13 to 12 years. The impact becomes increasingly pronounced with scale: at 200 TPD, the NPV rises from ₹933 lakhs ($1,051,812) (without subsidy) to ₹1334 lakhs ($1,503,877), with the IRR improving from 17.6% to 18.87% and the payback period shortening to 5 years. The 500 TPD plant exhibits the most substantial gains, with an NPV increasing from ₹6554 lakhs ($7,388,618) to ₹7554 lakhs ($8,515,958), an IRR of 25.7%, and a payback of only 4 years, highlighting the significant influence of capital support on investment attractiveness. Even in less profitable configurations, such as "Only CBG" or "With FOM" scenarios, subsidies improve financial performance. For instance, a 500 TPD plant relying solely on CBG transitions from a marginally negative NPV of –₹386 lakhs (-$440,073) to a positive ₹613 lakhs ($691,062), with the IRR surpassing the 15% discount rate (15.93%). These improvements illustrate that government incentives meaningfully enhance project feasibility, especially for medium-scale plants (100–200 TPD), where profitability is otherwise borderline.

5.3.2.3 Specific viability thresholds

Based on the assumed discount rate of 15%, the financial analysis indicates that a biogas plant is financially viable only at larger scales and with comprehensive revenue generation from co-products. Specifically, around 120 TPD of biogas plant, when revenues from both FOM and LFOM are accounted for, achieve a positive NPV and an IRR exceeding the 15% threshold. The 500 TPD plant, even with only FOM revenue, also crosses the viability threshold (NPV ₹3084 lakhs ($3,476,731), IRR 19.2%). All other combinations, particularly plants operating at 100 TPD or less, and scenarios that do not fully monetize the manure streams, fall below the viability criteria, presenting negative NPVs and IRRs below the discount rate. With the subsidy, however, the viability threshold slightly improves, allowing even 100 TPD plants with both manure revenues to achieve a near-positive NPV (–₹150 lakhs or -$169,102) and an IRR of 14%, close to the benchmark. Plants above 200 TPD comfortably exceed the viability threshold, while 500 TPD facilities demonstrate strong profitability (NPV ₹7554 lakhs; IRR 25.7%). These findings highlight how scale, manure valorization, and policy incentives jointly determine project success.

5.3.2.4 Revenue composition and operational considerations:

The revenue details in Table 2 confirms that CBG sales represent the largest component of annual revenue, scaling directly with plant capacity. However, FOM and LFOM revenues, while smaller individually, cumulatively form a substantial and crucial supplementary income stream. For a 500 TPD plant, FOM and LFOM combined contribute ₹1050 lakhs ($1,183,712) annually, which is approximately 42% of the CBG revenue, significantly bolstering the project's financial robustness. The initial CAPEX and annual OPEX increase with plant size, but the corresponding increase in revenue and the inherent efficiencies of larger-scale operations overcome these costs, driving the observed economies of scale.

5.4 Results and Discussion: Part II Chennai

5.4.1 Scenarios

The (Fig. 5.6) presents the system boundary and scenarios used for the life cycle assessment of the biogas plant, from waste collection to end-use of biogas and digestate management. It defines the main foreground processes within the boundary and shows two biogas offset scenarios: one linked to fuel stations and the other to restaurants.

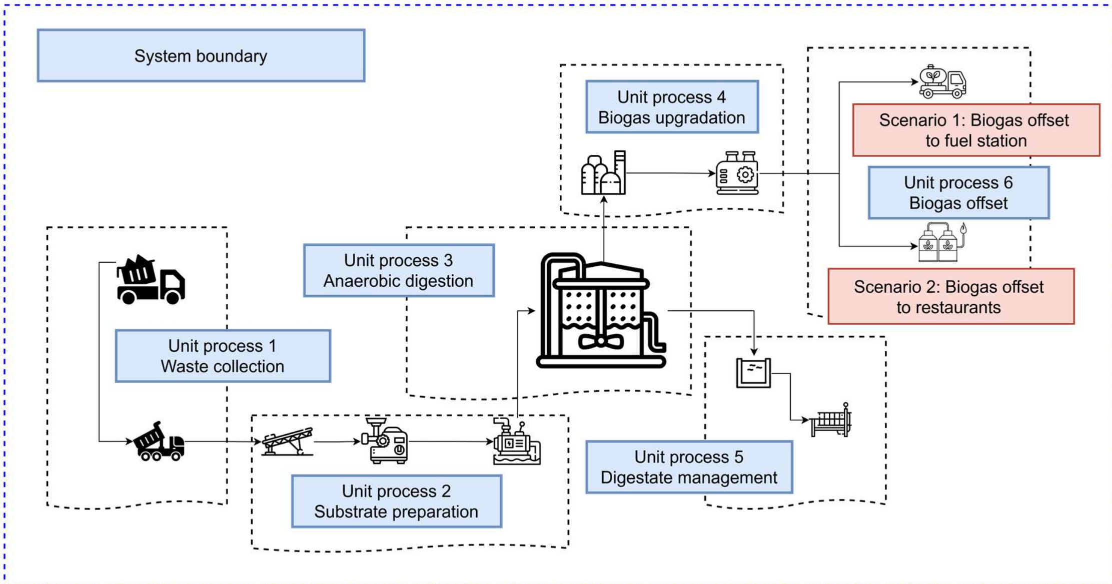


Fig. 5.6 System boundary and scenarios considered for LCA of biogas plant

Unit process 1: Waste collection. Municipal or organic waste is collected and transported to the processing facility, forming the first stage of the biogas supply chain.

Unit process 2: Substrate preparation. The collected waste is sorted, size-reduced, and conditioned to make it suitable for digestion.

Unit process 3: Anaerobic digestion. The prepared substrate is converted by microorganisms into biogas and digestate under oxygen-free conditions.

Unit process 4: Biogas upgradation. Raw biogas is purified and upgraded to increase methane content and remove impurities before end use.

Unit process 5: Digestate management. The solid or liquid residue from digestion is treated, stored, or utilized, typically as a fertilizer or soil amendment.

Unit process 6: Biogas offset. The upgraded biogas is used to displace conventional energy use, with the study considering two offset routes: biogas offset to fuel stations and biogas offset to restaurants.

- **Scenario 1: CBG offset to fuel stations.** In this scenario, the compressed biogas (CBG) produced by the plant is treated as a transportation fuel substitute and credited against conventional transportation fuel use. The environmental benefit arises from displacement of fossil-based fuel in vehicle applications, so the avoided burden is linked primarily to reduced emissions from transport energy demand. This scenario is typically sensitive to the assumed fuel substitution ratio, combustion efficiency, and the amount of CBG actually supplied to the fuel station.

- **Scenario 2: CBG offset to restaurants.** Here, CBG is considered as a direct substitute for LPG used in restaurant cooking applications. The LCA benefit is derived from avoiding LPG production and consumption, which reduces fossil fuel-related greenhouse gas emissions and associated upstream burdens. This scenario reflects a cleaner domestic/commercial cooking pathway and generally captures a strong avoided-burden credit when CBG replaces bottled LPG.
- **Scenario 3: Plant operations on renewable electricity grid mix.** In this case, the biogas plant electricity demand is supplied by a renewable-dominated grid mix rather than the conventional electricity supply. This reduces the indirect environmental burden from plant operations, especially in categories associated with fossil-based power generation. As a result, the scenario improves the overall environmental profile of the system by lowering the impacts of substrate preparation, anaerobic digestion support equipment, upgrading, and auxiliary plant operations.

5.4.2 Life cycle inventory

The biogas plant LCA was parameterized using two scenarios, S1 and S2, with the same operational inventory but different waste sources and corresponding avoided burden assumptions. In both cases, the system considered waste reception, substrate preparation, anaerobic digestion, biogas upgrading, digestate management, and system expansion credits, with a total waste input of 1 ton and 0.15 tons rejected as plastics/inerts. Upstream transport was modeled using a 30 km one-way collection radius, 61.81 kWh of plant electricity, 2.4 L/ton diesel use, and a mixed truck fleet with 9.47 km/L fuel efficiency and 190 L/month diesel consumption. The anaerobic digestion unit processed 260–280 m3/day of slurry at 2.3–2.6% TS and 1.5–1.8% VS, producing 11,174 Nm^3/day of raw biogas with 53–59% CH_4 at 38°C and an HRT of 29–31 days, while a 3–4% methane leakage rate was included. Biogas upgrading was represented by NaOH-based CO_2 scrubbing, biomethane membrane purification, and compression, yielding 5,600–6,200 Nm3/day of upgraded gas with 95–98% CH_4 and 3–5% methane slip. Digestate was further separated into liquid and solid fractions, with 200–220 TPD of wet digestate, 125–140 L/day of liquid effluent, and 10–15 TPD of solids, producing 4–7 TPD of compost with measurable N, P, and K contents. Finally, system expansion credited the plant for avoiding conventional products through 1,500 kg/month of CBG displacing LPG, 2,000 kg/month of CBG displacing vehicle fuel/CNG, and 15–16 tons/month of compost substituting synthetic fertilizer, making the avoided burden contribution an important determinant of the net environmental outcome. The table summarizes the key foreground inputs, operating conditions, and co-product credits used to model the two biogas supply scenarios, S1 and S2.

Table 5.4 Life cycle inventory and system assumptions for the biogas plant scenarios

Parameter	Unit	S1	S2	Comments
Total Food Waste Received	ton	1	1	Split by source if possible (Restaurants vs. Koyambedu market)
Total Reject Waste (plastics/inerts)	ton	0.15	0.15	Plastics removed by manual sorting & depacker
Fresh Water Consumption	L			Water added to bio-grinder to achieve required TS%
Total Plant Electricity Use	kWh	61.81	61.81	If possible, specify grid vs. backup diesel generator
Total Plant Diesel Use	L/ton	2.4	2.4	Fuel used for onsite vehicles, loaders, or generators
Upstream Transport				
Collection Radius/Distance	km (one way)	30	30	Average distance from restaurants/market to plant
Truck Type / Payload Capacity	ton	5 ton-3 No 3 ton-12 No 10 ton-1 No	5 ton-3 No 3 ton-12 No 10 ton-1 No	
Fuel Efficiency of Trucks	km/Liter	9.47	9.47	Total diesel consumed per month for Collection-190 L
Anaerobic digestion and biogas production				
Total Slurry Fed to Digesters	m^3/day	260-280	260-280	
Total Solids (TS)	%	2.3-2.6	2.3-2.6	Lab data for the slurry entering the AD unit
Volatile Solids (VS)	%	1.5-1.8	1.5-1.8	
Total Raw Biogas Production	Nm^3/day	11174	11174	Metered data
CH_4 Concentration in Raw Biogas	% volume	53-59	53-59	Ranges 55–60%
Digester Temperature	°C	38	38	
HRT	Days	29-31	29-31	
Estimated CH_4 Leakage Rate	% of production	3-4 %	3-4 %	
Biogas upgrading and compression				
Caustic Soda (NaOH) Consumption	kg/month	3000-4000	3000-4000	For the CO_2 scrubber

Spent Wash/Effluent from Scrubber	Liters/month	30000-40000	30000-40000	Volume of Na_2CO_3 disposed
Biomethane Yield (Post-Membrane)	Nm³/day	5600-6200	5600-6200	Metered yield of upgraded gas
CH_4 Concentration in Upgraded Gas	% volume	95-98 %	95-98 %	Target is usually 96-98%
Membrane CH_4 Slip (Off-gas loss)	% or Nm³/day	3-5 %	3-5 %	Amount of methane lost in the separated CO_2 stream
CBG Production (Bottled)	kg/day	3900-4200	3900-4200	Final compressed product ready for dispatch
Digestate Management & Composting				
Total Wet Digestate from AD	TPD	200-220	200-220	
Liquid Effluent (Post-Separator)	Liters/day	125-140	125-140	Volume sent to WWTP or sewer
Solid Fraction (Post-Separator)	TPD	10-15	10-15	Mass sent to sun drying
Final Compost Yield	TPD	4-7	4-7	Mass of compost generated after drying/processing
Nitrogen (N) Content in Compost	% of mass	0.04-0.07	0.04-0.07	Lab analysis
Phosphorus (P) Content in Compost	% of mass	0.001-0.05	0.001-0.05	Lab analysis
Potassium (K) Content in Compost	% of mass	0.05-0.2	0.05-0.2	Lab analysis
Avoided burdens (System Expansion)				
CBG Sold as Cooking Fuel	kg/month	1500	1500	Proportion displacing commercial LPG 1000-1500
CBG Sold as Vehicle Fuel	kg/month	2000	2000	Proportion displacing CNG 1500-2000
Compost Sold/Given to Farms	Tons/month	15-16	15-16	Amount actually displacing synthetic fertilizer

5.4.3 Life cycle impact assessment

5.4.3.1 Global warming potential

The global warming potential of three scenarios were calculated with process-wise contribution breakdown. (Fig. 5.7) compares the global warming potential of the three biogas utilization scenarios and shows clear differences in their net climate performance. The results indicate that the three scenarios differ mainly in the balance between avoided burdens and operational emissions. Scenario 1 (S1) shows a net global warming potential of 46.34 kg CO_2 eq/ton OFMSW, where the credit from offsetting fuel is partially reduced by electricity demand, methane emissions, and transport-related burdens. Scenario 2 (S2) performs slightly worse, with a net impact of 51.76 kg CO_2 eq/ton OFMSW, suggesting that offsetting LPG in restaurants provides a smaller overall benefit than the fuel-station substitution case under the present inventory assumptions. In contrast, Scenario 3 (S3) achieves a net negative impact of -16.06 kg CO_2 eq/ton OFMSW, indicating that renewable electricity supply is sufficient to more than offset the remaining process burdens and yield a climate benefit. Overall, the figure shows that the environmental outcome is highly sensitive to the choice of end-use and supporting energy system, with renewable electricity delivering the most favorable net result.

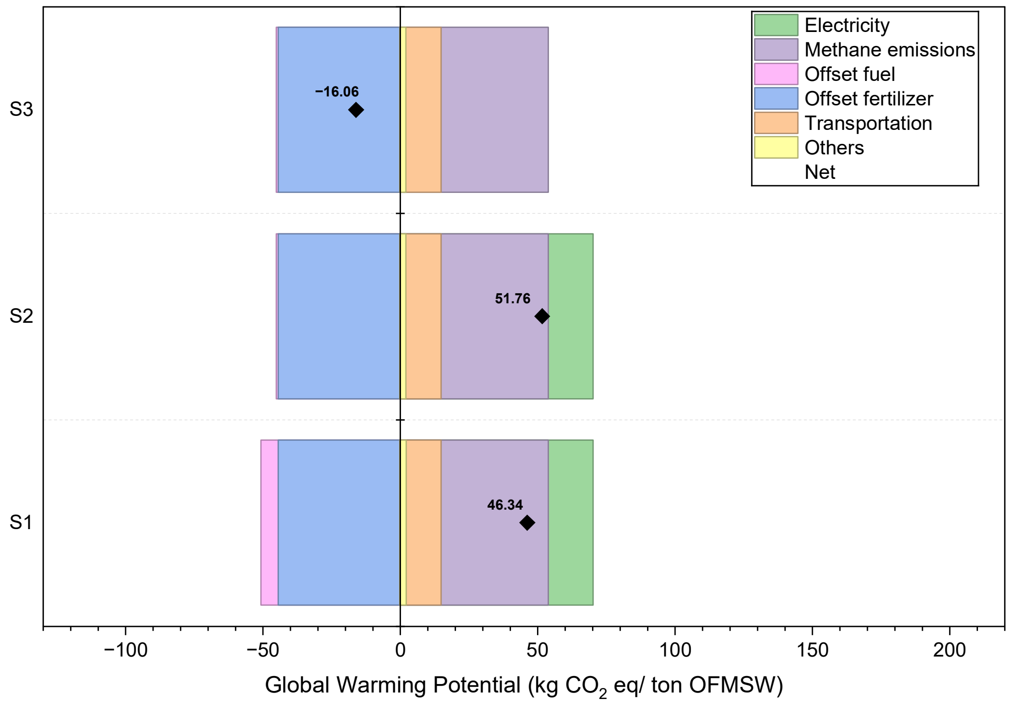


Fig. 5.7 Process contribution of global warming potential of three scenarios of biogas plant

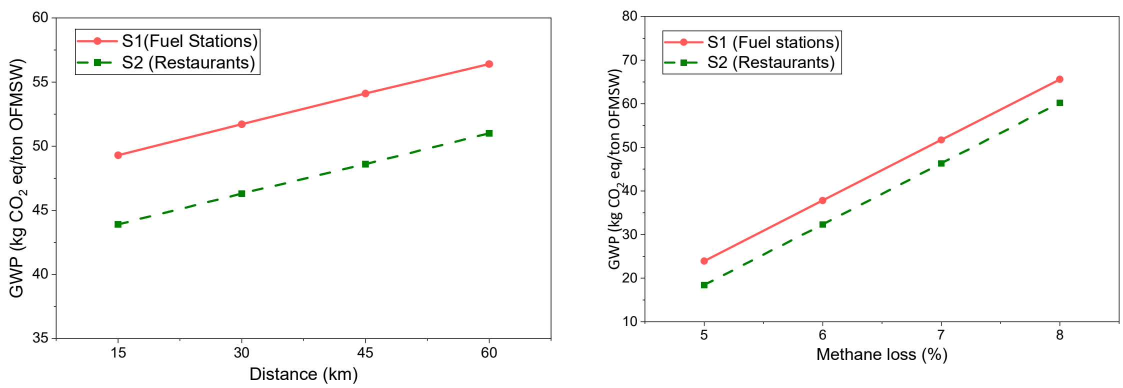
5.4.3.2 Sensitivity analysis

(Fig. 5.8) presents the sensitivity of global warming potential for the biogas plant under the two utilization scenarios, S1 (fuel stations) and S2 (restaurants), as a function of waste collection distance, methane loss, and methane yield. Across all three panels, S1 consistently shows a higher GWP than S2, indicating that the fuel-station pathway is more climate intensive under the studied assumptions.

Distance: For distance of waste collection, GWP increases steadily with collection distance from 15 to 60 km, rising from about 49.5 to 56.0 kg CO_2 eq/ton OFMSW for S1 and from 43.8 to 50.9 kg CO_2 eq/ton OFMSW for S2. This trend reflects the growing transport burden as waste must be hauled over longer distances, which reduces the net environmental benefit of the plant. The restaurant scenario remains lower throughout, suggesting that the avoided burden from LPG substitution offsets operational emissions more effectively than the fuel-station case.

Methane loss: GWP increases sharply as methane loss rises from 5% to 8%, from roughly 22.8 to 65.9 kg CO_2 eq/ton OFMSW in S1 and 17.9 to 60.3 kg CO_2 eq/ton OFMSW in S2. This indicates that methane leakage is a dominant driver of climate impact because fugitive methane has a strong greenhouse effect and directly reduces the usable biogas yield. The steeper increase in the fuel-station scenario shows that methane losses are particularly harmful when the system depends more heavily on delivered biogas credits.

In the methane yield: GWP increases only modestly with methane yield from 50% to 65%, rising from about 50.8 to 53.2 kg CO_2 eq/ton OFMSW in S2 and from 45.8 to 46.8 kg CO_2 eq/ton OFMSW in S1. This comparatively weak response suggests that methane yield has a smaller influence than transport distance or methane loss within the tested range. Nonetheless, higher methane yield still improves process efficiency by increasing biogas recovery, which helps partially offset upstream emissions and supports better net performance.



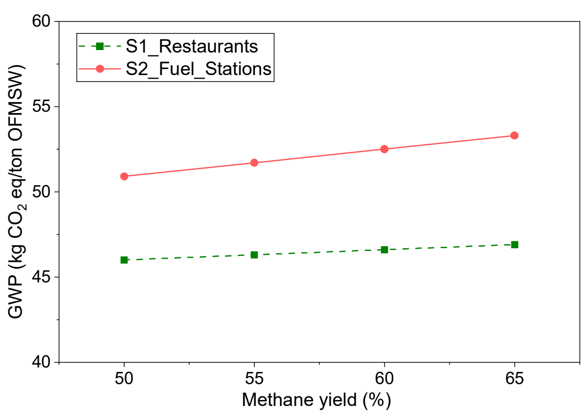


Fig. 5.8 Sensitivity analysis: influence of various parameters a) Distance of waste collection, b) Methane loss, and c) Methane yield on GWP of biogas plant

The sensitivity results imply that the biogas system's climate performance is driven more by logistics and leakage control than by small gains in methane yield. The strong upward trend with collection distance shows that transporting feedstock farther quickly erodes the climate benefit, so decentralized sourcing or shorter haulage routes would improve net GWP. The steep response to methane loss is even more critical: fugitive methane can dominate the footprint of biogas systems, which means leak prevention, tight digester sealing, and effective gas handling are essential for credible mitigation benefits.

By contrast, methane yield has a comparatively modest influence within the tested range, suggesting that yield improvement alone cannot compensate for transport-related emissions or methane leakage. This is an important LCA message: a plant can appear “renewable” on paper, yet still underperform if collection distances are long or operational losses are high. The difference between the fuel-station and restaurant scenarios also implies that the value of avoided burdens depends strongly on the displaced product and the system boundary assumptions; therefore, scenario selection is not just a modeling choice but a determinant of the conclusion.

5.5 Practical implications

The following recommendation are suggested based on the finding of the work:

- **Prioritize energy recovery and diversify end-use:** Biogas flaring should be avoided as it consistently leads to net environmental damage, particularly in global warming and human health impacts. Instead, focus on energy recovery. While electricity generation offers the most significant overall environmental benefits, particularly in GW reduction and human health benefits, utilizing biogas as purified cooking fuel or vehicle fuel also provides substantial environmental advantages by displacing fossil fuels. The choice of end-use should consider local energy demands and market conditions. The 100% of offtake of biogas-based electricity, or CBG should be guaranteed by oil and gas companies or relevant parties through renewable purchase obligations.
- **Maximize co-product utilization for dual benefits:** The sales of both FOM and LFOM digestate are critical (non-negotiable) for both environmental impact mitigation and financial viability. These co-products could significantly offset the environmental burden by replacing synthetic fertilizers across almost all impact categories, including toxicity and resource scarcity. Economically, revenue from manure sales provides the necessary financial margin, substantially boosting NPV and IRR, especially for larger plants. The FCO standards (as per FCO 2025) could be strengthen and mandate the use (starting with partial substitution) of organic fertilizers. The CO_2 component of biogas which is often released after separating out methane could be captured and utilized, this could further enhance the financial viability of the biogas plants in whole.
- **Embrace large-scale operations, especially for high-end products:** Looking at the economic results, it is evident that large-scale biogas plants (e.g., 120 TPD and above) are crucial for financial viability. These larger capacities consistently exhibit improved financial

performance, higher NPV, and IRR, alongside shorter payback periods. Furthermore, high-end products like CBG can only be produced economically viable at large-scale plants. This is because the significant capital and operational expenditures associated with upgrading biogas for purification and compression are more effectively liquidate over a greater volume of product at larger scales, enabling the profitable production and sale of these higher-value fuels. However, in spite of policy initiatives such as SATAT, less than 1.5% of total target is achieved. To achieve the target, the major challenges and mitigation pathways (financing strategies, partnership, changes in rules and standard, and resource mapping) of overcoming barriers dissemination of large-scale biogas plants is discussed by in detail by (Singh and Kalamdhad, 2024).

- **Optimize site selection to minimize transportation:** Feedstock transportation distance significantly influences the GW. Beyond a critical distance (approximately 75 km for purified cooking and 60-65 km for vehicle fuel), the environmental benefits can be entirely offset by transport emissions. Therefore, locating biogas plants as close as possible to the source of OFMSW is crucial to maintain overall climate benefits. Policy should introduce a GIS-based planning mandate requiring biogas plants to be located within critical radii.
- **Invest in efficient production and purification technologies:** Maximizing biogas yield directly correlates with enhanced climate benefits (lower GW) as it translates into greater fossil fuel displacement. Minimizing methane losses during biogas purification is paramount; losses exceedingly approximately 8% can negate all environmental benefits and turn the system into a net contributor to global warming. The regulatory limits for operational permits should be established, compelling investment in the most efficient purification and compression technologies and regular third-party leakage audits. Furthermore, higher biogas yield and low losses will also result in better economic viability of the biogas plants.
- **Supportive policies:** The government should introduce viability gap funding and loan guarantee schemes for AD projects, especially those focused on decentralized models. The economic analysis presented is conservative as it explicitly excludes salvage value, insurance, or interest on loans. Including such financial incentives or support mechanisms could significantly improve the viability of biogas projects, particularly for smaller scales that are currently financially unviable, thereby promoting broader adoption of sustainable waste management.

5.6 Summary

The anaerobic digestion of OFMSW offers a low-impact solution for India's dual challenges of waste management and energy security. This study performs cradle-to-grave LCA and techno-economic comparison of biogas utilization options tailored specifically for the Indian context, addressing a major gap in the literature. This study demonstrates that simple energy recovery pathways particularly electricity generation (-123 kg CO_2-eq/ton) and direct cooking (-108 kg CO_2-eq/ton) applications deliver substantial climate mitigation. In contrast, purification-intensive pathways such as upgraded biomethane for cooking or vehicle fuel offer lower benefits (-12 to -11 kg CO_2-eq/ton) due to methane slip and higher energy inputs. Economically, large-scale biogas plants integrated with digestate valorization are essential for financial sustainability. Plants above 120 TPD capacity, particularly those at 500 TPD, demonstrate strong returns on investment and short payback periods (< 5 years). These findings offer contextualized data to guide sustainable waste-to-energy investment in India and other developing economies.

References:

Aereon, 2022. Retrofitting Air-Assisted Flares to Attain 99.5% Destruction Efficiency [WWW Document]. URL https://aereon.com/retrofitting-air-assisted-flares-to-attain-99-5-destruction-efficiency/?utm_source=chatgpt.com

Alengebawy, A., Mohamed, B.A., Ghimire, N., Jin, K., Liu, T., Samer, M., Ai, P., 2022. Understanding the environmental impacts of biogas utilization for energy production through life cycle assessment: An action towards reducing emissions. Environ. Res. 213, 113632. https://doi.org/10.1016/j.envres.2022.113632

American Biogas Council, 2025. FAQs [WWW Document]. URL https://americanbiogascouncil.org/resources/biogas-faqs-american-biogas-council/#leakage

Arias, A., Rama, M., González-García, S., Feijoo, G., Moreira, M.T., 2020. Environmental analysis of servicing centralised and decentralised wastewater treatment for population living in neighbourhoods. Journal of Water Process Engineering 37, 101469. https://doi.org/10.1016/j.jwpe.2020.101469

Ayyad, A., Abbas, A., Elminshawy, N., 2021. A simulation study of the effect of post-combustion amine-based carbon-capturing integrated with solar thermal collectors for combined cycle gas power plant. Discover Sustainability 2, 9. https://doi.org/10.1007/s43621-021-00018-x

Bernstad, A., la Cour Jansen, J., 2012. Review of comparative LCAs of food waste management systems – Current status and potential improvements. Waste Management 32, 2439–2455. https://doi.org/10.1016/j.wasman.2012.07.023

Biancini, G., Marchetti, B., Cioccolanti, L., Moglie, M., 2022. Comprehensive Life Cycle Assessment Analysis of an Italian Composting Facility concerning Environmental Footprint Minimization and Renewable Energy Integration. Sustainability 14, 14961. https://doi.org/10.3390/su142214961

Bisinella, V., Hulgaard, T., Riber, C., Damgaard, A., Christensen, T.H., 2021. Environmental assessment of carbon capture and storage (CCS) as a post-treatment technology in waste incineration. Waste Management 128, 99–113. https://doi.org/10.1016/j.wasman.2021.04.046

Buffi, M., Hurtig, O., Scarlat, N., 2024. Methane emissions in the biogas and biomethane supply chains in the EU An analysis to update the greenhouse gas emissions accounting. https://doi.org/10.2760/7927411

Cañote, S.J.B., Barros, R.M., Lora, E.E.S., del Olmo, O.A., dos Santos, I.F.S., Piñas, J.A.V., Ribeiro, E.M., de Freitas, J.V.R., de Castro e Silva, H.L., 2021. Energy and Economic Evaluation of the Production of Biogas from Anaerobic and Aerobic Sludge in Brazil. Waste Biomass Valorization 12, 947–969. https://doi.org/10.1007/s12649-020-01046-w

Chandel, M.K., Kwok, G., Jackson, R.B., Pratson, L.F., 2012. The potential of waste-to-energy in reducing GHG emissions. Carbon Manag. 3, 133–144. https://doi.org/10.4155/cmt.12.11

Cheela, V.R.S., John, M., Biswas, W., Dubey, B., 2023. Environmental impact evaluation of landfill mining of legacy waste with on-site sorting using life cycle assessment. Environmental Science and Pollution Research 30, 30033–30047. https://doi.org/10.1007/S11356-022-24210-2/TABLES/3

Cherubini, F., Strømman, A.H., 2011. Life cycle assessment of bioenergy systems: State of the art and future challenges. Bioresour. Technol. 102, 437–451. https://doi.org/10.1016/j.biortech.2010.08.010

Chicaiza-Ortiz, C., Peñafiel-Arcos, P., Herrera-Feijoo, R.J., Ma, W., Logroño, W., Tian, H., Yuan, W., 2024. Waste-to-Energy technologies for municipal solid waste management: Bibliometric review, life cycle assessment, and energy potential case study. J. Clean. Prod. 480, 143993. https://doi.org/10.1016/j.jclepro.2024.143993

Chmelíková, L., Schmid, H., Anke, S., Hülsbergen, K.-J., 2021. Nitrogen-use efficiency of organic and conventional arable and dairy farming systems in Germany. Nutr. Cycl. Agroecosyst. 119, 337–354. https://doi.org/10.1007/s10705-021-10126-9

Christensen, T.H., Bisinella, V., 2021. Climate change impacts of introducing carbon capture and utilisation (CCU) in waste incineration. Waste Management 126, 754–770. https://doi.org/10.1016/j.wasman.2021.03.046

Clasen, A.P., Agostinho, F., Almeida, C.M.V.B., Liu, G., Giannetti, B.F., 2024. Advancing towards circular economy: Environmental benefits of an innovative biorefinery for municipal solid waste management. Sustain. Prod. Consum. 46, 571–581. https://doi.org/10.1016/j.spc.2024.03.015

Colón, J., Martínez-Blanco, J., Gabarrell, X., Artola, A., Sánchez, A., Rieradevall, J., Font, X., 2010. Environmental assessment of home composting. Resour. Conserv. Recycl. 54, 893–904. https://doi.org/10.1016/j.resconrec.2010.01.008

E., P., Sarkar, S., Maji, P.K., 2024. A review on slow-release fertilizer: Nutrient release mechanism and agricultural sustainability. J. Environ. Chem. Eng. 12, 113211. https://doi.org/10.1016/j.jece.2024.113211

Elgas, 2023. LPG Gas Composition: LPG Gas Mixture of Propane & Butane [WWW Document]. URL https://www.elgas.com.au/elgas-knowledge-hub/residential-lpg/lpg-composition/

Esteves, E.M.M., Herrera, A.M.N., Esteves, V.P.P., Morgado, C. do R.V., 2019. Life cycle assessment of manure biogas production: A review. J. Clean. Prod. 219, 411–423. https://doi.org/10.1016/j.jclepro.2019.02.091

Evangelisti, S., Clift, R., Tagliaferri, C., Lettieri, P., 2017. A life cycle assessment of distributed energy production from organic waste: Two case studies in Europe. Waste Management 64, 371–385. https://doi.org/10.1016/j.wasman.2017.03.028

Ferreira, S.F., Buller, L.S., Berni, M., Forster-Carneiro, T., 2019a. Environmental impact assessment of end-uses of biomethane. J. Clean. Prod. 230, 613–621. https://doi.org/10.1016/j.jclepro.2019.05.034

Ferreira, S.F., Buller, L.S., Berni, M., Forster-Carneiro, T., 2019b. Environmental impact assessment of end-uses of biomethane. J. Clean. Prod. 230, 613–621. https://doi.org/10.1016/j.jclepro.2019.05.034

Fuchsz, M., Kohlheb, N., 2015. Comparison of the environmental effects of manure- and crop-based agricultural biogas plants using life cycle analysis. J. Clean. Prod. 86, 60–66. https://doi.org/10.1016/j.jclepro.2014.08.058

Gao, C., Bian, R., Li, P., Yin, C., Teng, X., Zhang, J., Gao, S., Niu, Y., Sun, Y., Wang, Y., Wang, H., 2025. Analysis of carbon reduction potential from typical municipal solid waste incineration plants under MSW classification. J. Environ. Manage. 373, 123844. https://doi.org/10.1016/j.jenvman.2024.123844

González, R., Rosas, J.G., Blanco, D., Smith, R., Martínez, E.J., Pastor-Bueis, R., Gómez, X., 2020. Anaerobic digestion of fourth range fruit and vegetable products: comparison of three different scenarios for its valorisation by life cycle assessment and life cycle costing. Environ. Monit. Assess. 192, 551. https://doi.org/10.1007/s10661-020-08521-w

Guo, H., Zhao, Y., Damgaard, A., Wang, Q., Wang, H., Christensen, T.H., Lu, W., 2021. Quantifying global warming potential of alternative biorefinery systems for producing fuels from Chinese food waste. Waste Management 130, 38–47. https://doi.org/10.1016/j.wasman.2021.05.004

Guo, Y., Hatton, T.A., 2025. Enhancing continuous-flow CO2 capture and release from aqueous carbonates via thermal pH regulation. Nature Chemical Engineering. https://doi.org/10.1038/s44286-025-00313-8

Hakawati, R., Smyth, B.M., McCullough, G., De Rosa, F., Rooney, D., 2017a. What is the most energy efficient route for biogas utilization: Heat, electricity or transport? Appl. Energy 206, 1076–1087. https://doi.org/10.1016/j.apenergy.2017.08.068

Hakawati, R., Smyth, B.M., McCullough, G., De Rosa, F., Rooney, D., 2017b. What is the most energy efficient route for biogas utilization: Heat, electricity or transport? Appl. Energy 206, 1076–1087. https://doi.org/10.1016/j.apenergy.2017.08.068

Havukainen, J., Zhan, M., Dong, J., Liikanen, M., Deviatkin, I., Li, X., Horttanainen, M., 2017. Environmental impact assessment of municipal solid waste management incorporating mechanical treatment of waste and incineration in Hangzhou, China. J. Clean. Prod. 141, 453–461. https://doi.org/10.1016/j.jclepro.2016.09.146

Henderson, C., 2015. Power plant CO2 capture heat integration. IEA Clean Coal Centre.

IEA Bioenergy, 2017. Methane emissions from biogas plants, IEA Bioenergy - Task 37.

IPCC, 2005. IPCC Special report on Carbon dioxide capture and storage. Prepared by Working Group III of the Intergovernmental Panel on Climate Change, Cambridge University Press. Cambridge, United Kingdom and New York, NY, USA.

Jayawickrama, K., Ruparathna, R., Seth, R., Biswas, N., Hafez, H., Tam, E., 2024. Challenges and Issues of Life Cycle Assessment of Anaerobic Digestion of Organic Waste. Environments 11, 217. https://doi.org/10.3390/environments11100217

Jin, Q., Yang, L., Poe, N., Huang, H., 2018. Integrated processing of plant-derived waste to produce value-added products based on the biorefinery concept. Trends Food Sci. Technol. 74, 119–131. https://doi.org/10.1016/j.tifs.2018.02.014

Kalita, S., Ohlsson, J.A., Karlsson Potter, H., Nordberg, Å., Sandgren, M., Hansson, P.-A., 2023. Energy performance of compressed biomethane gas production from co-digestion of Salix and dairy manure: factoring differences between Salix varieties. Biotechnology for Biofuels and Bioproducts 16, 165. https://doi.org/10.1186/s13068-023-02412-1

Keogh, N., Corr, D., Monaghan, R.F.D., 2024. An environmental and economic assessment for biomethane injection and natural gas heavy goods vehicles. Appl. Energy 360, 122800. https://doi.org/10.1016/j.apenergy.2024.122800

Khandelwal, H., Dhar, H., Thalla, A.K., Kumar, S., 2019. Application of life cycle assessment in municipal solid waste management: A worldwide critical review. J. Clean. Prod. 209, 630–654. https://doi.org/10.1016/j.jclepro.2018.10.233

Koornneef, J., van Keulen, T., Faaij, A., Turkenburg, W., 2008. Life cycle assessment of a pulverized coal power plant with post-combustion capture, transport and storage of CO2. International Journal of Greenhouse Gas Control 2, 448–467. https://doi.org/10.1016/j.ijggc.2008.06.008

Kristensen, P.G., Jensen, J.K., Nielsen, M., Illerup, J.B., 2004. Emission factors for gas fired CHP units < 25 Mw, in: International Gas Research Conference Proceedings.

Kumar, A., Agrawal, A., 2020. Recent trends in solid waste management status, challenges, and potential for the future Indian cities – A review. Current Research in Environmental Sustainability 2, 100011. https://doi.org/10.1016/j.crsust.2020.100011

Kumar, M., 2023. Lack of market support for bio-manure hindering growth of compressed biogas plants [WWW Document]. URL https://india.mongabay.com/2023/01/lack-of-market-support-for-bio-manure-hindering-growth-of-compressed-biogas-plants/

Lausselet, C., Cherubini, F., Oreggioni, G.D., del Alamo Serrano, G., Becidan, M., Hu, X., Rørstad, P.Kr., Strømman, A.H., 2017. Norwegian Waste-to-Energy: Climate change, circular economy and carbon capture and storage. Resour. Conserv. Recycl. 126, 50–61. https://doi.org/10.1016/j.resconrec.2017.07.025

Liu, W., Zhang, Z., Xie, X., Yu, Z., von Gadow, K., Xu, J., Zhao, S., Yang, Y., 2017. Analysis of the Global Warming Potential of Biogenic CO2 Emission in Life Cycle Assessments. Sci. Rep. 7, 39857. https://doi.org/10.1038/srep39857

López González, L.M., Pereda Reyes, I., Pedraza Garciga, J., Barrera, E.L., Romero Romero, O., 2020. Energetic, economic and environmental assessment for the anaerobic digestion of pretreated and codigested press mud. Waste Management 102, 249–259. https://doi.org/10.1016/j.wasman.2019.10.053

Martínez-Arce, A., Kargupta, W., Domínguez, C.G., Odey, E.A., McMahon, H., Huerta, J.D., Zimmermann, J., Bishop, G., Gaffey, J., Styles, D., 2025. An integrated technoeconomic and environmental assessment of biomethane production via anaerobic digestion of food waste in Ireland: Updated insights under market volatility. Sustainable Energy Technologies and Assessments 82, 104563. https://doi.org/10.1016/j.seta.2025.104563

Masson-Delmotte, V., Zhai, P., Pirani, A., Connors, S., Péan, C., Berger, S., Caud, N., Chen, Y., Goldfarb, L., Gomis, M., Huang, M., 2021. Climate change 2021: the physical science basis. Contribution of working group I to the sixth assessment report of the intergovernmental panel on climate change.

Materazzi, M., Chari, S., Sebastiani, A., Lettieri, P., Paulillo, A., 2024. Waste-to-energy and waste-to-hydrogen with CCS: Methodological assessment of pathways to carbon-negative waste treatment from an LCA perspective. Waste Management 173, 184–199. https://doi.org/10.1016/j.wasman.2023.11.020

Mendieta, O., Castro, L., Rodríguez, J., Escalante, H., 2020. Management and valorization of waste from a non-centrifugal cane sugar mill via anaerobic co-digestion: Technical and economic potential. Bioresour. Technol. 316, 123962. https://doi.org/10.1016/j.biortech.2020.123962

MoHUA, 2021. Circular Economy in Municipal solid and liquid waste. Ministry of Housing and Urban Affairs, GOI 1–112.

Montejo, C., Tonini, D., Márquez, M. del C., Fruergaard Astrup, T., 2013. Mechanical–biological treatment: Performance and potentials. An LCA of 8 MBT plants including waste characterization. J. Environ. Manage. 128, 661–673. https://doi.org/10.1016/j.jenvman.2013.05.063

MoPNG, 2025. SATAT.

Mukherjee, A., Chatterjee, S., 2022. Carbon Capture Utilization and Storage (CCUS) – Policy Framework and Deployment Mechanism in India (NITI Aayog).

Naaz, I., Thengane, S.K., Arora, P., Thirumoorthy, G., Singal, S.K., 2025. Waste-to-energy pathways for fresh and legacy waste management: A case study in India. Energy Nexus 19, 100472. https://doi.org/10.1016/j.nexus.2025.100472

Nanlin, L., Fan, L., Hua, Z., Liming, S., Pinjing, H., 2023. Environmental and economic assessment of the construction, operation, and demolition of a decentralized composting facility. Science of The Total Environment 884, 163724. https://doi.org/10.1016/j.scitotenv.2023.163724

Nordahl, S.L., Devkota, J.P., Amirebrahimi, J., Smith, S.J., Breunig, H.M., Preble, C. V., Satchwell, A.J., Jin, L., Brown, N.J., Kirchstetter, T.W., Scown, C.D., 2020. Life-Cycle Greenhouse Gas Emissions and Human Health Trade-Offs of Organic Waste Management Strategies. Environ. Sci. Technol. 54, 9200–9209. https://doi.org/10.1021/acs.est.0c00364

Oviedo-Ocaña, E.R., Abendroth, C., Domínguez, I.C., Sánchez, A., Dornack, C., 2023. Life cycle assessment of biowaste and green waste composting systems: A review of applications and implementation challenges. Waste Management 171, 350–364. https://doi.org/10.1016/j.wasman.2023.09.004

Pasciucco, F., Francini, G., Pecorini, I., Baccioli, A., Lombardi, L., Ferrari, L., 2023. Valorization of biogas from the anaerobic co-treatment of sewage sludge and organic waste: Life cycle assessment and life cycle costing of different recovery strategies. J. Clean. Prod. 401, 136762. https://doi.org/10.1016/j.jclepro.2023.136762

Paulillo, A., Sebastiani, A., Lettieri, P., Materazzi, M., 2024. Decarbonising waste-to-energy: A life cycle assessment study. Resour. Conserv. Recycl. 209, 107812. https://doi.org/10.1016/j.resconrec.2024.107812

Poeschl, M., Ward, S., Owende, P., 2012. Environmental impacts of biogas deployment – Part II: life cycle assessment of multiple production and utilization pathways. J. Clean. Prod. 24, 184–201. https://doi.org/10.1016/j.jclepro.2011.10.030

Pujara, Y., Govani, J., Patel, H.T., Pathak, P., Mashru, D., Ganesh, P.S., 2023. Quantification of environmental impacts associated with municipal solid waste management in Rajkot city, India using Life Cycle Assessment. Environmental Advances 12, 100364. https://doi.org/10.1016/j.envadv.2023.100364

Ravindran, J.K., Fagg, D.P., Coelho, M.C., 2025. Current production routes and life cycle analysis of "Green Energy-Dense Fuels" from biogas: A comprehensive review. Appl. Energy 402, 126832. https://doi.org/10.1016/j.apenergy.2025.126832

Rosa Aon Cardoso Fernandes, A., Eduardo Lobo Baêta, B., Damgaard, A., 2023. Life-cycle assessment as a prospection stage for the biochemical methane potential of pretreated lignocellulosic biomass. Bioresour. Technol. 386, 129584. https://doi.org/10.1016/j.biortech.2023.129584

Sadiq, M., Sharma, R., Kalita, H.J., Pandey, P., 2025. CCUS in India: A Techno-Economic and Policy Roadmap to Net-Zero Amid Climate and Environmental Challenges. Journal Of The Geological Society Of India 101, 1663–1673. https://doi.org/10.17491/jgsi/2025/174290

Sandström, J., Van Heusden, R., Morrison, H., Puleo, M., Murray, L., 2020. Aluminium for Climate: Exploring pathways to decarbonize the aluminium industry. WEF, Cologny/Geneva, Switzerland.

Serafini, L.F., Praça, P.J.G.M., González-Andrés, F., Gonçalves, A., 2025a. Life cycle approach as a tool for assessing municipal biowaste treatment units: A systematic review. Waste Management & Research: The Journal for a Sustainable Circular Economy 43, 1509–1524. https://doi.org/10.1177/0734242X251326866

Serafini, L.F., Praça, P.J.G.M., González-Andrés, F., Gonçalves, A., 2025b. Life cycle approach as a tool for assessing municipal biowaste treatment units: A systematic review. Waste Management & Research: The Journal for a Sustainable Circular Economy. https://doi.org/10.1177/0734242X251326866

Shi, Z., He, P., Guo, J., Zou, J., Peng, W., Zhang, H., Lü, F., 2024. Carbon reduction trade-off between pretreatment and anaerobic digestion: A field study of an industrial-scale biogas plant. Environ. Res. 246, 118139. https://doi.org/10.1016/j.envres.2024.118139

Shinde, A.M., Dikshit, A.K., Odlare, M., Thorin, E., Schwede, S., 2021. Life cycle assessment of bio-methane and biogas-based electricity production from organic waste for utilization as a vehicle fuel. Clean Technol. Environ. Policy 23, 1715–1725. https://doi.org/10.1007/s10098-021-02054-7

Singh, A.D., Upadhyay, A., Shrivastava, S., Vivekanand, V., 2020. Life-cycle assessment of sewage sludge-based large-scale biogas plant. Bioresour. Technol. 309, 123373. https://doi.org/10.1016/j.biortech.2020.123373

Singh, P., Babu, G.L.S., Hoysall, C., Rao, L., 2026. Assessing biogas valorization from municipal organic waste in India: Integrated environmental-economic analysis. Bioresour. Technol. 442, 133675. https://doi.org/10.1016/j.biortech.2025.133675

Singh, P., Kalamdhad, A.S., 2024. Unravelling barriers associated with dissemination of large-scale biogas plant with analytical hierarchical process and fuzzy analytical hierarchical process approach: Case study of India. Bioresour. Technol. 413, 131543. https://doi.org/10.1016/j.biortech.2024.131543

Singh, P., Kalamdhad, A.S., 2022a. Biomethane plants based on municipal solid waste and wastewater and its impact on vehicle sector in India — An Environmental-economic-resource assessment. Environ. Technol. Innov. 26, 102330. https://doi.org/10.1016/j.eti.2022.102330

Singh, P., Kalamdhad, A.S., 2022b. Assessment of agricultural residue-based electricity production from biogas in India: Resource-environment-economic analysis. Sustainable Energy Technologies and Assessments 54, 102843. https://doi.org/10.1016/j.seta.2022.102843

Singh, P., Kalamdhad, A.S., 2022c. Assessment of agricultural residue-based electricity production from biogas in India: Resource-environment-economic analysis. Sustainable Energy Technologies and Assessments 54, 102843. https://doi.org/10.1016/j.seta.2022.102843

Singh, P., Kalamdhad, A.S., 2022d. Biomethane plants based on municipal solid waste and wastewater and its impact on vehicle sector in India — An Environmental-economic-resource assessment. Environ. Technol. Innov. 26, 102330. https://doi.org/10.1016/j.eti.2022.102330

Slorach, P.C., Jeswani, H.K., Cuéllar-Franca, R., Azapagic, A., 2019. Environmental and economic implications of recovering resources from food waste in a circular economy. Science of The Total Environment 693, 133516. https://doi.org/10.1016/j.scitotenv.2019.07.322

Soni, A., Gupta, S.K., Rajamohan, N., Yusuf, M., 2025. Waste-to-energy technologies: a sustainable pathway for resource recovery and materials management. Mater. Adv. 6, 4598–4622. https://doi.org/10.1039/D5MA00449G

Su, D., Herraiz, L., Lucquiaud, M., Thomson, C., Chalmers, H., 2023. Thermal integration of waste to energy plants with Post-combustion CO2 capture. Fuel 332, 126004. https://doi.org/10.1016/j.fuel.2022.126004

TERI, 2023. Financing Decarbonization of the Secondary Steel Sector in India: Towards an Enabling Environment. New Delhi, India: The Energy and Resources Institute.

Tian, P., Wu, Y., Shang, B., Qi, C., Xu, Z., Li, G., Luo, W., Zhang, W., Li, Y., 2025. LCA as a decision support tool for the environmental improvement of organic fraction of municipal solid waste composting in China. J. Clean. Prod. 495, 145068. https://doi.org/10.1016/j.jclepro.2025.145068

Tisserant, A., Morales, M., Cavalett, O., O'Toole, A., Weldon, S., Rasse, D.P., Cherubini, F., 2022. Life-cycle assessment to unravel co-benefits and trade-offs of large-scale biochar deployment in Norwegian agriculture. Resour. Conserv. Recycl. 179, 106030. https://doi.org/10.1016/j.resconrec.2021.106030

Vinayak, A.K., Chauhan, G., 2026. Circularity in polyethylene waste management through multidimensional integration. Next Sustainability 7, 100247. https://doi.org/10.1016/J.NXSUST.2026.100247

Whiting, A., Azapagic, A., 2014. Life cycle environmental impacts of generating electricity and heat from biogas produced by anaerobic digestion. Energy 70, 181–193. https://doi.org/10.1016/j.energy.2014.03.103

Woon, K.S., Lo, I.M.C., Chiu, S.L.H., Yan, D.Y.S., 2016. Environmental assessment of food waste valorization in producing biogas for various types of energy use based on LCA approach. Waste Management 50, 290–299. https://doi.org/10.1016/j.wasman.2016.02.022

Chapter 6

Waste-to-energy Plants

6.1 Preamble

In this chapter an India-specific, integrated LCA and economic assessment framework to compare three WTE configurations: conventional WTE, WTE with CCS, and WTE with CCU is discussed. The analysis explicitly reflects Indian operating conditions, including the absence of district heat utilisation, heterogeneous MSW quality, and prevailing energy and market constraints. By systematically evaluating three representative waste compositions and linking environmental performance with financial indicators, this work provides decision-relevant insights into the conditions under which advanced WTE pathways can contribute to sustainable waste management and climate mitigation in India.

The specific objectives of this chapter are to:

- compare the environmental impacts of conventional WTE, WTE-CCS, and WTE-CCU using life cycle assessment;
- evaluate the financial feasibility of a 600 TPD WTE plant using net present value (NPV), internal rate of return (IRR), and payback period; and
- assess the influence of MSW quality (GCV, moisture content, and biogenic fraction) on both environmental and economic performance.

6.2 Methodology

This study employed a dual approach, integrating a LCA for environmental analysis with a thorough economic evaluation to assess financial feasibility.

6.2.1 Life cycle assessment (LCA)

The LCA was conducted using SimaPro (version 9.6.0.1) as the analytical framework to compare the environmental performance of the different WTE management alternatives. The primary objective was to compare the environmental impacts of managing MSW in WTE plants under three different technological configurations. The functional unit, which serves as the reference basis for all calculations, was defined as the treatment of 1,000 kg (1 ton) of MSW (Chicaiza-Ortiz et al., 2024; Christensen and Bisinella, 2021; Gao et al., 2025; Naaz et al., 2025; Paulillo et al., 2024).

The choice of a mass-based functional unit reflects the primary function of waste-to-energy systems, which is the treatment and disposal of a given quantity of municipal solid waste, while energy recovery is treated as a secondary function and accounted for through system expansion. Although waste characteristics vary across Sets A, B, and C (which is defined in section 2.1.3), these variations represent realistic heterogeneity in waste quality rather than different functional services. Maintaining a constant mass-based functional unit therefore enables a consistent comparison of the environmental implications of waste quality variability. An energy-service-based functional unit was not adopted, as it would obscure the waste management function of the system and reduce comparability with regulatory practice and existing WTE LCA literature.

6.2.1.1 System boundary

The system boundary of the LCA was carefully defined to focus on the core processes of the WTE facility. The temporal boundary was limited to the operation phase of the plant. The environmental burdens associated with the initial construction and final decommissioning of the facility were excluded from this analysis. These phases were excluded because their environmental burdens are amortized over the long operational lifetime of the plant and are expected to contribute marginally to comparative outcomes. As the objective of the study is to compare alternative operational configurations under identical infrastructure assumptions, the exclusion of construction and end-of-life stages does not affect the relative results and conclusions. This boundary choice is nevertheless acknowledged as a limitation of the study.

The spatial boundary of the operation stage included several key processes: the collection and transportation of MSW to the plant, the processing of waste via power generation through incineration coupled to high pressure steam turbine, the treatment of flue gas, the disposal of residual bottom and fly ash to an engineered landfill, and the environmental credits gained from the substitution of coal-based electricity.

Although transportation of bottom ash and fly ash is included within the system boundary, detailed landfill or utilization impact modelling was not explicitly performed. Ash management represents a downstream process that is assumed to be identical across all scenarios, and the study focuses on comparative differences arising from upstream waste treatment and energy recovery pathways. Excluding detailed ash disposal or utilization modelling therefore does not affect the relative comparison and is acknowledged as a scope limitation.

System expansion was applied to handle multi-functionality in accordance with ISO 14044. Electricity exported from the WTE plant was assumed to displace marginal coal-based grid electricity, reflecting the current Indian electricity mix. For Scenario 3, utilized CO_2 was assumed to displace an equivalent amount of conventionally produced fossil-derived CO_2 used in industrial applications.

6.2.1.2 Scenario descriptions

Three distinct Scenarios were modelled to provide a comprehensive comparison (Fig. 6.1):

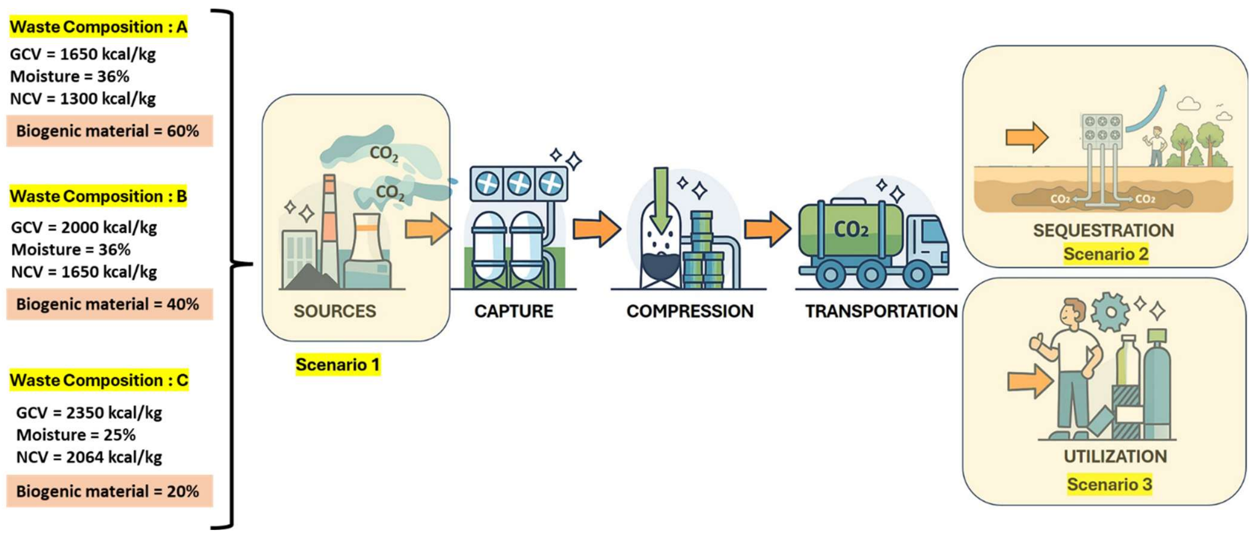


Fig. 6.1 Process flow of various Scenarios of waste to energy plant based on municipal solid waste

- **Scenario 1: Conventional WTE without carbon capture:** This Scenario represents a standard incineration-based WTE plant. MSW is combusted at high temperatures (850°C to 1,000°C) to generate heat, which produces high-pressure steam in a boiler. This steam drives a turbine to generate electricity. The process includes extensive flue gas treatment to control pollutants before release, and the resulting ash is sent for further management (either landfilled or utilization).

- **Scenario 2: WTE with carbon capture and storage (CCS):** This Scenario builds upon the first by integrating a post-combustion carbon capture unit. Instead of a generator-only setup, a combined heat and power (CHP) unit (at 1:2 power to heat ratio**)** is installed. The heat recovered from the CHP unit is used to regenerate an amine solution that captures 85% of the CO_2 (at purity above 95%) from the flue gas (Koornneef et al., 2008; Paulillo et al., 2024). This captured CO_2 is then compressed and transported over 100 km to be sequestered in suitable geological storage sites.

- **Scenario 3: WTE with carbon capture and utilisation (CCU):** The process flow for this Scenario is identical to Scenario 2 up to the CO_2 regeneration stage. However, instead of being stored, the captured CO_2 is assumed to be transported within a 40 km proximity and utilized as a feedstock in other industrial processes, thereby displacing the production of CO_2 from conventional fossil-derived CO_2 production.

6.2.1.3 Waste composition and inventory data

To account for the variability in Indian MSW, each of the three Scenarios was assessed using three different waste compositions, defined as sets A, B, and C. These sets represent low-, medium-, and high-quality waste scenarios, respectively, reflecting differences in segregation efficiency, moisture content, and biogenic fraction commonly observed across Indian cities (Kumar and Agrawal, 2020; Naaz et al., 2025).

- **Set A:** Represents typical Indian MSW with higher biogenic content (60%), a lower GCV of 1650 kcal/kg, and higher moisture (36%). This set reflects conditions commonly observed in cities with limited source segregation and high fractions of food and green waste, where wet organic matter dominates the waste stream. Such waste characteristics are frequently reported as challenging for WTE operation in India and serve as a conservative case.

- **Set B:** Represents the baseline waste composition based on site-measured ultimate and proximate analysis obtained from routine sampling at the operational WTE facility. The measured composition (C - 19%, H - 2.71%, O - 13.13%, N - 0.62%, S - 0.16%, Cl - 0.23%, ash - 28.06%, moisture - 36.09%, and GCV - 2,000 kcal/kg) represents average operating conditions at the plant and is therefore considered representative of typical mixed Indian MSW supplied to existing WTE facilities. The biogenic fraction in Set B was estimated as 40%.

- **Set C:** Represents an improved waste quality scenario corresponding to enhanced segregation or pre-treatment level, with lower biogenic content (20%), a higher GCV of 2350 kcal/kg, and reduced moisture content (25%). This set reflects the upper-bound performance potential of Indian MSW under improved waste management practices that are increasingly promoted in policy and pilot projects.

Set B defines the measured baseline waste characteristics. Sets A and C were modelled as parametric variations around this baseline to evaluate the influence of waste quality on environmental performance while maintaining internal consistency and comparability across scenarios.

Biogenic CO_2 emissions from MSW combustion were treated as climate-neutral (GW = 0), consistent with common bioenergy and WTE LCA practice in which CO_2 from short-cycle biomass is excluded from GW, while fossil CO_2 emissions were fully counted. In the CCS and CCU scenarios, captured biogenic CO_2 was modelled as a carbon-removal (negative emission), while captured fossil CO_2 contributed to avoided emissions through storage or utilisation pathways (Christensen and Bisinella, 2021; Liu et al., 2017).

The life cycle inventory (LCI) data for scenario 1 were based on one-year average plant data from Bidadi WTE plant facility (located in Karnataka, India). Inputs include 1 ton of MSW, electricity (55 kWh), water (130 L), ammonia (2.6 kg), and other chemicals for flue gas treatment. Outputs include electricity (360 kWh for set A), ash (198 kg total), and air emissions including 782 kg of CO_2 (60% of which is biogenic). For scenarios 2 and 3, additional energy inputs of 3.9 GJ thermal energy and 1 GJ of electricity per ton of CO_2 captured were included (Bisinella et al., 2021; Paulillo et al., 2024), along with 65 kWh/t CO_2 for compression (Bisinella et al., 2021). The CO_2 losses during the storage in a good site is generally 1-2% over the 1000 years period (IPCC, 2005), however given the small quantity over significant timeframe, no leakage was assumed (Paulillo et al., 2024). Detailed life cycle inventory table of three scenario is mentioned in Table 6.1 and background data for processes were obtained from the ecoinvent 3.11 database.

6.2.1.4 Impact assessment

The environmental performance was evaluated across nine mid-point impact categories (ReciPe 2016 H): global warming (GW), terrestrial acidification (TA), freshwater eutrophication (FE), terrestrial ecotoxicity (TE), freshwater ecotoxicity (FET), human carcinogenic toxicity (HCT), human non-carcinogenic toxicity (HNCT), mineral resource scarcity (MRS), and fossil resource scarcity (FRS). Using ReCiPe 2016 Endpoint (H) v1.11 / World (2010) H/A, endpoint results were normalized against the 2010 global per-capita environmental burden for each damage category (human health, ecosystems, and resource depletion), and subsequently weighted using the average perspective factors (400 for human health, 400 for ecosystems, and 200 for resources) to derive a single aggregated score expressed in points (Pt).

Table 6.1 Inventory data for waste to energy plant for three scenarios (per functional unit)

	Unit	Scenario 1			Scenario 2 (CCS)			Scenario 3 (CCU)			Comments
		Set A	Set B	Set C	Set A	Set B	Set C	Set A	Set B	Set C	
Inputs											
Waste to energy plant											
Raw material	ton	1	1	1	1	1	1	1	1	1	
Transportation	km	40	40	40	40	40	40	40	40	40	
Electricity (A)	kWh	55	55	55	55	55	55	55	55	55	*plant data*
Ammonia	kg	2.6	2.6	2.6	2.6	2.6	2.6	2.6	2.6	2.6	*to reduce NOx in flue gas*
Hydrated Lime	kg	19.1	19.1	19.1	19.1	19.1	19.1	19.1	19.1	19.1	*to control pollutant like SO_2, SO_3 (Sulphur trioxide), HCl, HF (Hydrogen fluoride) in flue gas*
Activated carbon	kg	0.23	0.23	0.23	0.23	0.23	0.23	0.23	0.23	0.23	*used to control heavy metal compounds and organic pollutants such as dioxins and furans, VOC (volatile organic compound), mercury*
Carbon dioxide capture											
Electricity (B)	kWh	-	-	-	183	183	183	183	183	183	*Electricity req. – 277 kWh/ton CO_2* (Bisinella et al., 2021; Paulillo et al., 2024)
Heat	GJ	-	-	-	2.58	2.58	2.58	2.58	2.58	2.58	*Heat req. – 3.9 GJ/ton CO_2* (Bisinella et al., 2021; Paulillo et al., 2024)
Monoethanolamine (MEA)	kg	-	-	-	~1	~1	~1	~1	~1	~1	*MEA req. – 1.5 kg/ton CO_2* (Christensen and Bisinella, 2021)
Carbon dioxide compression											
Electricity (C)	kWh	-	-	-	43	43	43	43	43	43	*Electricity req. – 65 kWh/ton CO_2* (Bisinella et al., 2021; Paulillo et al., 2024)
Outputs											

Emissions to air											
CO_2	kg	313	469	626	47	70	94	47	70	94	*Calculated at 13.5% CO_2 (plant data)*
CO_2 (biogenic)	kg	469	313	156	70	47	23	70	47	23	
Outputs											
Electricity (D)	kWh	363	460	576	353*	448*	560*	353*	448*	560*	*Plant efficiency*
Heat	GJ	-	-	-	2.54*	3.22*	4.03*	2.54*	3.22*	4.03*	*WTE plant – 24% (plant data)* **WTE plant (with CHP) – 70% with (1:2 power to heat ratio)*
Captured CO_2	kg	-	-	-	665	665	665	665	665	665	*Capture efficiency – 85%* (Koornneef et al., 2008; Paulillo et al., 2024)
Bottom Ash	kg	185	185	185	185	185	185	185	185	185	*Sent to further management (25 km)*
Fly Ash	kg	28	28	28	28	28	28	28	28	28	*Sent to further management (25 km)*
Offset											
Coal-based electricity	kWh	308	405	521	71	166	278	71	166	278	*Calculated on based of [(D- (A+B+C)]*
CO_2 sequestration	kg	-	-	-	665 (-399)	665 (-266)	665 (-133)	-	-	-	*Value mentioned in bracket is of biogenic carbon*
CO_2 for foods and beverages, fire extinguishers, refrigerants.	kg	-	-	-	-	-	-	665	665	665	

6.2.1.5 Sensitivity analysis

To ensure the robustness of the environmental assessment, a comprehensive one-at-a-time sensitivity analysis was conducted by varying key parameters across established ranges. This approach isolates the influence of individual variables on the global warming and identifies the break-even points where a system transitions from a net carbon source to a net carbon sink. Six parameters were varied: biogenic content (20-80%), plant efficiency (18-24% for Scenario 1; 50-80% for Scenarios 2 and 3), flue gas CO_2 concentration (8-14%), CO_2 capture rate (65-95%), electricity substitution (0-100%), and utilisation substitution for CCU (0-100%).

A probabilistic uncertainty analysis was not performed due to the absence of statistically distributed Indian datasets for WTE-CCS/CCU systems; therefore, the structured sensitivity analysis serves as a transparent and robust alternative. This framework explicitly tests the robustness of CCS and CCU performance under conservative and optimistic assumptions rather than relying on fixed or idealised values. All model assumptions and parameter ranges are explicitly reported, enabling reproducibility within the defined system boundaries.

6.2.2 Economic analysis

The economic analysis was designed to evaluate the project-level financial feasibility of a WTE plant under current Indian operating and market conditions, rather than to perform a detailed engineering cost optimisation of individual subsystems, particularly for emerging CCS and CCU technologies. Accordingly, the analysis focuses on overall capital and operating costs and their implications for investment performance.

The assessment was conducted for a 600 TPD WTE plant using the following assumptions: a plant conversion efficiency of 24%, 350 operating days per year, a project lifetime of 20 years, and a discount rate of 15%. Economic performance was evaluated across a range of gross calorific values (GCVs) from 1650 to 2350 kcal/kg and at two representative moisture contents (36% and 25%) to reflect variability in Indian MSW quality.

Capital expenditure (CAPex) and operating expenditure (OPex) data were derived from an operational WTE facility at Bidadi, Karnataka (India), ensuring consistency with real plant conditions. The detailed economic input parameters used in the analysis are provided in Table 2. Project revenues were calculated solely from the sale of generated electricity at a tariff of ₹7.1/kWh, reflecting prevailing power purchase arrangements for WTE projects in India. Tipping fees were not included, as Indian WTE plants typically do not receive gate fees from municipalities and electricity sales constitute the primary direct revenue stream.

To assess financial performance, three standard investment indicators were employed: net present value (NPV), discounted payback period, and internal rate of return (IRR). Potential revenues from by-products (bottom ash), carbon credits, or CCS/CCU-related incentives were excluded from the base-case analysis to maintain a conservative assessment and avoid reliance on policy- or market-dependent assumptions.

Table 6.2 Data for economic analysis of 600 TPD waste to energy plant

GCV, kcal/kg		1650	1850	2000	2150	2350
Quantity of waste				600 TPD		
CAPEX, ₹ Crores ($)				310 ($37,231,000)		
OPEX, ₹ Crores/year ($/year)				28.4 ($3,408,000)		
Electricity, MW/day	@36% Moisture	217	250	276	301	335
	@25% Moisture	228	262	287	312	345
Electricity Price, ₹/kWh ($/kWh)				7.1($0.085)		
Electricity Revenue, ₹ Crores/year ($/year)	@36% Moisture	54.1 ($6,492,000)	62.4 ($7,488,000)	68.6 ($8,232,000)	74.8 ($8,976,000)	83.2 ($9,984,000)
	@25% Moisture	56.7 ($6,804,000)	65.1 ($7,812,000)	71.2 ($8,544,000)	77.5 ($9,300,000)	85.8 ($10,296,000)

6.3 Results and Discussions

6.3.1 Life cycle impact assessment

6.3.1.1 Global warming

For Scenario 1 i.e., WTE plant (without carbon capture), the GW depends on the biogenic fraction, GCV and moisture content of waste. As the biogenic fraction decreases, the gross carbon footprint of the WTE plant increases. A higher biogenic content leads to a considerably lower overall carbon footprint, as emissions from biogenic carbon are considered part of the short-term carbon cycle and hence not considered (Masson-Delmotte et al., 2021). Also, with the increase of GCV and decrease in moisture content, the quantity of power production is higher and hence the increase the offset. Overall, the net GW from waste to energy plants producing only power for offsetting coal-based electricity is in the range of -124 to -139 kg CO_2-eq./ton (Fig. 6.2a) and for offsetting grid-mix electricity is 13 to 79 kg CO_2-eq.

The implementation of carbon capture and storage (CCS) technology in a WTE plant significantly impacts its GW, shifting the overall environmental footprint from a net positive contribution to a net beneficial, or negative, one. This significant reduction is primarily attributable to two key factors: the substantial decrease in direct CO_2 emissions released from the flue gas into the atmosphere, and the subsequent effective removal of the captured CO_2 from the atmospheric system through geological storage. The net GW from waste to energy plants producing power with CCS for offsetting coal-based electricity is in the range of -739 to -1030 kg CO_2-eq./ton (Fig. 6.2b) and for offsetting grid-mix electricity is in the range of -609 to -819 kg CO_2-eq. This confirms that CCS is a highly effective strategy for significantly mitigating the carbon footprint of WTE facilities, regardless of the precise biogenic fraction, GCV, or moisture content of the waste within the analyzed ranges.

In Scenario 3, which involves carbon capture and utilization (CCU), the overall carbon footprint of the WTE plant remains almost identical to that observed in Scenario 2 (carbon capture and storage - CCS). This consistent GW across both capture Scenarios holds true for all three waste sets, with set A yielding -739 kg CO_2-eq./ton, set B at -879 kg CO_2-eq./ton, and set C at -998 kg CO_2-eq./ton (Fig. 6.2c) and for offsetting grid-mix electricity is in the range of -583 to -794 kg CO_2-eq./ton. This similarity in net GW of CCU with CCS is attributed to two primary reasons. Firstly, the initial reduction in CO_2 emissions from the flue gas due to the capture process is the same as in scenario 2. Secondly, the environmental credit gained from the utilization of the captured CO_2 is considered equivalent to the impact from CO_2 production in conventional processes that the captured CO_2 displaces.

Our study's findings compare well to the previously published work. For instance, with CO_2 recovery and storage, (Bisinella et al., 2021) reported the GW in the range of -530 to -800 kg CO_2 eq./ton MSW for various incineration technology (Bisinella et al., 2021). (Materazzi et al., 2024) and (Paulillo et al., 2024) reported it be -556 and -437 kg CO_2 eq./ton, respectively (Materazzi et al., 2024; Paulillo et al., 2024). For carbon capture and utilization, (Christensen and Bisinella, 2021), reported the impact to be around -700 kg CO_2 eq./ton and mentioned it be in similar range on carbon capture and storage (Christensen and Bisinella, 2021). In the Indian context, Naaz et al. (2025) reported a global warming impact of 14 kg CO_2 eq./ton of legacy MSW for conventional WTE assuming grid electricity substitution (Naaz et al., 2025), which aligns well with the results of the present study under similar assumptions. Most other Indian WTE LCAs are embedded within integrated MSW management frameworks or comparative studies with landfilling and composting, where differing system boundaries, functional units, and allocation methods prevent direct quantitative comparison with the standalone WTE scenarios analysed here.

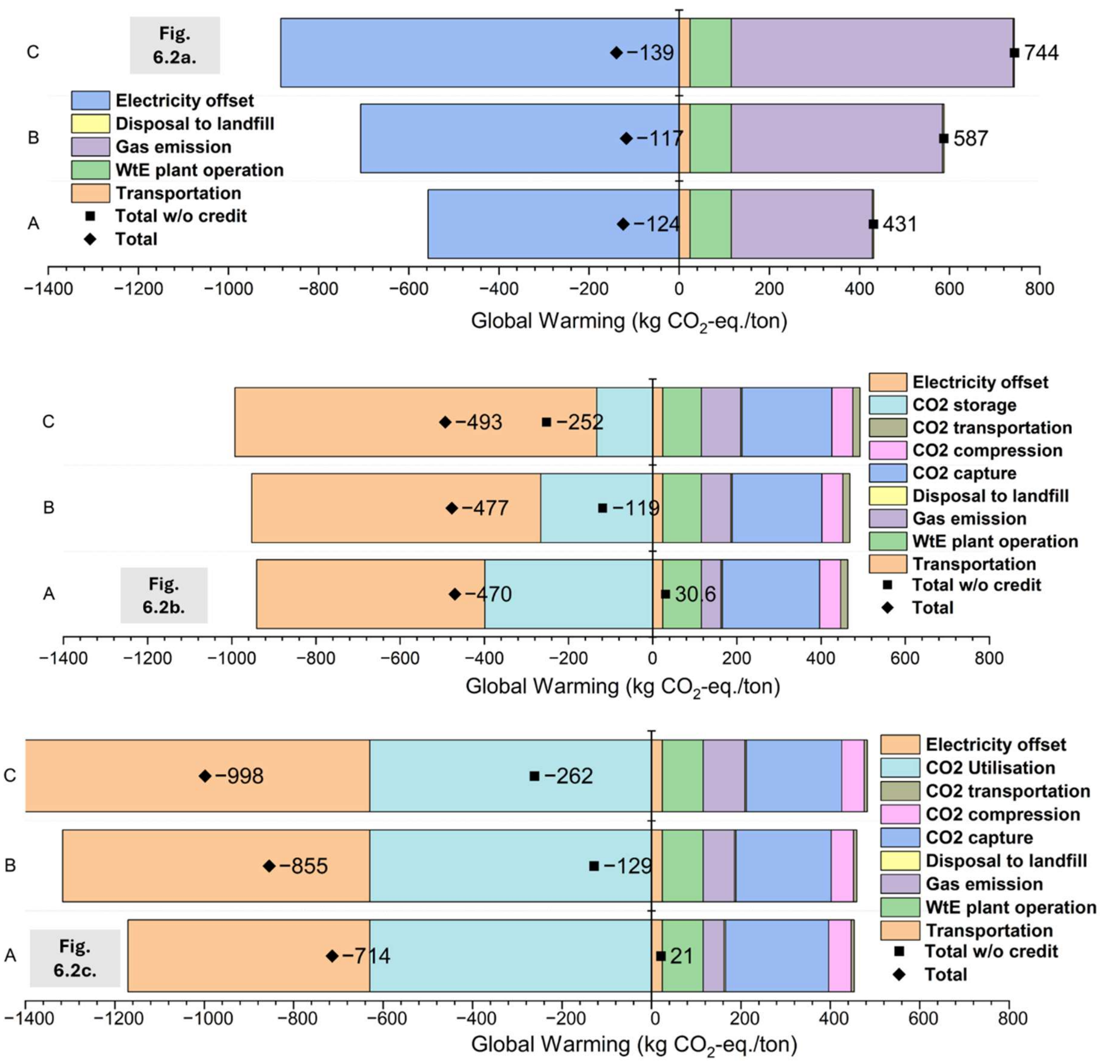


Fig. 6.2 Impact on global warming from waste to energy plant a) producing only power without carbon capture b) coupled with combined heat and power with carbon capture and storage c) coupled with combined heat and power with carbon capture and utilization (Waste composition A) represents 60% biogenic mass of GCV – 1650 kcal/kg and moisture 36% B) represents 40% biogenic mass of GCV – 2000 kcal/kg and moisture 36% C) represents 20% biogenic mass of GCV – 2350 kcal/kg and moisture 25%)

6.3.2 Influence of various parameters on global warming of WTE scenarios

The robustness of global warming results was evaluated through sensitivity analysis by varying biogenic content, plant efficiency, flue gas CO_2 concentration, capture rate, and substitution assumptions across the three waste sets (A-C). Overall, the analysis confirms that waste quality and energy efficiency are the dominant drivers of climate performance across all WTE configurations (Fig. 6.3).

Biogenic carbon content exerts the strongest influence. Increasing the biogenic fraction from 20% to 80% shifts all scenarios toward increasingly negative GW, reaching values as low as

−1070 kg CO_2-eq per ton in Scenario 3 due to BECCS accounting (Fig. 6.3a). However, this theoretical benefit is constrained in practice, as high-biogenic Indian MSW is typically associated with excessive moisture, reduced net calorific value, and poor thermodynamic and economic performance. This reinforces that WTE deployment should prioritise high-calorific, non-recyclable dry fractions rather than wet organic waste streams.

Plant efficiency shows a consistent inverse relationship with GW across all scenarios. In Scenario 1, improving efficiency from 18% to 24% shifts the system from marginally positive to clearly negative emissions (Fig. 6.3b). In capture-integrated systems, higher CHP efficiency is essential to offset the parasitic energy demand of solvent regeneration and CO_2 compression; for example, increasing efficiency from 50% to 80% in Scenario 2 reduces GW by nearly 40% for Set B.

The influence of CO_2 concentration in flue gas diverges by configuration (Fig. 6.3c). In conventional WTE, higher CO_2 concentration increases direct emissions, whereas in CCS and CCU scenarios it enhances carbon removal potential. Under an 85% capture rate, higher biogenic CO_2 generation translates directly into larger negative emission credits.

Increasing the CO_2 capture rate from 65% to 95% produces a near-linear improvement in GW; however, the marginal environmental gains diminish at higher capture levels due to rapidly increasing energy demand, indicating practical limits to capture efficiency optimisation (Fig. 6.3d).

Finally, electricity and utilisation substitution rates strongly affect outcomes. Conventional WTE requires electricity substitution rates above ~80% to achieve carbon neutrality (Fig. 6.3e), whereas CCS and CCU remain carbon negative even without grid displacement. For CCU, climate benefits scale linearly with utilisation rates, highlighting the strong dependence of CCU performance on the availability of nearby CO_2 markets (Fig. 6.3f).

Overall, the sensitivity analysis demonstrates that while CCS and CCU substantially improve climate performance, their effectiveness is conditional on feedstock quality, high system efficiency, and realistic substitution pathways.

Scenario 1 (WTE plant without carbon capture) | **Scenario 2 (Carbon capture and storage)** | **Scenario 3 (Carbon capture and utilisation)**

Fig. 6.3a. **Biogenic fraction**

Fig. 6.3b. **Plant efficiency**

Fig. 6.3c. **CO_2 emissions**

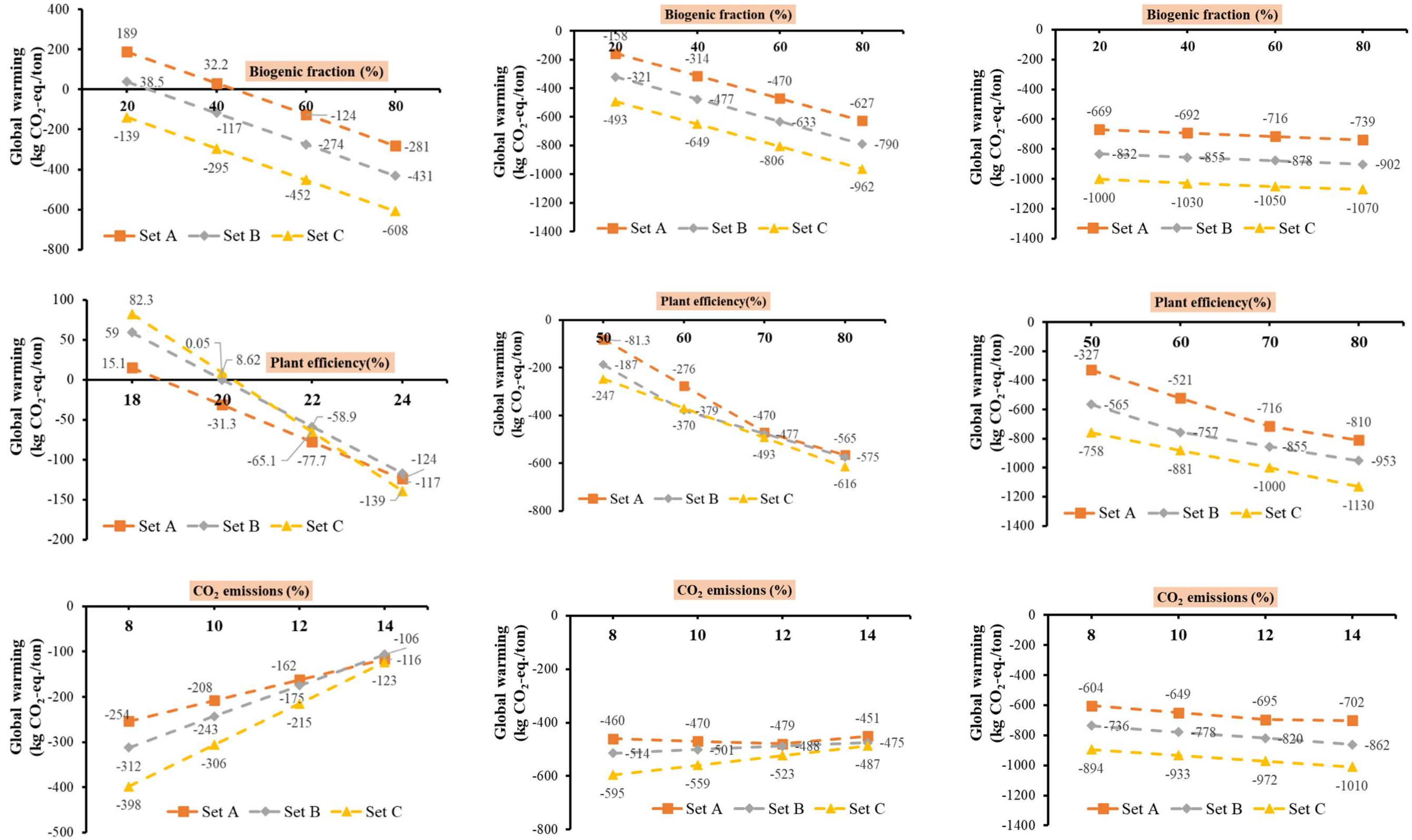
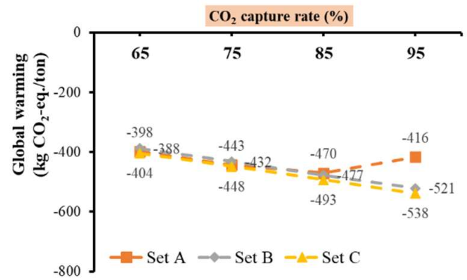


Fig. 6.3d.

CO_2 capture rate

-



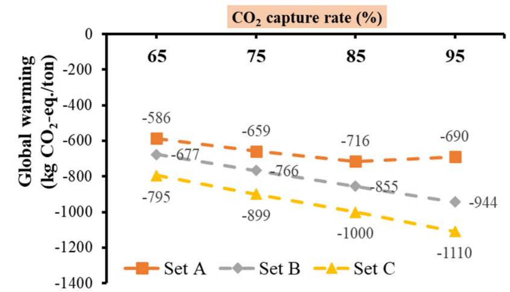
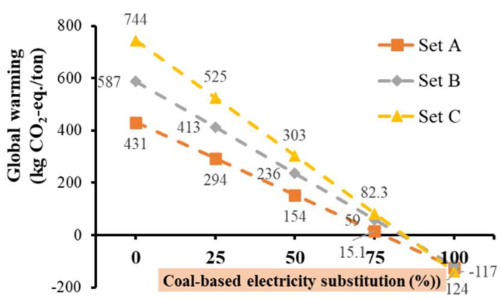
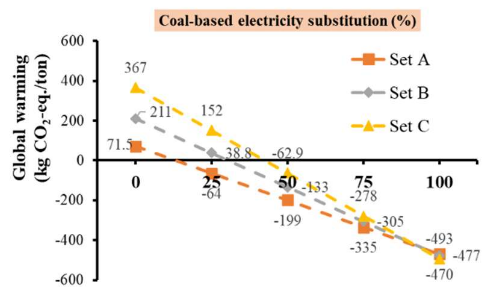


Fig. 6.3e.

Coal based electricity substitution





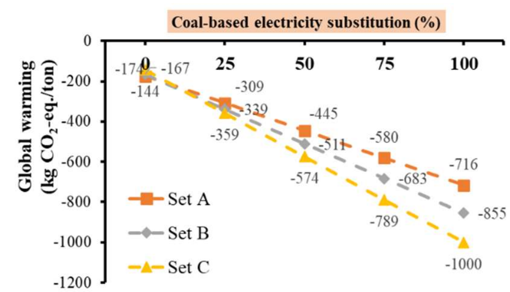


Fig. 6.3f.

CO_2 substitution

-

-

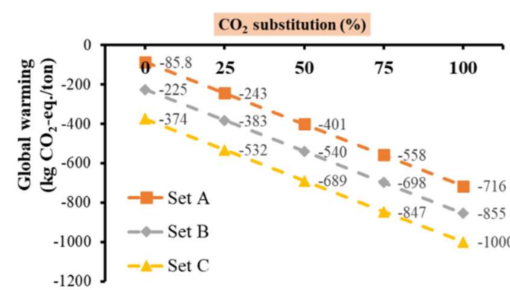


Fig. 6.3 Influence of variation in different parameters on global warming of different scenarios of waste-to-energy plants a) biogenic fraction b) plant efficiency c) CO_2 emissions d) CO_2 capture rate e) Coal-based electricity substitution f) CO_2 substitution

6.3.2.1 Midpoint scores

Beyond climate change, clear differences emerge across toxicity and resource-related impact categories. Conventional WTE (Scenario 1) performs comparatively better in certain toxicity and resource indicators, largely due to the absence of additional chemicals, materials, and auxiliary energy demands associated with carbon capture systems (see Table 6.3 for offsetting coal-based electricity). However, these advantages are insufficient to offset its limitations in a low-carbon waste management context.

The introduction of CCS (Scenario 2) increases environmental burdens in terrestrial ecotoxicity and mineral resource scarcity. These impacts are primarily linked to the added solvent consumption, and energy use required for CO_2 capture, compression, and storage. Such trade-offs between climate mitigation and other environmental categories are consistent with earlier studies on CCS-integrated WTE systems and highlight the need for careful system-level evaluation (Chandel et al., 2012; Lausselet et al., 2017; Paulillo et al., 2024).

In contrast, CCU (Scenario 3) demonstrates lower impacts across most toxicity-related categories, including terrestrial and freshwater ecotoxicity as well as human carcinogenic and non-carcinogenic toxicity. These improvements arise mainly from avoided impacts associated with conventional production routes displaced by utilised CO_2. CCU also shows notable reductions in fossil and mineral resource scarcity, reflecting partial substitution of virgin materials and fossil-based inputs (Fig. 6.4).

Across all scenarios, a clear trend is observed as the waste composition shifts from Set A to Set C. The increasing gross calorific value and decreasing moisture content improve energy efficiency, but also elevate fossil-derived emissions (by decrease in biogenic content) if not mitigated by carbon capture technologies. Therefore, while Set C may be the most energy-efficient configuration, it also presents the greatest climate risk unless paired with CCS or CCU.

Overall, CCS and CCU introduce environmental trade-offs beyond climate change, with CCU offering a more balanced performance profile across toxicity and resource use, while CCS remains primarily a climate-focused mitigation option.

Table 6.3 Mid impact categories scores of different Scenarios of waste-to-energy plants offsetting coal-based electricity (Scenario1: Without carbon capture, Scenario 2: With carbon capture and storage, Scenario 3: With carbon capture and utilisation) of waste-to-energy plant with different composition of waste type

Impact Categories	Unit	**Scenario 1**			**Scenario 2 (CCS)**			**Scenario 3 (CCU)**		
		Set A	Set B	Set C	Set A	Set B	Set C	Set A	Set B	Set C
Global warming	kg CO_2 eq	-124	-117	-139	-470	-477	-493	-714	-855	-998
Terrestrial acidification	kg SO_2 eq	-1.06	-1.54	-2.11	-0.18	-0.64	-1.19	-1.45	-1.97	-2.53
Freshwater eutrophication	kg P eq	-0.31	-0.41	-0.53	0.02	-0.09	-0.22	-0.18	-0.29	-0.42
Terrestrial ecotoxicity	kg 1,4-DCB	27.4	-60.3	-164	437	340	239	-3170	-3270	-3370
Freshwater ecotoxicity	kg 1,4-DCB	-7.7	-10.7	-14.2	2.74	-0.75	-4.18	-30.2	-33.7	-37.2
Human carcinogenic toxicity	kg 1,4-DCB	-56.7	-76.2	-99.3	-15.3	-36.5	-58.9	-112	-134	-156
Human non-carcinogenic toxicity	kg 1,4-DCB	-478	-642	-835	-44.9	-228	-42	-781	-965	-1150
Mineral resource scarcity	kg Cu eq	0.02	-0.01	-0.05	0.19	0.15	0.12	-1.9	-1.94	-1.97
Fossil resource scarcity	kg oil eq	-116	-155	-201	-37.5	-79.6	-124	-151	-193	-238

- *Set A: Represents typical Indian MSW with 60% biogenic content, a GCV of 1650 kcal/kg, and 36% moisture.*
- *Set B: Represents a mix with 40% biogenic content, a GCV of 2000 kcal/kg, and 36% moisture.*
- *Set C: Represents waste with a higher segregation or pre-treatment level, with 20% biogenic content, a GCV of 2350 kcal/kg, and 25% moisture.*

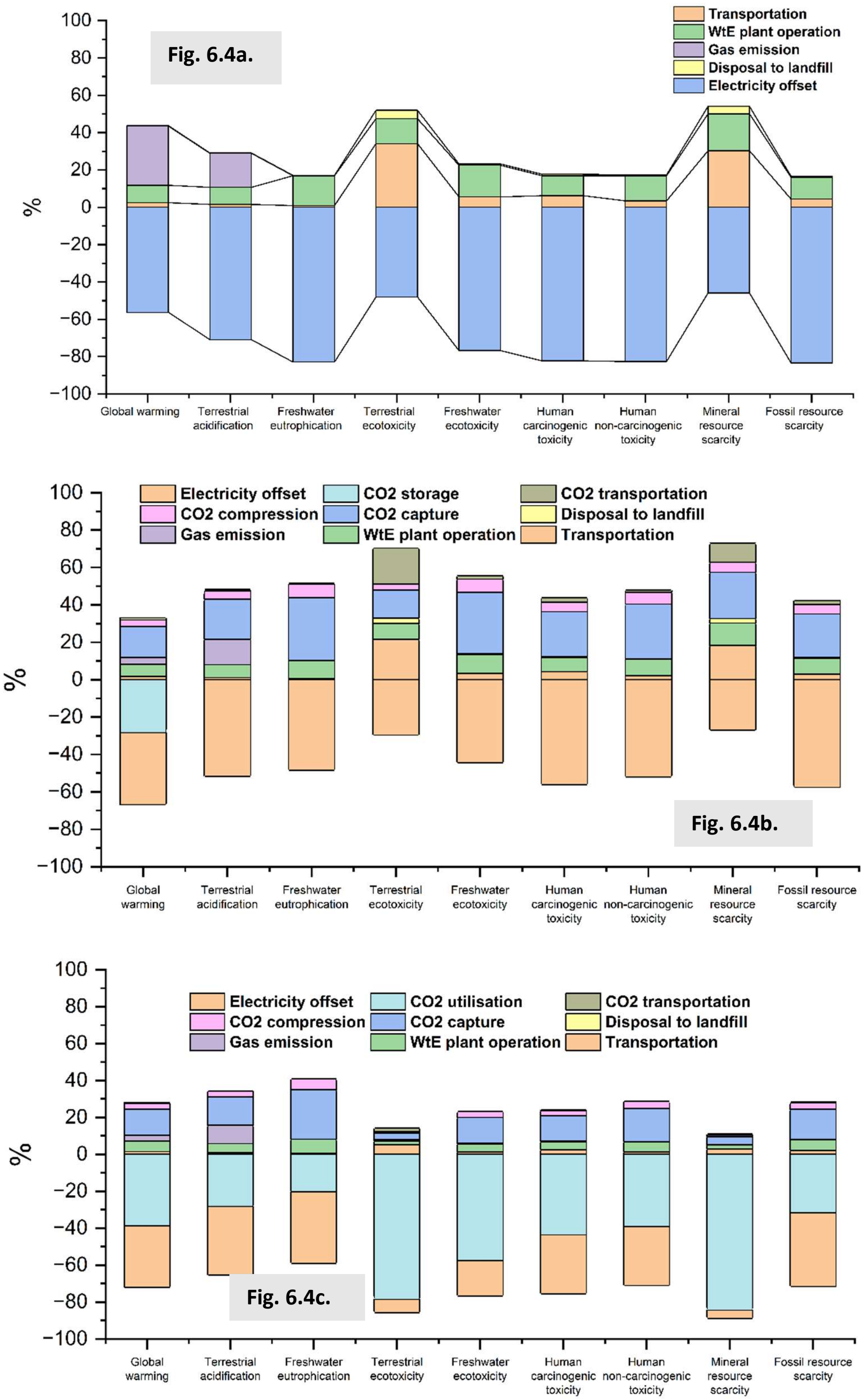


Fig. 6.4 Contribution of each process to the life cycle environmental impacts (Mid-point score) of waste-to-energy plants a) producing power only without carbon capture b) coupled with combined heat and power with carbon capture and storage c) coupled with combined heat and power with carbon capture and utilization

6.3.2.2 Endpoint score

Human health impacts dominate total endpoint damage across all scenarios (Fig. 6.5). Conventional WTE (Scenario 1) shows moderate reductions (-12.1 to -24.7 Pt), while the integration of CCS (Scenario 2) further improves performance (-9.8 to -27 Pt). The largest reductions are observed for CCU (Scenario 3), with human health damage decreasing to -26 to -44 Pt, primarily due to avoided emissions and displaced conventional CO_2 production. It should be noted that for a waste composition like Set A, characterized by a low calorific value, the addition of CCS technology leads to a counterintuitive increase in negative health scores. This occurs because CCS is an energy-intensive process requiring significant heat and electricity for its operation (Ayyad et al., 2021; Su et al., 2023). With low-quality fuel, the WTE plant produces very little surplus energy, so the net exportable power to the grid is significantly reduced. This reduction means less displacement of fossil fuel-based power plants, which are a major source of pollutants affecting human health. Consequently, the avoided health impacts are smaller, leading to a less beneficial overall score for this specific waste composition.

Ecosystem damage follows a similar pattern. Scenario 1 delivers limited improvements (-0.24 to -0.39 Pt), CCS provides stronger reductions (-0.55 to -0.91 Pt), and CCU achieves the greatest benefits (-0.73 to -1.09 Pt). In contrast, resource depletion impacts are negligible in Scenario 1 and slightly adverse in Scenario 2 due to additional material and energy requirements, whereas CCU consistently reduces resource damage (-0.21 to -0.26 Pt) by displacing virgin material production.

Overall, total environmental damage decreases from Scenario 1 to Scenario 3 across all waste compositions, with CCU exhibiting the most balanced endpoint performance. Improvements are amplified as waste quality shifts toward higher calorific value and lower moisture content, particularly for Set C.

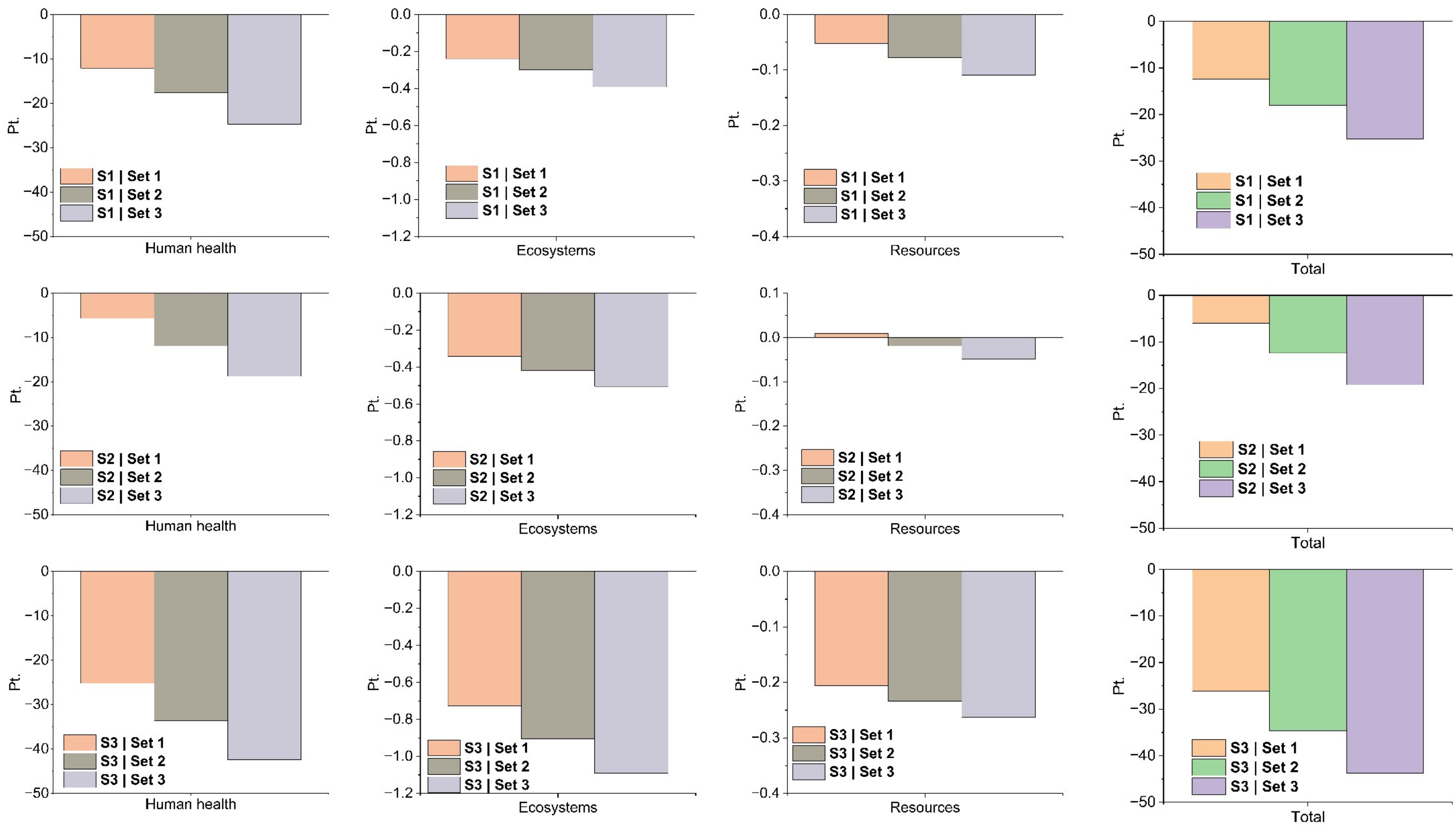


Fig. 6.5 Damage category and single point score of different Scenarios of waste-to energy plants (S1: producing only without carbon capture, S2: coupled with combined heat and power with carbon capture and storage, and S3 coupled with combined heat and power with carbon capture and utilization) and different waste composition (Set 1: 60% biogenic mass of GCV – 1650 kcal/kg and moisture 36% Set 2 represents 40% biogenic mass of GCV – 2000 kcal/kg and moisture 36% Set 3 represents 20% biogenic mass of GCV – 2350 kcal/kg and moisture 25%)

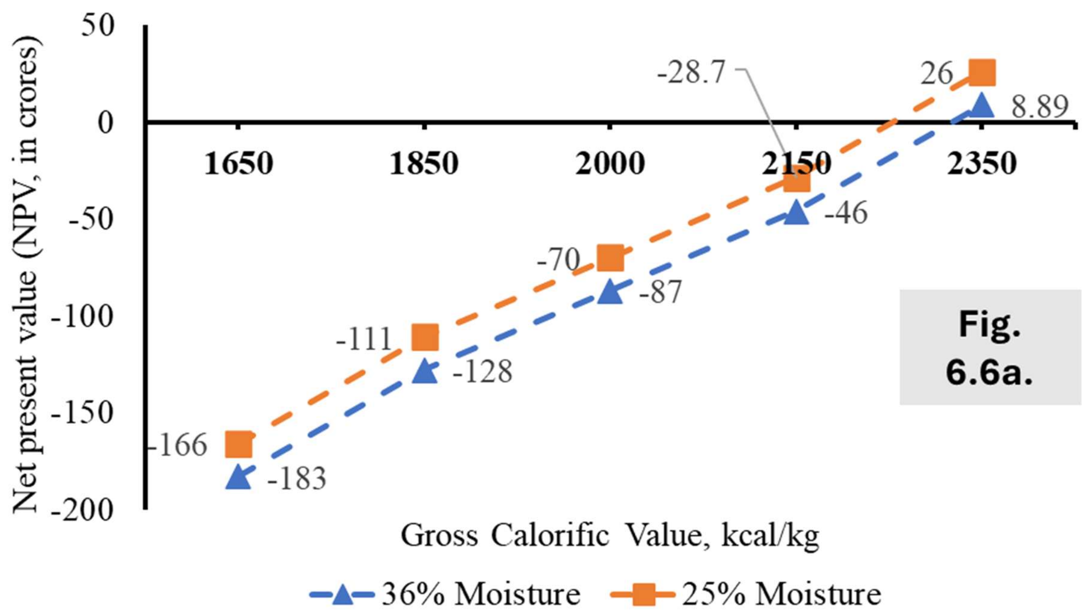
6.3.3 Economic analysis

6.3.3.1 Economic assessment of WTE plant without carbon capture

The economic performance of the WTE plant was evaluated across varying gross calorific values (GCVs) and moisture contents, using three financial indicators: net present value (NPV), internal rate of return (IRR), and payback period. The analysis considered two moisture levels (36% and 25%) and GCVs ranging from 1650 to 2350 kcal/kg.

- *Net present value*

Net present value (NPV) is the summation of expected cash flow (costs and benefits) in today's currency. The results indicate that economic viability improves significantly with increasing GCV and decreasing moisture content. At the lowest GCV of 1650 kcal/kg and 36% moisture, the project yields a negative NPV of -₹183 crores (-$21,923,400), indicating poor financial feasibility. However, as the GCV increases and moisture decreases, the NPV steadily improves. At 2350 kcal/kg and 25% moisture, the project achieves a positive NPV of ₹26 crores ($2,930,980), indicating profitability (Fig. 6.6a). This positive shift demonstrates the strong influence of waste quality particularly energy content and moisture level on project viability. Lower moisture content reduces energy losses, enhancing plant efficiency and revenue generation.



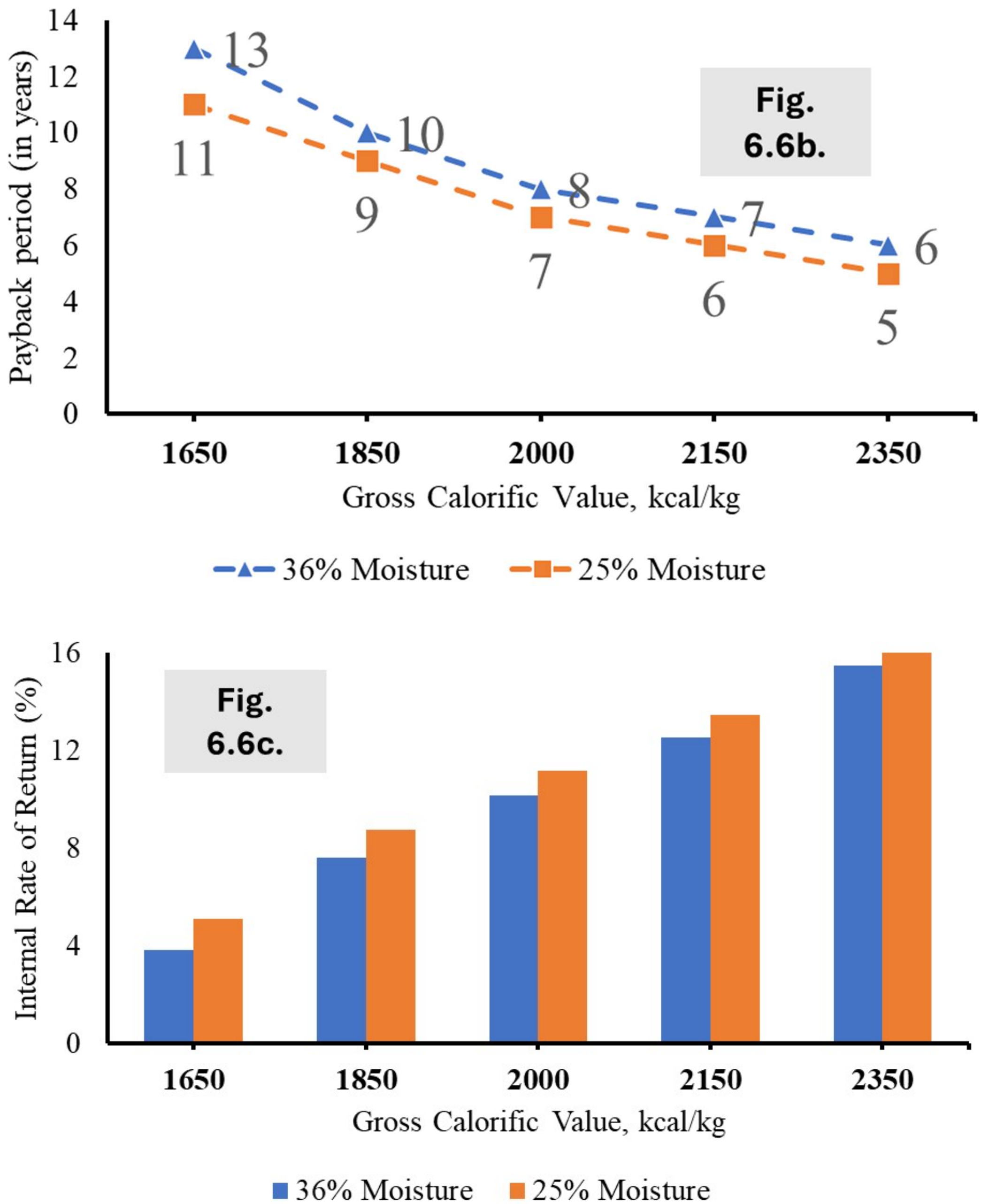


Fig. 6.6 Economic indicators of waste-to-energy plant varying gross calorific values (GCVs) and moisture contents, a) Net present value b) Payback period and c) Internal rate of return

- *Payback period*

The discounted payback period is the length of time required for the present value of a project's future cash inflows to equal the initial cash outflow (investment). The payback period also shortens notably with improved waste quality. At 36% moisture, the payback period reduces from 13 years at 1650 kcal/kg to 6 years at 2350 kcal/kg. With 25% moisture, the project becomes more lucrative, with payback reducing from 11 years to just 5 years across the same

GCV range (Fig. 6.6b). These findings imply that both high energy content and low moisture content in waste significantly enhance the economic attractiveness of the WTE plant by accelerating capital recovery.

- *Internal rate of return*

The IRR is the discount rate at which the net present value (NPV) of an investment becomes zero. In other words, it's the rate of return that the investment is expected to generate. At 36% moisture, IRR increases from 3.8% at 1650 kcal/kg to 15.47% at 2350 kcal/kg. A more favorable performance is observed at 25% moisture conditions, where IRR ranges from 5.08% to 16.36% across the same GCV range (Fig. 6.6c). These values clearly show that higher calorific value and lower moisture content improve project returns. An IRR above 13-15% is typically considered attractive for infrastructure investments, suggesting that the project becomes financially appealing once the GCV exceeds 2150 kcal/kg, particularly at lower moisture levels.

The strong sensitivity of economic performance to moisture content arises from fundamental thermodynamic and operational constraints. Higher moisture levels increase the latent heat demand during combustion, requiring a significant fraction of the released energy to evaporate water rather than generate useful steam. This directly reduces net steam availability, lowers turbine electricity output, and increases auxiliary power consumption. As a result, less electricity is exported to the grid, leading to reduced revenue while capital and fixed operating costs remain unchanged. In contrast, lower-moisture waste enables higher net power generation, improved plant efficiency, and greater electricity sales, thereby enhancing cash flows, shortening payback periods, and increasing IRR. These effects explain the consistently superior financial performance observed at 25% moisture compared to 36% moisture across all GCV levels.

Overall, the economic analysis highlights that waste quality defined by its calorific value and moisture content is a critical determinant of the financial feasibility of WTE plants. Projects based on low-calorific value, high-moisture waste are unlikely to be viable without subsidies or incentives. Conversely, WTE systems processing higher-GCV, lower-moisture waste streams can deliver positive returns, with shorter payback periods and higher profitability. These results underscore the need for careful waste characterization and potential pre-treatment measures to improve waste feedstock quality before project implementation.

6.3.3.2 Economic assessment of CCS and CCU in the Indian context

In the Indian context, CCS and CCU are currently implemented as modular add-on systems to existing power and industrial facilities rather than as revenue-generating core plant components. Accordingly, their economic performance is assessed using levelised costs per ton of CO_2 captured, transported, and stored or utilised, consistent with national CCUS roadmaps and techno-economic studies, rather than being integrated into the base waste-to-energy (WTE) project cash-flow analysis.

CCS and CCU are increasingly recognised as essential technologies for India's long-term decarbonisation, particularly for hard-to-abate sectors such as power generation, cement, steel, and chemicals. These sectors are expected to remain reliant on fossil-based processes in the near to medium term, making capture-based mitigation strategies critical for achieving national climate targets. Despite their significant emissions-reduction potential, the large-scale deployment of CCS and CCU in India remains constrained by high capital and operating costs, limited transport and storage infrastructure, and the absence of strong carbon pricing or dedicated financial incentives.

- *Cost structure of CCS in India*

Based on India-specific cost data, the levelised cost of CCS including capture, transport, and storage ranges from ₹4,900 to ₹6,000 per ton of CO_2 (Mukherjee and Chatterjee, 2022; Sadiq et al., 2025). Capture costs dominate the total expenditure, with capital costs estimated at ₹1,200-1,400/t CO_2 and operating costs (energy, solvent, maintenance, labour) at ₹2,700-3,100/t CO_2, resulting in a total capture cost of ₹3,900-4,500/t CO_2. Downstream costs for CO_2 transportation, injection, and monitoring add an additional ₹1,000–1,500/t CO_2. These values are consistent with sector-wide techno-economic assessments reported for Indian power and industrial facilities.

When converted to international terms, the total CCS cost corresponds to approximately $ 59–72 per t CO_2, placing India at the lower end of global CCS cost ranges, largely due to lower capital, labour, and construction costs. However, these costs remain high relative to current carbon prices and internal abatement costs in most Indian industries.

- *Role of carbon pricing and incentives*

At present, carbon credit values in India are estimated at $10-15 per ton CO_2, which can offset only 15-25% of total CCS costs. Even after accounting for such credits, the net cost of CCS remains in the range of $44-62per ton CO_2, indicating that CCS is not yet commercially viable without additional policy support. National-level studies emphasise that large-scale CCS deployment in India will require a combination of fiscal incentives, subsidies, viability gap funding, concessional finance, and dedicated carbon markets, similar to mechanisms adopted in the United States and the European Union.

- *Economic differentiation between CCS and CCU*

Compared to pure storage, carbon capture and utilisation (CCU) offers partial cost recovery by converting captured CO_2 into value-added products (current price of industrial grade CO_2 is ₹3000-4000/t CO_2). Indian policy and techno-economic assessments identify utilisation pathways such as building materials (carbonated concrete and aggregates), urea, methanol, and synthetic fuels as particularly promising due to large domestic demand and lower transport requirements. In some applications, especially mineralisation-based utilisation, CO_2 can be used without full purification or high-pressure compression, thereby reducing overall system costs.

However, CCU pathways are inherently market-limited and cannot absorb CO_2 volumes at the scale required for deep decarbonisation. Consequently, national roadmaps emphasise CCS as the backbone of long-term mitigation, with CCU serving as a complementary pathway that can improve near-term project economics and facilitate early deployment.

6.4 Practical Implications

The results of this study indicate that integrating carbon capture technologies with WTE systems can substantially enhance environmental performance under suitable operating conditions. Among the scenarios evaluated, WTE systems coupled with carbon capture and utilisation (CCU) demonstrate the highest environmental mitigation potential across climate change, toxicity, and resource depletion categories. However, these outcomes should be interpreted as forward-looking potential rather than guaranteed performance, as they are contingent on waste quality, system efficiency, and downstream utilisation pathways.

Both CCS and CCU transform WTE plants from conventional waste treatment facilities into systems capable of contributing to broader climate mitigation strategies by enabling significant reductions in net greenhouse gas emissions. Nevertheless, the choice between CCS and CCU in practice is inherently context-specific. CCS requires access to suitable geological storage sites and transport infrastructure, whereas CCU depends on the availability of nearby industrial markets capable of absorbing captured CO_2. Accordingly, regional planning approaches such as developing integrated WTE-CCUS hubs co-located with utilisation industries or storage sites-may be necessary to realise these benefits.

A critical operational constraint common to both CCS and CCU pathways relates to heat integration. Although the total quantity of recoverable heat from the combined heat and power (CHP) unit is sufficient for solvent regeneration, its temperature may be inadequate for efficient operation of conventional amine-based capture systems. Insufficient heat quality can reduce capture efficiency or necessitate supplemental energy input, thereby increasing costs and environmental burdens. This highlights that the feasibility of carbon capture in WTE applications depends not only on overall energy balance but also on thermodynamic quality, which remains a key technical challenge (Henderson, 2015; Su et al., 2023). It should be noted that the heat-quality constraint is not necessarily static. Recent advances in solvent chemistry suggest that CO_2 regeneration may be achievable at substantially lower temperatures than those required by conventional amine systems. For example, pH-stabilising additives such as tris(hydroxymethyl)aminomethane have been shown to enable CO_2 release at temperatures as low as ~60 °C, compared to >120 °C for conventional solvents. While such approaches are not yet widely deployed, they indicate a potential pathway to better utilise low-grade waste heat in future WTE-CCS/CCU applications (Guo and Hatton, 2025).

The analysis also underscores the decisive role of waste feedstock quality. Low-calorific, high-moisture waste streams significantly constrain both environmental and economic performance, particularly for capture-integrated systems that impose additional energy demands. Under such conditions, the parasitic energy load of carbon capture can substantially reduce net electricity export, diminishing avoided emissions and, in some cases, reducing human health benefits. Conversely, high-quality waste with higher calorific value and lower moisture content enables greater energy recovery, improves financial viability, and maximises the mitigation potential of CCS and CCU.

From a strategic perspective, these findings suggest that upstream investments in waste segregation, drying, and pre-treatment may yield greater overall benefits than downstream capture technologies alone (Soni et al., 2025). Improving waste quality enhances the performance of all WTE configurations and is a prerequisite for the effective deployment of advanced carbon capture systems. While CCU offers a more balanced environmental profile under favourable conditions, CCS remains a viable alternative where utilisation markets are limited, albeit with broader environmental trade-offs that must be carefully managed.

Overall, conventional WTE without carbon capture, while preferable to uncontrolled landfilling, is unlikely to align with long-term climate-neutral waste management objectives on its own. Its future relevance lies primarily in integration with carbon mitigation strategies, supported by improved waste quality and system-level optimisation.

6.5 Summary

This study integrates environmental and economic assessments to evaluate conventional and carbon-capture-integrated waste-to-energy (WTE) pathways for India. The results indicate that while CCU-integrated systems exhibit the highest theoretical environmental mitigation potential, their practical performance is constrained by operational, infrastructural, and market limitations. The economic analysis shows that financial viability is strongly dependent on waste quality, with positive returns achievable only for high-calorific (>2150 kcal/kg), low-moisture (<25%) waste streams. Accordingly, carbon capture technologies cannot be considered standalone solutions; their effective deployment requires upstream measures such as improved source segregation, waste pre-treatment, and system integration. These findings should be interpreted as forward-looking potential within the limitations identified, highlighting that aligning waste management practices with feedstock quality improvement is essential for realizing the environmental benefits of advanced WTE systems while maintaining financial sustainability in India.

Reference:

Aereon, 2022. Retrofitting Air-Assisted Flares to Attain 99.5% Destruction Efficiency [WWW Document]. URL https://aereon.com/retrofitting-air-assisted-flares-to-attain-99-5-destruction-efficiency/?utm_source=chatgpt.com

Alengebawy, A., Mohamed, B.A., Ghimire, N., Jin, K., Liu, T., Samer, M., Ai, P., 2022. Understanding the environmental impacts of biogas utilization for energy production through life cycle assessment: An action towards reducing emissions. Environ. Res. 213, 113632. https://doi.org/10.1016/j.envres.2022.113632

American Biogas Council, 2025. FAQs [WWW Document]. URL https://americanbiogascouncil.org/resources/biogas-faqs-american-biogas-council/#leakage

Arias, A., Rama, M., González-García, S., Feijoo, G., Moreira, M.T., 2020. Environmental analysis of servicing centralised and decentralised wastewater treatment for population living in neighbourhoods. Journal of Water Process Engineering 37, 101469. https://doi.org/10.1016/j.jwpe.2020.101469

Ayyad, A., Abbas, A., Elminshawy, N., 2021. A simulation study of the effect of post-combustion amine-based carbon-capturing integrated with solar thermal collectors for combined cycle gas power plant. Discover Sustainability 2, 9. https://doi.org/10.1007/s43621-021-00018-x

Bernstad, A., la Cour Jansen, J., 2012. Review of comparative LCAs of food waste management systems – Current status and potential improvements. Waste Management 32, 2439–2455. https://doi.org/10.1016/j.wasman.2012.07.023

Biancini, G., Marchetti, B., Cioccolanti, L., Moglie, M., 2022. Comprehensive Life Cycle Assessment Analysis of an Italian Composting Facility concerning Environmental Footprint Minimization and Renewable Energy Integration. Sustainability 14, 14961. https://doi.org/10.3390/su142214961

Bisinella, V., Hulgaard, T., Riber, C., Damgaard, A., Christensen, T.H., 2021. Environmental assessment of carbon capture and storage (CCS) as a post-treatment technology in waste incineration. Waste Management 128, 99–113. https://doi.org/10.1016/j.wasman.2021.04.046

Buffi, M., Hurtig, O., Scarlat, N., 2024. Methane emissions in the biogas and biomethane supply chains in the EU An analysis to update the greenhouse gas emissions accounting. https://doi.org/10.2760/7927411

Cañote, S.J.B., Barros, R.M., Lora, E.E.S., del Olmo, O.A., dos Santos, I.F.S., Piñas, J.A.V., Ribeiro, E.M., de Freitas, J.V.R., de Castro e Silva, H.L., 2021. Energy and Economic Evaluation of the Production of Biogas from Anaerobic and Aerobic Sludge in Brazil. Waste Biomass Valorization 12, 947–969. https://doi.org/10.1007/s12649-020-01046-w

Chandel, M.K., Kwok, G., Jackson, R.B., Pratson, L.F., 2012. The potential of waste-to-energy in reducing GHG emissions. Carbon Manag. 3, 133–144. https://doi.org/10.4155/cmt.12.11

Cheela, V.R.S., John, M., Biswas, W., Dubey, B., 2023. Environmental impact evaluation of landfill mining of legacy waste with on-site sorting using life cycle assessment. Environmental Science and Pollution Research 30, 30033–30047. https://doi.org/10.1007/S11356-022-24210-2/TABLES/3

Cherubini, F., Strømman, A.H., 2011. Life cycle assessment of bioenergy systems: State of the art and future challenges. Bioresour. Technol. 102, 437–451. https://doi.org/10.1016/j.biortech.2010.08.010

Chicaiza-Ortiz, C., Peñafiel-Arcos, P., Herrera-Feijoo, R.J., Ma, W., Logroño, W., Tian, H., Yuan, W., 2024. Waste-to-Energy technologies for municipal solid waste management: Bibliometric review, life cycle assessment, and energy potential case study. J. Clean. Prod. 480, 143993. https://doi.org/10.1016/j.jclepro.2024.143993

Chmelíková, L., Schmid, H., Anke, S., Hülsbergen, K.-J., 2021. Nitrogen-use efficiency of organic and conventional arable and dairy farming systems in Germany. Nutr. Cycl. Agroecosyst. 119, 337–354. https://doi.org/10.1007/s10705-021-10126-9

Christensen, T.H., Bisinella, V., 2021. Climate change impacts of introducing carbon capture and utilisation (CCU) in waste incineration. Waste Management 126, 754–770. https://doi.org/10.1016/j.wasman.2021.03.046

Clasen, A.P., Agostinho, F., Almeida, C.M.V.B., Liu, G., Giannetti, B.F., 2024. Advancing towards circular economy: Environmental benefits of an innovative biorefinery for municipal solid waste management. Sustain. Prod. Consum. 46, 571–581. https://doi.org/10.1016/j.spc.2024.03.015

Colón, J., Martínez-Blanco, J., Gabarrell, X., Artola, A., Sánchez, A., Rieradevall, J., Font, X., 2010. Environmental assessment of home composting. Resour. Conserv. Recycl. 54, 893–904. https://doi.org/10.1016/j.resconrec.2010.01.008

E., P., Sarkar, S., Maji, P.K., 2024. A review on slow-release fertilizer: Nutrient release mechanism and agricultural sustainability. J. Environ. Chem. Eng. 12, 113211. https://doi.org/10.1016/j.jece.2024.113211

Elgas, 2023. LPG Gas Composition: LPG Gas Mixture of Propane & Butane [WWW Document]. URL https://www.elgas.com.au/elgas-knowledge-hub/residential-lpg/lpg-composition/

Esteves, E.M.M., Herrera, A.M.N., Esteves, V.P.P., Morgado, C. do R.V., 2019. Life cycle assessment of manure biogas production: A review. J. Clean. Prod. 219, 411–423. https://doi.org/10.1016/j.jclepro.2019.02.091

Evangelisti, S., Clift, R., Tagliaferri, C., Lettieri, P., 2017. A life cycle assessment of distributed energy production from organic waste: Two case studies in Europe. Waste Management 64, 371–385. https://doi.org/10.1016/j.wasman.2017.03.028

Ferreira, S.F., Buller, L.S., Berni, M., Forster-Carneiro, T., 2019a. Environmental impact assessment of end-uses of biomethane. J. Clean. Prod. 230, 613–621. https://doi.org/10.1016/j.jclepro.2019.05.034

Ferreira, S.F., Buller, L.S., Berni, M., Forster-Carneiro, T., 2019b. Environmental impact assessment of end-uses of biomethane. J. Clean. Prod. 230, 613–621. https://doi.org/10.1016/j.jclepro.2019.05.034

Fuchsz, M., Kohlheb, N., 2015. Comparison of the environmental effects of manure- and crop-based agricultural biogas plants using life cycle analysis. J. Clean. Prod. 86, 60–66. https://doi.org/10.1016/j.jclepro.2014.08.058

Gao, C., Bian, R., Li, P., Yin, C., Teng, X., Zhang, J., Gao, S., Niu, Y., Sun, Y., Wang, Y., Wang, H., 2025. Analysis of carbon reduction potential from typical municipal solid waste incineration plants under MSW classification. J. Environ. Manage. 373, 123844. https://doi.org/10.1016/j.jenvman.2024.123844

González, R., Rosas, J.G., Blanco, D., Smith, R., Martínez, E.J., Pastor-Bueis, R., Gómez, X., 2020. Anaerobic digestion of fourth range fruit and vegetable products: comparison of three different scenarios for its valorisation by life cycle assessment and life cycle costing. Environ. Monit. Assess. 192, 551. https://doi.org/10.1007/s10661-020-08521-w

Guo, H., Zhao, Y., Damgaard, A., Wang, Q., Wang, H., Christensen, T.H., Lu, W., 2021. Quantifying global warming potential of alternative biorefinery systems for producing fuels from Chinese food waste. Waste Management 130, 38–47. https://doi.org/10.1016/j.wasman.2021.05.004

Guo, Y., Hatton, T.A., 2025. Enhancing continuous-flow CO2 capture and release from aqueous carbonates via thermal pH regulation. Nature Chemical Engineering. https://doi.org/10.1038/s44286-025-00313-8

Hakawati, R., Smyth, B.M., McCullough, G., De Rosa, F., Rooney, D., 2017a. What is the most energy efficient route for biogas utilization: Heat, electricity or transport? Appl. Energy 206, 1076–1087. https://doi.org/10.1016/j.apenergy.2017.08.068

Hakawati, R., Smyth, B.M., McCullough, G., De Rosa, F., Rooney, D., 2017b. What is the most energy efficient route for biogas utilization: Heat, electricity or transport? Appl. Energy 206, 1076–1087. https://doi.org/10.1016/j.apenergy.2017.08.068

Havukainen, J., Zhan, M., Dong, J., Liikanen, M., Deviatkin, I., Li, X., Horttanainen, M., 2017. Environmental impact assessment of municipal solid waste management incorporating mechanical treatment of waste and incineration in Hangzhou, China. J. Clean. Prod. 141, 453–461. https://doi.org/10.1016/j.jclepro.2016.09.146

Henderson, C., 2015. Power plant CO2 capture heat integration. IEA Clean Coal Centre.

IEA Bioenergy, 2017. Methane emissions from biogas plants, IEA Bioenergy - Task 37.

IPCC, 2005. IPCC Special report on Carbon dioxide capture and storage. Prepared by Working Group III of the Intergovernmental Panel on Climate Change, Cambridge University Press. Cambridge, United Kingdom and New York, NY, USA.

Jayawickrama, K., Ruparathna, R., Seth, R., Biswas, N., Hafez, H., Tam, E., 2024. Challenges and Issues of Life Cycle Assessment of Anaerobic Digestion of Organic Waste. Environments 11, 217. https://doi.org/10.3390/environments11100217

Jin, Q., Yang, L., Poe, N., Huang, H., 2018. Integrated processing of plant-derived waste to produce value-added products based on the biorefinery concept. Trends Food Sci. Technol. 74, 119–131. https://doi.org/10.1016/j.tifs.2018.02.014

Kalita, S., Ohlsson, J.A., Karlsson Potter, H., Nordberg, Å., Sandgren, M., Hansson, P.-A., 2023. Energy performance of compressed biomethane gas production from co-digestion of Salix and dairy manure: factoring differences between Salix varieties. Biotechnology for Biofuels and Bioproducts 16, 165. https://doi.org/10.1186/s13068-023-02412-1

Keogh, N., Corr, D., Monaghan, R.F.D., 2024. An environmental and economic assessment for biomethane injection and natural gas heavy goods vehicles. Appl. Energy 360, 122800. https://doi.org/10.1016/j.apenergy.2024.122800

Khandelwal, H., Dhar, H., Thalla, A.K., Kumar, S., 2019. Application of life cycle assessment in municipal solid waste management: A worldwide critical review. J. Clean. Prod. 209, 630–654. https://doi.org/10.1016/j.jclepro.2018.10.233

Koornneef, J., van Keulen, T., Faaij, A., Turkenburg, W., 2008. Life cycle assessment of a pulverized coal power plant with post-combustion capture, transport and storage of CO2. International Journal of Greenhouse Gas Control 2, 448–467. https://doi.org/10.1016/j.ijggc.2008.06.008

Kristensen, P.G., Jensen, J.K., Nielsen, M., Illerup, J.B., 2004. Emission factors for gas fired CHP units < 25 Mw, in: International Gas Research Conference Proceedings.

Kumar, A., Agrawal, A., 2020. Recent trends in solid waste management status, challenges, and potential for the future Indian cities – A review. Current Research in Environmental Sustainability 2, 100011. https://doi.org/10.1016/j.crsust.2020.100011

Kumar, M., 2023. Lack of market support for bio-manure hindering growth of compressed biogas plants [WWW Document]. URL https://india.mongabay.com/2023/01/lack-of-market-support-for-bio-manure-hindering-growth-of-compressed-biogas-plants/

Lausselet, C., Cherubini, F., Oreggioni, G.D., del Alamo Serrano, G., Becidan, M., Hu, X., Rørstad, P.Kr., Strømman, A.H., 2017. Norwegian Waste-to-Energy: Climate change, circular economy and carbon capture and storage. Resour. Conserv. Recycl. 126, 50–61. https://doi.org/10.1016/j.resconrec.2017.07.025

Liu, W., Zhang, Z., Xie, X., Yu, Z., von Gadow, K., Xu, J., Zhao, S., Yang, Y., 2017. Analysis of the Global Warming Potential of Biogenic CO2 Emission in Life Cycle Assessments. Sci. Rep. 7, 39857. https://doi.org/10.1038/srep39857

López González, L.M., Pereda Reyes, I., Pedraza Garciga, J., Barrera, E.L., Romero Romero, O., 2020. Energetic, economic and environmental assessment for the anaerobic digestion of pretreated and codigested press mud. Waste Management 102, 249–259. https://doi.org/10.1016/j.wasman.2019.10.053

Martínez-Arce, A., Kargupta, W., Domínguez, C.G., Odey, E.A., McMahon, H., Huerta, J.D., Zimmermann, J., Bishop, G., Gaffey, J., Styles, D., 2025. An integrated technoeconomic and environmental assessment of biomethane production via anaerobic digestion of food waste in Ireland: Updated insights under market volatility. Sustainable Energy Technologies and Assessments 82, 104563. https://doi.org/10.1016/j.seta.2025.104563

Masson-Delmotte, V., Zhai, P., Pirani, A., Connors, S., Péan, C., Berger, S., Caud, N., Chen, Y., Goldfarb, L., Gomis, M., Huang, M., 2021. Climate change 2021: the physical science basis. Contribution of working group I to the sixth assessment report of the intergovernmental panel on climate change.

Materazzi, M., Chari, S., Sebastiani, A., Lettieri, P., Paulillo, A., 2024. Waste-to-energy and waste-to-hydrogen with CCS: Methodological assessment of pathways to carbon-negative waste treatment from an LCA perspective. Waste Management 173, 184–199. https://doi.org/10.1016/j.wasman.2023.11.020

Mendieta, O., Castro, L., Rodríguez, J., Escalante, H., 2020. Management and valorization of waste from a non-centrifugal cane sugar mill via anaerobic co-digestion: Technical and economic potential. Bioresour. Technol. 316, 123962. https://doi.org/10.1016/j.biortech.2020.123962

MoHUA, 2021. Circular Economy in Municipal solid and liquid waste. Ministry of Housing and Urban Affairs, GOI 1–112.

Montejo, C., Tonini, D., Márquez, M. del C., Fruergaard Astrup, T., 2013. Mechanical–biological treatment: Performance and potentials. An LCA of 8 MBT plants including waste characterization. J. Environ. Manage. 128, 661–673. https://doi.org/10.1016/j.jenvman.2013.05.063

MoPNG, 2025. SATAT.

Mukherjee, A., Chatterjee, S., 2022. Carbon Capture Utilization and Storage (CCUS) – Policy Framework and Deployment Mechanism in India (NITI Aayog).

Naaz, I., Thengane, S.K., Arora, P., Thirumoorthy, G., Singal, S.K., 2025. Waste-to-energy pathways for fresh and legacy waste management: A case study in India. Energy Nexus 19, 100472. https://doi.org/10.1016/j.nexus.2025.100472

Nanlin, L., Fan, L., Hua, Z., Liming, S., Pinjing, H., 2023. Environmental and economic assessment of the construction, operation, and demolition of a decentralized composting facility. Science of The Total Environment 884, 163724. https://doi.org/10.1016/j.scitotenv.2023.163724

Nordahl, S.L., Devkota, J.P., Amirebrahimi, J., Smith, S.J., Breunig, H.M., Preble, C. V., Satchwell, A.J., Jin, L., Brown, N.J., Kirchstetter, T.W., Scown, C.D., 2020. Life-Cycle Greenhouse Gas Emissions and Human Health Trade-Offs of Organic Waste Management Strategies. Environ. Sci. Technol. 54, 9200–9209. https://doi.org/10.1021/acs.est.0c00364

Oviedo-Ocaña, E.R., Abendroth, C., Domínguez, I.C., Sánchez, A., Dornack, C., 2023. Life cycle assessment of biowaste and green waste composting systems: A review of applications and implementation challenges. Waste Management 171, 350–364. https://doi.org/10.1016/j.wasman.2023.09.004

Pasciucco, F., Francini, G., Pecorini, I., Baccioli, A., Lombardi, L., Ferrari, L., 2023. Valorization of biogas from the anaerobic co-treatment of sewage sludge and organic waste: Life cycle assessment and life cycle costing of different recovery strategies. J. Clean. Prod. 401, 136762. https://doi.org/10.1016/j.jclepro.2023.136762

Paulillo, A., Sebastiani, A., Lettieri, P., Materazzi, M., 2024. Decarbonising waste-to-energy: A life cycle assessment study. Resour. Conserv. Recycl. 209, 107812. https://doi.org/10.1016/j.resconrec.2024.107812

Poeschl, M., Ward, S., Owende, P., 2012. Environmental impacts of biogas deployment – Part II: life cycle assessment of multiple production and utilization pathways. J. Clean. Prod. 24, 184–201. https://doi.org/10.1016/j.jclepro.2011.10.030

Pujara, Y., Govani, J., Patel, H.T., Pathak, P., Mashru, D., Ganesh, P.S., 2023. Quantification of environmental impacts associated with municipal solid waste management in Rajkot city, India using Life Cycle Assessment. Environmental Advances 12, 100364. https://doi.org/10.1016/j.envadv.2023.100364

Ravindran, J.K., Fagg, D.P., Coelho, M.C., 2025. Current production routes and life cycle analysis of “Green Energy-Dense Fuels” from biogas: A comprehensive review. Appl. Energy 402, 126832. https://doi.org/10.1016/j.apenergy.2025.126832

Rosa Aon Cardoso Fernandes, A., Eduardo Lobo Baêta, B., Damgaard, A., 2023. Life-cycle assessment as a prospection stage for the biochemical methane potential of pretreated lignocellulosic biomass. Bioresour. Technol. 386, 129584. https://doi.org/10.1016/j.biortech.2023.129584

Sadiq, M., Sharma, R., Kalita, H.J., Pandey, P., 2025. CCUS in India: A Techno-Economic and Policy Roadmap to Net-Zero Amid Climate and Environmental Challenges. Journal Of The Geological Society Of India 101, 1663–1673. https://doi.org/10.17491/jgsi/2025/174290

Sandström, J., Van Heusden, R., Morrison, H., Puleo, M., Murray, L., 2020. Aluminium for Climate: Exploring pathways to decarbonize the aluminium industry. WEF, Cologny/Geneva, Switzerland.

Serafini, L.F., Praça, P.J.G.M., González-Andrés, F., Gonçalves, A., 2025a. Life cycle approach as a tool for assessing municipal biowaste treatment units: A systematic review. Waste Management & Research: The Journal for a Sustainable Circular Economy 43, 1509–1524. https://doi.org/10.1177/0734242X251326866

Serafini, L.F., Praça, P.J.G.M., González-Andrés, F., Gonçalves, A., 2025b. Life cycle approach as a tool for assessing municipal biowaste treatment units: A systematic review. Waste Management & Research: The Journal for a Sustainable Circular Economy. https://doi.org/10.1177/0734242X251326866

Shi, Z., He, P., Guo, J., Zou, J., Peng, W., Zhang, H., Lü, F., 2024. Carbon reduction trade-off between pretreatment and anaerobic digestion: A field study of an industrial-scale biogas plant. Environ. Res. 246, 118139. https://doi.org/10.1016/j.envres.2024.118139

Shinde, A.M., Dikshit, A.K., Odlare, M., Thorin, E., Schwede, S., 2021. Life cycle assessment of bio-methane and biogas-based electricity production from organic waste for utilization as a vehicle fuel. Clean Technol. Environ. Policy 23, 1715–1725. https://doi.org/10.1007/s10098-021-02054-7

Singh, A.D., Upadhyay, A., Shrivastava, S., Vivekanand, V., 2020. Life-cycle assessment of sewage sludge-based large-scale biogas plant. Bioresour. Technol. 309, 123373. https://doi.org/10.1016/j.biortech.2020.123373

Singh, P., Babu, G.L.S., Hoysall, C., Rao, L., 2026. Assessing biogas valorization from municipal organic waste in India: Integrated environmental-economic analysis. Bioresour. Technol. 442, 133675. https://doi.org/10.1016/j.biortech.2025.133675

Singh, P., Kalamdhad, A.S., 2024. Unravelling barriers associated with dissemination of large-scale biogas plant with analytical hierarchical process and fuzzy analytical hierarchical process approach: Case study of India. Bioresour. Technol. 413, 131543. https://doi.org/10.1016/j.biortech.2024.131543

Singh, P., Kalamdhad, A.S., 2022a. Biomethane plants based on municipal solid waste and wastewater and its impact on vehicle sector in India — An Environmental-economic-resource assessment. Environ. Technol. Innov. 26, 102330. https://doi.org/10.1016/j.eti.2022.102330

Singh, P., Kalamdhad, A.S., 2022b. Assessment of agricultural residue-based electricity production from biogas in India: Resource-environment-economic analysis. Sustainable Energy Technologies and Assessments 54, 102843. https://doi.org/10.1016/j.seta.2022.102843

Singh, P., Kalamdhad, A.S., 2022c. Assessment of agricultural residue-based electricity production from biogas in India: Resource-environment-economic analysis. Sustainable Energy Technologies and Assessments 54, 102843. https://doi.org/10.1016/j.seta.2022.102843

Singh, P., Kalamdhad, A.S., 2022d. Biomethane plants based on municipal solid waste and wastewater and its impact on vehicle sector in India — An Environmental-economic-resource assessment. Environ. Technol. Innov. 26, 102330. https://doi.org/10.1016/j.eti.2022.102330

Slorach, P.C., Jeswani, H.K., Cuéllar-Franca, R., Azapagic, A., 2019. Environmental and economic implications of recovering resources from food waste in a circular economy. Science of The Total Environment 693, 133516. https://doi.org/10.1016/j.scitotenv.2019.07.322

Soni, A., Gupta, S.K., Rajamohan, N., Yusuf, M., 2025. Waste-to-energy technologies: a sustainable pathway for resource recovery and materials management. Mater. Adv. 6, 4598–4622. https://doi.org/10.1039/D5MA00449G

Su, D., Herraiz, L., Lucquiaud, M., Thomson, C., Chalmers, H., 2023. Thermal integration of waste to energy plants with Post-combustion CO2 capture. Fuel 332, 126004. https://doi.org/10.1016/j.fuel.2022.126004

TERI, 2023. Financing Decarbonization of the Secondary Steel Sector in India: Towards an Enabling Environment. New Delhi, India: The Energy and Resources Institute.

Tian, P., Wu, Y., Shang, B., Qi, C., Xu, Z., Li, G., Luo, W., Zhang, W., Li, Y., 2025. LCA as a decision support tool for the environmental improvement of organic fraction of municipal solid waste composting in China. J. Clean. Prod. 495, 145068. https://doi.org/10.1016/j.jclepro.2025.145068

Tisserant, A., Morales, M., Cavalett, O., O'Toole, A., Weldon, S., Rasse, D.P., Cherubini, F., 2022. Life-cycle assessment to unravel co-benefits and trade-offs of large-scale biochar deployment in Norwegian agriculture. Resour. Conserv. Recycl. 179, 106030. https://doi.org/10.1016/j.resconrec.2021.106030

Vinayak, A.K., Chauhan, G., 2026. Circularity in polyethylene waste management through multidimensional integration. Next Sustainability 7, 100247. https://doi.org/10.1016/J.NXSUST.2026.100247

Whiting, A., Azapagic, A., 2014. Life cycle environmental impacts of generating electricity and heat from biogas produced by anaerobic digestion. Energy 70, 181–193. https://doi.org/10.1016/j.energy.2014.03.103

Woon, K.S., Lo, I.M.C., Chiu, S.L.H., Yan, D.Y.S., 2016. Environmental assessment of food waste valorization in producing biogas for various types of energy use based on LCA approach. Waste Management 50, 290–299. https://doi.org/10.1016/j.wasman.2016.02.022

Chapter 7
Recycling Facility

7.1 Preamble

This study evaluates the operational and environmental performance of MSW-material recycling facilities in India. Current recycling practices fluctuate between informal recovery and centralized MRF. This chapter aims to bridge the data gap by providing a quantitative analysis of recycling processes. The primary objectives are:

- To analyze the material flow and efficiency of recycling facilities, focusing on high-value fractions such as plastics, paper, metals, and glass.
- To quantify and compare the GHG emission reduction potential of major recyclable fractions in MSW

7.2 Methodology

The study adopts an integrated approach combining MFA and LCA to quantify the resource efficiency and environmental credits associated with recycling in India.

Primary data were collected through field visits to MRFs, waste processing units, and recycling centres, supplemented by stakeholder consultations involving facility operators, municipal authorities, and informal sector participants. Secondary data were obtained from published literature, government reports, and recognised life cycle inventory databases.

MFA was employed to map the flow of waste fractions from collection to final recovery, including sorting, processing, and residual disposal. Recovery efficiencies were estimated for key material streams (plastics, paper, metals, and glass) based on input–output analysis.

7.2.1 Life cycle assessment (LCA)

The LCA of recycling systems is material-specific, as the processes, energy requirements, and associated emissions vary significantly across different material types. In this study, life cycle inventory data were primarily sourced from Ecoinvent version 3.12 database, ensuring consistency and methodological robustness (Wernet et. al., 2016). Wherever region-specific datasets for India were available, they were utilized to better reflect local conditions; otherwise, proxy datasets representing Rest of World (RoW) were adopted. The assessment focuses on quantifying GHG emissions associated with the major recyclable fractions of MSW, including metals (aluminum and steel), plastics (high-density polyethylene (HDPE), low-density polyethylene (LDPE), polyvinyl chloride (PVC), and polypropylene (PP)), paper and cardboard, and glass. The recycling data was then compared with primary production data from the Ecoinvent version 3.12 database. This approach enabled a comparative evaluation of emission reduction potential across key material streams within the MSW recycling system.

Recycled materials were supposed to replace virgin material production. The functional unit was defined as 1 kg sorted fraction. System boundaries included collection, sorting, processing, baling and transport to secondary recyclers, credits for displacing virgin raw material extraction (e.g., primary plastic resin or virgin aluminium production). Avoided emissions were calculated based on standard emission factors for virgin material production.

For the impact assessment, the ReCiPe 2016 (H) Midpoint v1.1 method was employed to evaluate global warming impacts. ReCiPe 2016 was selected because it is recognized as a state-of-the-art life cycle impact assessment method, providing globally representative characterization factors for climate change assessment (Huijbregts et al., 2017).

The recycling yield was incorporated to account for material losses occurring during collection, sorting, pre-treatment, recycling, and reprocessing stages. Lower recycling yields increase the environmental burden per kilogram of recovered material, as a larger quantity of waste must be processed to produce the same amount of secondary material.

In this study, the recycling product yields for PP, PS, and LDPE/HDPE under mechanical recycling conditions were assumed to be 85%, to account for mass losses during pre-treatment, recycling, and post-treatment processes. The recycling product yields for steel and aluminium were assumed to be 96% and 98%, respectively, considering material losses during collection, sorting, pre-treatment, and remelting processes (Bowyer et al., 2015; Alvim et al., 2025). The net emission savings were estimated using the following formula:

$$\text{Net emission savings} = \left(1 - \frac{recycling\ emission}{primary\ production\ emission\ \ X\ recycling\ yield}\right) \text{x } 100 \qquad (7.1)$$

where the recycling yield represents the fraction of usable secondary material recovered from the total waste input.

7.2.2 Life cycle inventory

The life cycle inventory for this study relies on the Ecoinvent version 3.12 database to establish the Global Warming Potential (GWP) for both the primary production and recycling pathways of the targeted municipal solid waste fractions. Table 7.1 details the baseline greenhouse gas emissions associated with the virgin production of these materials, while Table 7.2 outlines the emissions generated by various secondary recycling and recovery processes. Wherever possible, region-specific data for India was utilized such as for HDPE and LDPE primary production but proxy datasets representing Europe or the Rest of the World (RoW) were adopted for materials lacking local data. These specific GWP values serve as the foundational inputs for comparing the environmental impact of virgin material extraction against secondary material recovery.

Table 7.1 Ecoinvent data for production processes of different materials and their GW

Material	Production Process / Material	Geography	GW (kg CO_2eq. per kg)
Aluminium	aluminium, primary, cast alloy slab from continuous casting	RoW	17.4
Steel	steel production, converter, unalloyed	RoW	1.84
Steel	reinforcing steel production	RoW	2.22
HDPE	polyethylene production, high density, granulate	India	3.12
LDPE	polyethylene production, low density, granulate	India	3.61
PVC	polyvinyl chloride production, suspension polymerisation	Asia (except China)	2.60
PVC	polyvinyl chloride production, emulsion polymerisation	Asia (except China)	2.91

PP	polypropylene production, granulate	Asia (except China)	2.44
Paper & Cardboard	solid bleached and unbleached board carton production	RoW	1.38
Paper & Cardboard	folding boxboard carton production	RoW	2.35
Glass	flat glass production, uncoated	Rest-of-World (RoW)	1.07
Glass	flat glass production, coated	Rest-of-World (RoW)	1.17
Glass	packaging glass production, white	Rest-of-World (RoW)	1.10

Table 7.2 Ecoinvent data for recycling processes of different materials and their GW

Material	Recycling Process / Material	Geography	GW (kg CO_2 eq. per kg)
Aluminium	aluminium scrap, post-consumer, prepared for melting	RoW	0.322
Aluminium	aluminium, wrought alloy, at remelter	RoW	0.807
Aluminium	aluminium, cast alloy, at refiner	RoW	0.874
Steel	steel production, electric arc furnace, weathering A, 100% scrap	Europe	0.989

HDPE	Treatment of waste polyethylene, high density, recycling, flakes, recycled	Europe	0.204
LDPE	treatment of waste polyethylene, low density, packaging, recycling	Europe	0.661
LDPE	plastic, mixed, recycled	Europe(RER)	0.782
LDPE	polyethylene, low density, lumps	Europe(RER)	0.512
LDPE	polyethylene, low density, pellets, recycled	Europe(RER)	1.460
LDPE	treatment of waste polyethylene, open burning	Global (GLO)	3.250
PVC	polyvinylchloride, flexible, pellets, recycled	Europe (RER)	0.336
PVC	polyvinylchloride, micronised powder, recycled	Europe (RER)	0.390
PVC	polyvinylchloride, rigid, pellets, recycled	Europe (RER)	0.239
PVC	treatment of waste polyvinylchloride, open burning	Global (GLO)	1.780
PP	polypropylene, pellets, recycled	Europe (RER)	0.647
PP	polypropylene, recycled,granulate	Europe (RER)	1.410
Paper & cardboard	paper production, newsprint, recycled	Rest-of-World (RoW)	1.61

7.3 Results and discussion

7.3.1 Recycling process in India

Current waste management dynamics in India are characterized by a dual system where municipal bodies oversee the collection of 30–60% of urban waste, while a robust informal sector comprising waste pickers and kabadiwalas drives resource recovery. This informal network recovers approximately 23% of total waste, prioritizing high-value "dry waste" such as glass (nearly 100% recovery), metals, and plastics (50–80% recovery). However, the transition to a circular model is hindered by significant collection challenges. Although urban collection efficiency reaches 70–95%, a lack of source segregation leads to contaminated recyclables and downcycling, particularly for plastics and paper. While the informal sector's recovery process is economically beneficial, the unhygienic nature of manual segregation and the high rate of contamination necessitate a shift toward integrated, formal-informal partnerships.

A holistic circular economy framework must also consider socio-economic dimensions, particularly given that the informal sector recovers 23% of total waste. Formalizing the informal sector such as the rag pickers and kabadiwalas has profound implications for livelihoods. While formalization can improve occupational health, safety, and traceability, it may also alter the cost-competitiveness of secondary materials if informal labor is displaced or operational costs rise. Ensuring that marginalized workers are integrated into formal-informal partnerships or aggregator models without compromising their income streams is critical for achieving a socially just transition to a circular waste management system.

7.3.2 Material flow of recyclables

The Fig 7.1 highlighting the integration of formal (green) and informal (red) sectors. This dual-loop system characterizes the pathway from waste generation to resource recovery, forming the basis for a circular economy. The formal loop is initiated by producers and consumers, with waste channelled through municipality collection to MRFs.

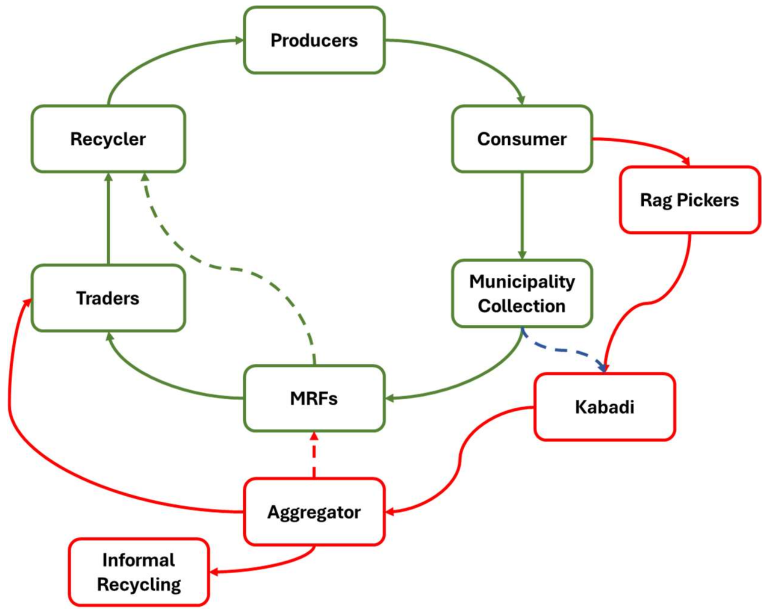


Fig. 7.1 Material flow of recyclables

In parallel, the informal sector comprising rag pickers and kabadiwalas intercepts high-value recyclables directly from the source or municipal streams. These actors feed into aggregators, who serve as the critical linkage between the two sectors. The diagram shows that aggregators either supply processed materials back into formal traders and MRFs (indicated by dashed lines) or divert them toward informal recycling units. The presence of traders and recyclers at the end of the chain completes the resource loop, returning secondary raw materials to producers. By formalizing the role of aggregators, the system can improve the quality of feedstock for recyclers, thereby reducing the overall carbon footprint of the materials' life cycle and enhancing the sustainability of the urban waste management framework.

7.3.3 Case study - Material recovery facility in Bengaluru

The compositional analysis of plastic waste collected at a MRF in Bengaluru reveals a significant skew toward specific polymer types, providing critical insights into local consumption and disposal patterns (Fig. 7.2). This may also indicate the interception of informal sector collections before reaching the MRF facilities.

Low density polyethylene (LDPE) constitutes 81.94% of the total plastic fraction. This high concentration representative of the massive influx of packaging materials, such as carry bags, milk pouches, and flexible food packaging, which are frequently discarded in urban municipal streams. From a circular economy perspective, this dominance presents a substantial challenge, as LDPE is often prone to contamination and is frequently "downcycled" rather than being returned to high-value applications.

Polypropylene (PP) represents the second-largest fraction at 13%, commonly originating from rigid containers. High-value engineering plastics such as polyethylene terephthalate (PET - 2.38%) and high-density polyethylene (HDPE - 2.05%) are present in low concentrations within the MRF stream. This indicates an efficient diversion by the informal sector (ragpickers and kabadiwalas), who typically intercept these high resale value materials before they reach municipal collection points.

Trace amounts of polystyrene (PS, 0.63%) and polyvinyl chloride (PVC, 0.01%) were also recorded. While these fractions are small, their presence in the mixed waste stream can complicate the recycling process due to chemical incompatibility and toxic byproducts during thermal processing.

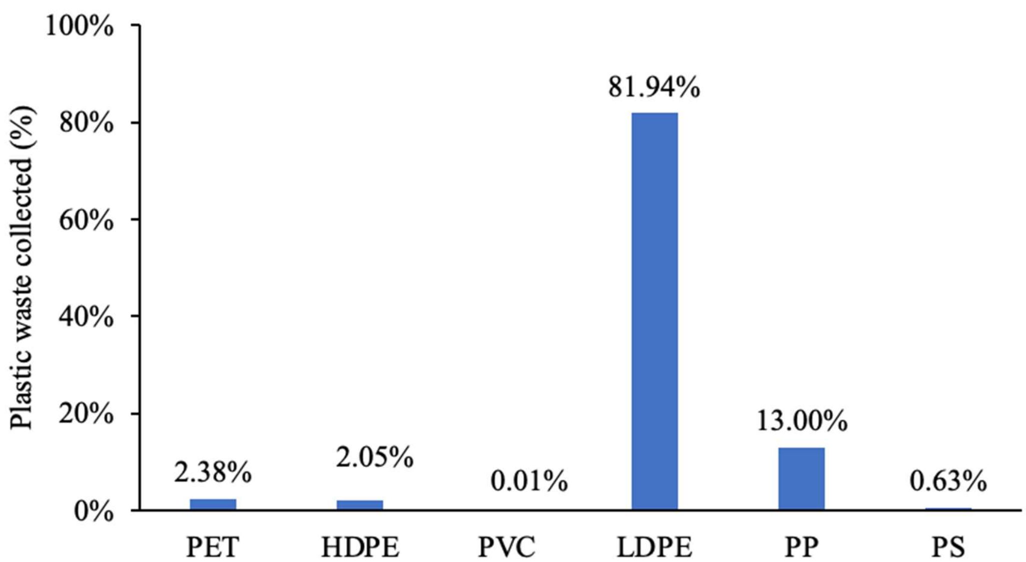


Fig. 7.2 Plastic waste fraction collected in a MRF facility in Bangalore

7.3.4 Life cycle impact assessment

The LCA of recycling systems is material-specific, as the processes, energy requirements, and associated emissions vary significantly across different material types. The assessment focuses on quantifying GHG emissions associated with the major recyclable fractions of MSW, including metals (aluminium and steel), plastics (HDPE/LDPE, PVC, and polypropylene), paper and cardboard, and glass. The recycling data was then compared with primary production data and emission reduction potential across key material streams within the MSW recycling system are discussed below.

All the data presented in the following section were obtained from the Ecoinvent version 3.12 database, considering a range of different processing methods. The ReCiPe 2016 (H) Midpoint v1.1 method was employed to evaluate global warming (GW) impacts.

7.3.4.1 Aluminum

The production of primary aluminium is notably energy-intensive, with impacts reaching 17.4 kg CO_2 eq./kg for cast alloy slabs. By bypassing bauxite extraction and the electrolytic Hall–Héroult reduction process, recycling presents a superior potential for GHG mitigation. Secondary production pathways exhibit a substantial decrease in emissions, with values as low as 0.322 kg CO_2 eq./kg for post-consumer scrap processed for melting and 0.874 kg CO_2 eq./kg for cast alloy at refiners. Consequently, these processes achieve a significant environmental credit, with estimated net emission savings between 95% and 98%. The aluminium industry generates more than 1.1 billion tonnes of CO_2 eq. emissions annually around 2% of global anthropogenic emissions. Therefore, aluminum recycling is considered as one of the most effective strategies for industrial decarbonization (Sandström et al., 2020). According to Olivares et. al., (2024), improving the environmental performance of aluminium recycling processes should primarily focus on minimizing metal losses and optimizing the recovery and utilization of by-products.

7.3.4.2 Steel

Primary manufacturing of steel is dependent upon energy-dense upstream activities, such as the extraction of iron ore and blast furnace refining, which yield a GWP of 1.84 kg CO_2 eq./kg for unalloyed converter variants and 2.22 kg CO_2 eq./kg for reinforcing bars. The recovery of end-of-life steel is primarily managed by the informal network owing to its significant economic worth, resulting in minimal volumes within municipal waste. Secondary manufacturing routes, employing electric arc furnaces (EAF) and induction technology, leverage this scrap as the fundamental feedstock, thereby necessitating reduced cumulative energy demands (TERI, 2023). Specifically, the utilization of 100% scrap within an EAF mitigates the GWP to 0.989 kg CO_2 eq./kg, which translates to a net environmental credit of 44-54% in emission savings.

7.3.4.3 Polyethylene (PE)

Primary production of polyethylene is largely dependent on fossil fuel feedstocks (e.g., ethylene derived from naphtha or natural gas cracking), making it carbon intensive. For high-density polyethylene (HDPE), primary manufacturing generates 3.12 kg CO_2 eq./kg, whereas the recycling pathway significantly mitigates this impact to 0.204 kg CO_2 eq./kg, thereby achieving a net environmental credit of 92% in emission savings. Similarly, low-density polyethylene (LDPE) produces 3.61 kg CO_2 eq./kg during virgin production, while secondary impacts fluctuate between 0.512 and 1.460 kg CO_2 eq./kg, resulting in savings of 50–82%. This relatively wide range reflects variability across waste management systems, specifically regarding sorting purity, contamination levels, and the process-related emissions inherent in washing, shredding, and reprocessing stages (Vinayak and Chauhan, 2026).

Emerging fractions such as multilayer packaging (such as mixed LDPE films) and textiles are limited by recycling inefficiencies (Anwar et al., 2024; Seifali Abbas-Abadi et al., 2025), represent critical areas for improving circularity and enhancing overall system-level environmental performance. In this context, advanced chemical recycling methods like pyrolysis represent a vital prospective pathway, enabling the conversion of heterogeneous polymers into secondary raw feedstocks. Although these thermo-chemical pathways require more energy than the mechanical baselines studied, their ability to reclaim value from landfill-bound mixed waste makes them a vital strategic addition to resource recovery infrastructure.

7.3.4.4 Polyvinyl chloride (PVC)

PVC is the second most widely used plastic and commonly found in pipes, cables, and construction applications. The virgin manufacturing process relies on chlorine chemistry and energy-dense stages, such as the synthesis of vinyl chloride monomers, resulting in a GWP of 2.60 to 2.91 kg CO_2 eq./kg. In contrast, recycling pathways offer a significantly reduced environmental footprint, with impacts for micronised powder and recycled pellets falling between 0.239 and 0.390 kg CO_2 eq./kg. This disparity facilitates substantial and reliable emission reductions of 82–90%. Mechanical recovery for PVC is highly efficient, as it permits multiple reprocessing cycles with minimal loss of material integrity, supported by the availability of uniform and consistent waste streams derived from demolition and construction activities.

7.3.4.5 Polypropylene (PP)

Polypropylene is extensively utilized in packaging and consumer applications, with primary production impacts reaching 2.44 kg CO_2 eq./kg. The recycling pathway mitigates these emissions to a range of 0.647–1.410 kg CO_2 eq./kg, achieving moderate emission savings of 32–69%. The comparatively lower environmental credits relative to polymers such as PVC are linked to the presence of highly heterogeneous and contaminated post-consumer streams, which necessitate energy-intensive sorting and cleaning stages. Additionally, the degradation of mechanical integrity during reprocessing frequently restricts the total number of viable recovery cycles, often requiring the incorporation of virgin resin to maintain material standards.

7.3.4.6 Paper and cardboards

Primary production emissions for board cartons range from 1.38 to 2.35 kg CO_2 eq./kg, driven by energy- and resource-intensive processes like wood harvesting, chemical pulping, and bleaching. Recycled newsprint production relies on recovered fiber and generates 1.61 kg CO_2 eq./kg. However, the benefits are constrained by fiber degradation over multiple recycling cycles, typically limiting reuse to 5–7 times, and by the need for de-inking and cleaning processes, which add to energy and water consumption (Abushammala et al., 2023). The pulp and paper industry contributes approximately 2–3% of global industrial CO_2 emissions, making recycling a key strategy for reducing its environmental footprint. Therefore, improving collection systems, minimizing contamination, and enhancing recycling efficiency are essential to maximize emission savings and support circularity in the paper sector.

7.3.4.7 Glass

Primary production emissions for glass range from 1.07 to 1.17 kg CO_2 eq./kg across uncoated flat, coated flat, and white packaging glass. However, the reduction in emissions from glass recycling is generally attributed to the use of cullet (recycled glass), which lowers the melting temperature required in furnaces and avoids process-related CO_2 emissions from carbonate decomposition. The effectiveness of glass recycling remains heavily influenced by factors such as color sorting, contamination (e.g., ceramics and stones), and transportation requirements (Indraratna et al., 2025).

Table 7.3 indicates that recycling is an effective GHG mitigation strategy across all material categories; its system-level impact depends on both per-unit emission savings and material composition in MSW streams. Therefore, prioritising high-impact materials such as metals is essential for maximising emission reductions. Additionally, these findings emphasise that material-specific strategies and efficient segregation and processing systems are critical to optimising the environmental performance of recycling within MSW management frameworks. While the system boundaries defined in this study include the transport of baled and sorted materials to secondary recyclers, the specific impact of these transportation distances requires site specific examination. For bulky, low-density materials like unbaled plastics or dense, heavy materials such as glass, transport-related emissions can severely cut into the net GHG savings. Consequently, the viability and overall environmental benefit of centralized recycling networks in India heavily depend on optimizing logistics and minimizing transport distances, ensuring that the carbon costs of transportation do not negate the climate benefits of material recovery.

Table 7.3 GHG emissions from primary production and recycling (data from the Ecoinvent database v 3.12)

Material Category	Recycling yield (%)	Primary production (kg CO_2 eq./kg)	Recycling (kg CO_2 eq./kg)	Emission savings (%)
Aluminium	98	17.4	0.3 – 0.9	95–98
Steel	96	1.8 – 2.2	0.9	44–54
HDPE	85	3.1	0.2	92
LDPE	85	3.6	0.5 – 1.5	50–82
PVC	85	2.6 – 2.9	0.2 – 0.4	82–90
PP	85	2.4	0.6 - 1.4	32–69

7.4 Practical implications

The major practical insights derived from this study for policymakers, urban local bodies, recycling industries, and other stakeholders engaged in MSW management are presented below.

- The results demonstrate that material prioritization is critical for maximizing climate benefits. Metals, especially aluminum, offer the highest emission reduction potential. Therefore, policy interventions should prioritize efficient recovery and channelization of metal waste streams, including strengthening buy-back systems and incentivizing formal collection networks.
- Implementing mandatory segregation at source, supported by behavioral interventions, economic incentives, and enforcement mechanisms, is essential to improve feedstock quality and recycling outcomes.

- Integrating informal workers into formal systems through structured partnerships, cooperatives, or aggregator models can enhance material recovery while improving working conditions and traceability.
- Formal recognition and support for aggregators can improve the linkage between informal collection and formal recycling systems, leading to better sorting efficiency, higher-quality recyclables, and reduced lifecycle emissions. Policies should focus on capacity building, digital traceability, and financial support mechanisms for these actors.
- Energy mix plays a significant role in determining recycling benefits. Transitioning recycling facilities toward renewable energy sources can further enhance GHG emission reductions, especially for energy-intensive processes such as plastic and metal recycling.
- Emerging waste streams such as multilayer packaging and textiles require targeted innovation. The low recycling efficiency of these materials indicates a need for research and development, alternative material design, and dedicated collection systems to improve circularity.

The study emphasizes that infrastructure development must be complemented by systemic integration, including improved segregation, strengthened formal–informal linkages, and the prioritization of high-impact materials. The study also indicates a need for technology and policy interventions targeting low-value and contaminated fractions. This includes promoting advanced recycling technologies encouraging design-for-recyclability and implementing extended producer responsibility frameworks that incentivize recovery of difficult-to-recycle materials. A holistic approach that combines policy reform, technological upgrades, stakeholder integration, and behavioral change is essential to enable the transition from a linear to a circular waste management system.

The primary aim of this study is to evaluate Indian recycling facilities, a notable limitation is the reliance on datasets representing Europe (RER) or Rest-of-World (RoW) from the Ecoinvent database. Currently, only the primary production data for high-density polyethylene (HDPE) and low-density polyethylene (LDPE) reflect specific Indian geographies. Additionally, given that India's energy grid is highly dependent on coal, it is likely that local primary material production and mechanical recycling processes possess higher actual carbon footprints than the European averages utilized in these impact models. Future assessments should prioritize developing region-specific life cycle inventories for India to capture these regional disparities accurately.

7.5 Summary

This study quantifies the GHG mitigation potential of key recyclable fractions in MSW by comparing primary production with recycling pathways. The results indicate that the magnitude of savings varies significantly across material types, and while most materials exhibit emission reductions, the outcomes are highly dependent on recycling yields and baseline primary production impacts. Metals, aluminium and steel, demonstrate the highest mitigation potential, with emission reductions reaching 95–98% and 44–54%, respectively, due to the avoidance of energy-intensive primary production processes. Plastics, specifically HDPE, LDPE, PVC, and PP showed moderate-to-high savings (ranging from 32% to 92%), although their performance is strongly influenced by collection efficiency, contamination levels, and specific recycling technologies. Paper and cardboard exhibit highly variable emission savings as the benefits are heavily constrained by mass loss during recovery and the energy required for de-inking and cleaning processes when compared against low-impact virgin board production. In contrast, glass and multilayer packaging present comparatively lower savings or ongoing recycling challenges, primarily due to processing limitations, and transport-related impacts. The analysis demonstrates that recycling system effectiveness varies depending on material type alongside operational and infrastructural factors like segregation efficiency, the quality of recovered feedstock, and the regional energy mix. These findings indicate achievable mitigation potential under optimised conditions, emphasising that improving source segregation, enhancing material recovery facilities, and adopting cleaner energy inputs are critical for maximising the environmental benefits of the recycling process.

References:

Abushammala, H., Masood, M. A., Ghulam, S. T., & Mao, J. (2023). On the conversion of paper waste and rejects into high-value materials and energy. Sustainability, 15(8), 6915.

Abbas-Abadi, M. S., Tomme, B., Goshayeshi, B., Mynko, O., Wang, Y., Roy, S., & Van Geem, K. M. (2025). Advancing textile waste recycling: Challenges and opportunities across polymer and non-polymer fiber types. *Polymers, 17*(5), 628. https://doi.org/10.3390/polym17050628

Alvim, D. S., de Almeida Flor, G., Teixeira, V. G., Suski, C. A., Kasemodel, M. C., D'Amelio, M. T. S., & de Alcântara, M. A. K. (2025). Aluminum recycling and its contribution to socio-environmental sustainability: A perspective from circular economy and environmental management. *Revista de Gestão Social e Ambiental, 19*(10), 1–19.

Anwar, M. A., Sasongko, N. A., Najib, M., & Pranoto, B. (2024). Challenges and prospects of multilayer plastic waste management in several countries: A systematic literature review. *Case Studies in Chemical and Environmental Engineering, 10*, 100911. https://doi.org/10.1016/j.cscee.2024.100911

Bowyer, J., Bratkovich, S. T., Fernholz, K. A., Frank, M. A., Groot, H. A., Howe, J. E., & Pepke, E. (2015). *Understanding steel recovery and recycling rates and limitations to recycling*. Dovetail Partners Inc.

Ferrara, C., & De Feo, G. (2021). Environmental assessment of recycled paper production: The effects of energy supply source. *Sustainability, 13*(9), 4841. https://doi.org/10.3390/su13094841

Huijbregts, M. A. J., Steinmann, Z. J. N., Elshout, P. M. F., Stam, G., Verones, F., Vieira, M., Zijp, M., Hollander, A., & van Zelm, R. (2017). ReCiPe2016: A harmonised life cycle impact assessment method at midpoint and endpoint level. *The International Journal of Life Cycle Assessment, 22*, 138–147. https://doi.org/10.1007/s11367-016-1246-y

Huysveld, S., Ragaert, K., Demets, R., Nhu, T. T., Civancik-Uslu, D., Kusenberg, M., Van Geem, K. M., De Meester, S., & Dewulf, J. (2022). Technical and market substitutability of recycled materials: Calculating the environmental benefits of mechanical and chemical recycling of plastic packaging waste. *Waste Management, 152*, 69–79. https://doi.org/10.1016/j.wasman.2022.08.006

Indraratna, B., Attanayake, A., & Rujikiatkamjorn, C. (2025). A critical review of the utilization of recycled glass in transportation infrastructure including roads and railways. *Sustainability*, *17*(7), 3187. https://doi.org/10.3390/su17073187

Intergovernmental Panel on Climate Change (IPCC). (2013). *Climate change 2013: The physical science basis. Working Group I contribution to the fifth assessment report of the Intergovernmental Panel on Climate Change*. Cambridge University Press.

Olivares, A. V., Pastor-Vallés, E., Pettersen, J. B., & Tranell, G. (2024). LCA of recycling aluminium incineration bottom ash, dross and shavings in a rotary furnace and environmental benefits of salt-slag valorisation. *Waste Management, 182*, 11–20. https://doi.org/10.1016/j.wasman.2024.03.021

Sandström, J., Van Heusden, R., Morrison, H., Puleo, M., & Murray, L. (2020). *Aluminium for climate: Exploring pathways to decarbonize the aluminium industry*. World Economic Forum.

TERI. (2023). *Financing decarbonization of the secondary steel sector in India: Towards an enabling environment*. The Energy and Resources Institute.

Vinayak, A. K., & Chauhan, G. (2026). Circularity in polyethylene waste management through multidimensional integration. *Next Sustainability, 7*, 100247. https://doi.org/10.1016/j.nxsust.2026.100247

Wernet, G., Bauer, C., Steubing, B., Reinhard, J., Moreno-Ruiz, E., & Weidema, B. (2016). The ecoinvent database version 3 (part I): Overview and methodology. *The International Journal of Life Cycle Assessment, 21*(9), 1218–1230. https://doi.org/10.1007/s11367-016-1087-8

Westbroek, C. D., Bitting, J., Craglia, M., Azevedo, J. M., & Cullen, J. M. (2021). Global material flow analysis of glass: From raw materials to end of life. *Journal of Industrial Ecology, 25*(2), 333–343. https://doi.org/10.1111/jiec.13073

Chapter 8
Leachate Treatment

8.1 Preamble

Existing studies on landfill leachate treatment in India primarily focus on treatment efficiency and regulatory compliance, while limited attention has been given to the environmental trade-offs associated with energy-intensive treatment systems, chemical consumption, and reject management. Furthermore, few field-scale studies have integrated LCA to evaluate the broader sustainability implications of operational leachate treatment plants under Indian conditions. Therefore, this chapter aims to bridge this gap by combining process-level analysis with LCA-based environmental assessment of a full-scale leachate treatment facility in Bangalore.

This chapter details a comprehensive performance evaluation of leachate treatment approaches in India. The primary objectives of the study are:

- To review existing leachate management strategies and regulatory compliance across Indian municipalities.
- To quantify the technical, and environmental impacts of a functional LTP in Bengaluru using the LCA framework.

8.2 Methodology

The methodology for this study follows an integrated framework that combines field-based performance analysis with standardized LCA to evaluate the sustainability of leachate management.

8.2.1 Site characteristics

The study identifies the Bellahalli leachate treatment plant (LTP) in Bangalore as the primary research site (Fig. 8.1). With a design capacity of 100 kLD, the plant processes leachate characterized by organic strength (avg. Influent COD: 800 ± 400 mg/L) and showed high variability due to monsoonal rainfall.

Fig. 8.1 Field visit to Bellahalli leachate treatment plant (2025)

8.2.2 Process flow analysis of LTP

The Bellahalli LTP utilizes a multi-stage configuration dominated by physicochemical separation and membrane-based advanced treatment (Fig. 8.2). The process begins with pre-treatment, where raw leachate passes through a vibro-separator and a primary settling tank to remove coarse debris and suspended solids. The clarified effluent then undergoes chemical conditioning in a flash mixer for coagulation and flocculation, followed by secondary settling to protect downstream units from premature fouling. Subsequent stages involve pH adjustment via acid dosing to prevent scaling, followed by sequential filtration through sand and cartridge filters. A Nanofiltration (NF) unit serves as a pre-polishing step, selectively removing multivalent ions and high-molecular-weight organics. The final stage comprises a two-pass Reverse Osmosis (RO) system; the first stage achieves ~80% recovery, while the second reaches ~85%. While this produces high-quality permeate meeting discharge standards, it generates a highly concentrated reject stream.

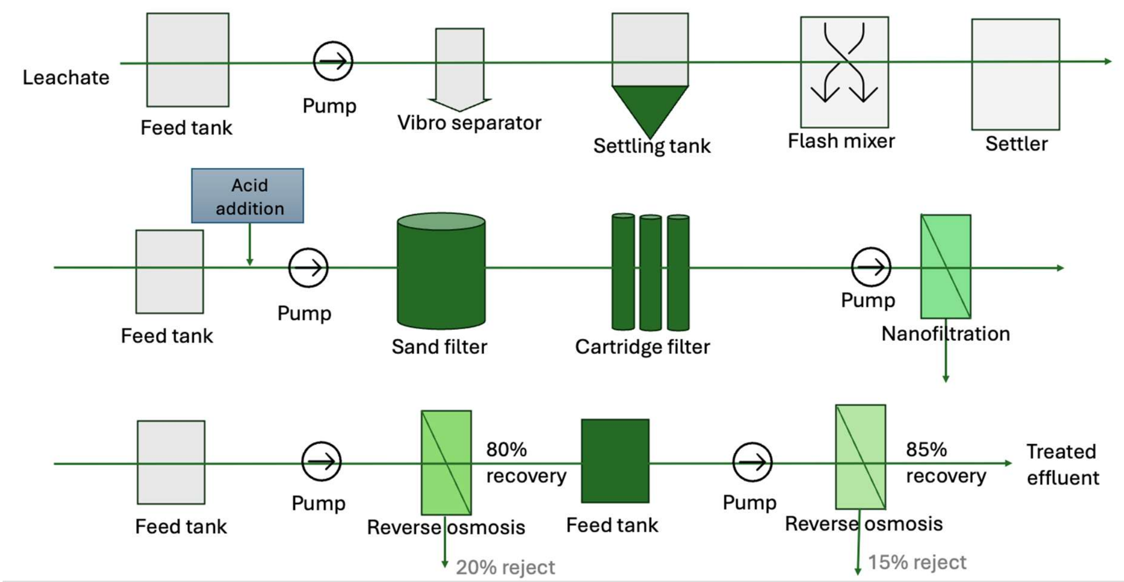


Fig. 8.2 Schematic diagram of leachate treatment process in Bellahalli LTP

8.2.3 Life cycle assessment (LCA)

The environmental burdens associated with leachate treatment were quantified using LCA for Experts (GaBi) software following the ISO 14040 and ISO 14044 framework for life cycle assessment (ISO, 2006a; ISO, 2006b). The impact assessment was performed using the ReCiPe 2016 methodology at midpoint and endpoint levels (Huijbregts et al., 2017). Background inventory datasets for electricity generation, chemical production, and material flows were obtained from the LCA for Experts (GaBi) Professional database.

8.2.3.1 Goal and Scope

The primary objective of the LCA was to identify environmental hotspots associated with the operation of the Bellahalli LTP and evaluate the sustainability implications of membrane-intensive treatment systems under Indian conditions. The functional unit selected for the study was the treatment of 1 m^3 of landfill leachate.

A gate-to-grave system boundary focusing on the operational phase of the treatment plant was adopted. The assessed processes included leachate pumping, chemical dosing, coagulation–flocculation, membrane filtration, electricity consumption, and disposal of RO reject streams. The construction and decommissioning phases of infrastructure were excluded from the assessment because the study primarily aimed to evaluate recurring operational impacts, which dominate the environmental footprint of membrane-based leachate treatment systems due to continuous electricity and chemical requirements. Previous LCA studies on wastewater and leachate treatment systems have similarly reported that operational energy consumption contributes significantly more to overall impacts than infrastructure construction, particularly in high-pressure membrane systems (Di Maria & Sisani, 2017; Zhang et al., 2021).

The infrastructure lifespan of the treatment plant was assumed to be 20 years, consistent with the typical design life of municipal leachate treatment facilities and membrane-based treatment systems. Since the construction phase was excluded, infrastructure lifespan was considered primarily to contextualize the long-term operational assessment period.

8.2.3.2 Life cycle inventory (LCI)

Primary operational inventory data were collected from annual average monitoring records and field observations at the Bellahalli LTP. The inventory included electricity consumption associated with pumping and membrane operation, chemical consumption for pH adjustment, influent and treated effluent characteristics, and reject generation rates.

The inventory data are considered temporally representative of typical plant operation under Indian climatic conditions, as they incorporate seasonal variations observed over the monitoring period. However, significant fluctuations in leachate quality were observed due to monsoonal rainfall, heterogeneous waste composition, and varying landfill conditions. These fluctuations influenced influent COD, TDS, and ammonia concentrations, which in turn affected operational energy demand, chemical dosing requirements, and membrane loading rates (Table 8.1).

Operational uncertainties are inherent in landfill leachate treatment systems due to dynamic waste degradation processes and seasonal hydraulic loading variations. To reduce uncertainty, annual average values were used for major inventory parameters. Nevertheless, short-term fluctuations associated with shock loading events, membrane fouling, and rainfall-induced dilution may not be fully captured within the present assessment. Therefore, the results should be interpreted as representative operational averages rather than fixed deterministic values.

Background datasets for electricity production were modelled using the Indian grid electricity mix available within the LCA for Experts professional database. The electricity profile reflects the relatively high dependence on coal-based thermal power generation in India, which substantially influences climate change and eutrophication impacts. Allocation within background processes followed the default allocation procedures embedded in the database.

Table 8.1 Life cycle inventory

		Reference
Electricity consumption	5 kWh per m^3	Field data
Chemical dosing, sulphuric acid	0.05 kg per m^3	Field data
Leachate COD value	800 mg/L	Field data
Treated effluent COD	<5 mg/L	Field data

8.2.3.3 Life cycle impact assessment (LCIA)

Environmental impacts were evaluated using the ReCiPe 2016 methodology at both midpoint and endpoint levels (Huijbregts et al., 2017). The midpoint categories assessed included global warming potential (GWP100), eutrophication potential (EP), freshwater aquatic ecotoxicity potential (FAETP), and marine aquatic ecotoxicity potential (MAETP). Endpoint assessment was conducted using the ReCiPe 2016 Endpoint (H) hierarchist perspective to aggregate impacts into human health, ecosystem quality, and resource scarcity damage categories.

8.3 Results and discussion

8.3.1 Leachate composition and treatment

In India, leachate is typically characterized by very high organic strength, with chemical oxygen demand (COD) values ranging from 5,000 to 1,00,000 mg/L, while biochemical oxygen demand (BOD_5) varies between 2,000 and 60,000 mg/L, and BOD/COD ratio often lies between 0.3 and 0.8 (Nalladiyil et al., 2026). The physico-chemical characterisation of different type of leachate is shown in Table 8.2.

Biological processes, specifically anaerobic processes, are effective for treating young leachate, achieving up to 90% BOD removal and 70–80% COD removal and recovering biogas (Zhou et al., 2021). Aerobic treatment may also be employed; however, it is energy-intensive and generates substantial quantities of excess biomass in the form of waste activated sludge. This sludge requires further processing like thickening, stabilization, and safe disposal or reuse, adding to downstream management requirements.

Medium to old leachate is characterized by high salinity, ammonia, and refractory organic compounds, biological processes alone are often insufficient(Nalladiyil et al., 2024). As a result, physico-chemical treatment methods such as coagulation–flocculation, chemical oxidation, and ammonia stripping are widely applied. While effective, these processes generate large volumes of chemical sludge often classified as hazardous waste, posing challenges in handling, disposal, and regulatory compliance. Additionally, the combined reliance on chemical dosing and energy-intensive operations significantly increases monthly operational expenditure.

Membrane-based systems, including reverse osmosis (RO) and membrane bioreactors (MBR), provide the highest contaminant removal efficiencies, exceeding 98% for COD, heavy metals, and total dissolved solids, enabling compliance with stringent discharge standards. However, their performance comes at the cost of high capital investment for membrane modules, high-pressure pumping, and ongoing replacement expenses (Talalaj, 2015). A critical environmental bottleneck associated with membrane systems is the generation of RO reject, which concentrates salts, heavy metals, and persistent organic pollutants. If inadequately managed such as through landfill recirculation or uncontrolled disposal this reject stream represents a significant environmental liability.

Table 8.2 Physicochemical characteristic of leachate (Bengaluru data, n = 5)

Parameter	Compost leachate	Operational landfill leachate	Closed landfill leachate
pH	3.54 ± 0.23	5.85 ± 0.18	7.80 ± 0.16
Electrical conductivity, µmhos/cm	16800 ± 1200	37350 ± 3350	23950 ± 9260
Total dissolved solids, mg/L	10800 ± 680	23280 ± 1770	16380 ± 5060
Chemical oxygen demand, mg/L	220000 ± 50000	31000 ± 2200	18000 ± 3500
BOD, mg/L	90000 ± 30000	21000 ± 3400	8500 ± 1800
Total alkalinity as $CaCO_3$, mg/L	NIL	12830 ± 1530	8900 ± 1560
Ammoniacal nitrogen as N, mg/L	710 ± 740	43 ± 14	510 ± 143
Total Kjeldahl nitrogen as N, mg/L	1325 ± 1310	1153 ± 484	855 ± 590
Nitrate as NO_3, mg/L	2360 ± 1790	1809 ± 469	1002 ± 530
Total phosphorous as P, mg/L	52 ± 30	56 ± 25	28 ± 15

Calcium as Ca mg/L	188 ± 90	3353 ± 673	88 ± 79
Magnesium as Mg, mg/L	214 ± 25	600 ± 176	35 ± 9
Potassium as K, mg/L	3245 ± 1280	2943 ± 674	573 ± 121
Sodium as Na, mg/L	2440 ± 1560	3828 ± 548	590 ± 181
Sulphate as SO_4, mg/L	254 ± 88	1427 ± 283	110 ± 79
Copper as Cu, mg/L	<0.05	0.251 ± 0.07	<0.05
Chromium as Cr, mg/L	ND	0.722 ± 0.042	0.290 ± 0.047
Cadmium as Cd, mg/L	<0.003	0.270 ± 0.056	0.009 ± 0.001
Lead as Pb, mg/L	<0.1	0.293 ± 0.098	0.204 ± 0.147
Zinc as Zn, mg/L	<0.1	4.600 ± 2.260	0.182 ± 0.115

8.4 Circular economy perspective in leachate management

Existing leachate treatment systems are predominantly evaluated on the basis of effluent quality, often overlooking energy efficiency, sludge and reject management, and environmental impacts (Kurniawan et al., 2006, Renou et al., 2008), where the principal objective is treatment and safe disposal of contaminated liquid streams. However, emerging circular economy principles advocate a transition from the conventional “treat-and-dispose” paradigm toward a “recover-and-reuse” framework, where leachate is increasingly recognized as a secondary resource stream containing recoverable water, nutrients, organic carbon, and dissolved materials (El-Saadony et al., 2026). This transition is particularly relevant in developing countries such as India, where rapid urbanization, increasing landfill volumes, freshwater stress, and rising treatment costs necessitate more sustainable resource management approaches.

Young and highly biodegradable leachate can serve as a substrate for anaerobic digestion and biogas recovery, while mature leachate streams offer opportunities for ammonia recovery, nutrient recycling, humic substance extraction, and treated water reuse. In this context, treatment technologies should not only be evaluated based on pollutant removal efficiency, but also on their ability to minimize secondary waste generation, reduce energy demand, and maximize resource recovery potential.

The growing emphasis on circular waste management has also highlighted the limitations of membrane-dominated "end-of-pipe" treatment systems. Although reverse osmosis (RO) and nanofiltration achieve high contaminant removal efficiencies, they frequently transfer pollutants into concentrated reject streams, resulting in environmental burden shifting rather than complete resource recovery. Therefore, sustainable leachate management requires integration of biological treatment, nutrient recovery, renewable energy generation, water reuse, and reject valorization pathways within a systems-based framework (Wang and Qiao 2024).

From a lifecycle perspective, resource recovery-based leachate management can reduce environmental burdens by offsetting virgin fertilizer production, reducing freshwater consumption, lowering greenhouse gas emissions, and minimizing landfill dependency. Consequently, future leachate treatment systems should be designed as integrated circular infrastructure that simultaneously addresses pollution control, energy recovery, nutrient circularity, and water sustainability rather than functioning solely as waste treatment facilities.

Sustainable performance assessment therefore requires a shift toward integrated metrics that account for energy recovery, by-product valorization, and reduction of secondary waste streams, particularly for aging landfills where leachate complexity increases over time. Therefore, a life cycle assessment of the existing plant LTP was carried out to identify these environmental impacts and the result are discussed in the following section.

8.4.1 Life cycle impact assessment

8.4.1.1 Global warming

The LCA results reveal that the GW of the leachate treatment process is dominated by electricity consumption, which contributes to 6.4 kg CO_2 eq./m^3 mainly due to operational demands of advanced membrane filtration units (Fig. 8.3). The carbon footprint of the facility is highly sensitive to the local grid's emission factor, highlighting a critical area for decarbonization through the integration of renewable energy. In contrast, the contributions from landfilling of RO reject, chemical dosing, and effluent discharge are comparatively marginal. The low GW associated with the treated effluent (<0.2 kg CO_2 eq./m^3) indicates high removal efficiencies of organic matter, thereby minimizing downstream fugitive methane or nitrous oxide emissions. While, the current process effectively treats the leachate, its long-term sustainability is dependent upon optimizing electrical efficiency or transitioning to a less energy-intensive process to mitigate its substantial climate impact. Therefore, expanding the development and deployment of clean energy can significantly reduce the environmental impacts of treatment processes (Zhou et al., 2011). As most facilities rely on the national power grid for electricity, prioritising a transition toward cleaner and renewable energy sources is essential.

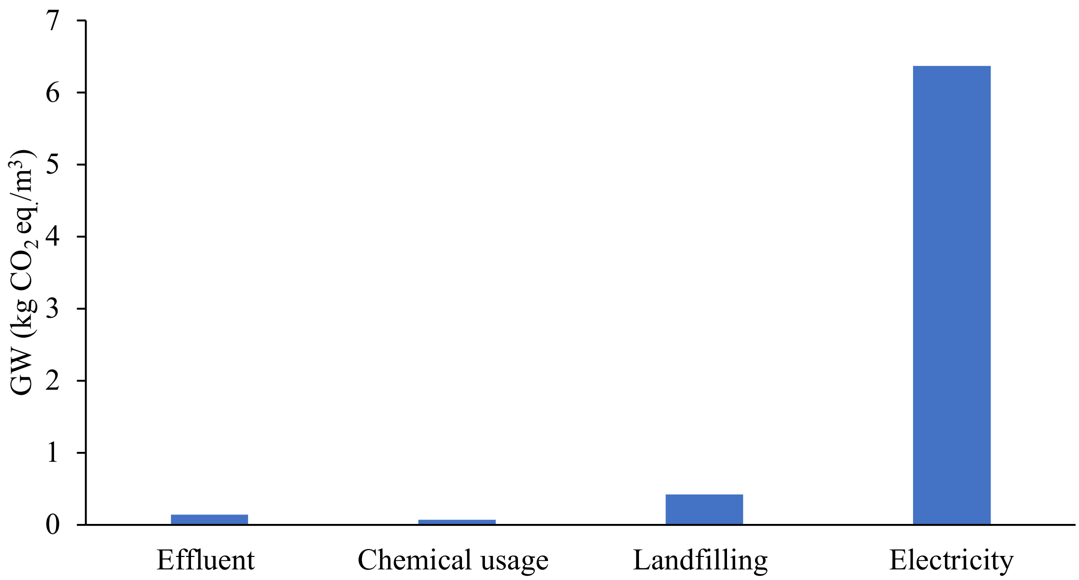


Fig. 8.3 Global warming of the leachate plant

8.4.1.2 Eutrophication potential

The eutrophication potential (EP) analysis of the leachate treatment process reveals a distribution profile similar to that of the GW, with electricity consumption emerging as the primary contributor (Fig. 8.4). This contribution is largely indirect, stemming from the upstream resource extraction and emissions associated with the energy grid, particularly if the power mix relies on fossil fuels which release nitrogen and phosphorus compounds during production. These results indicate that while the process successfully prevents direct nutrient enrichment of local water bodies, its "hidden" eutrophication footprint is tied to high energy demand.

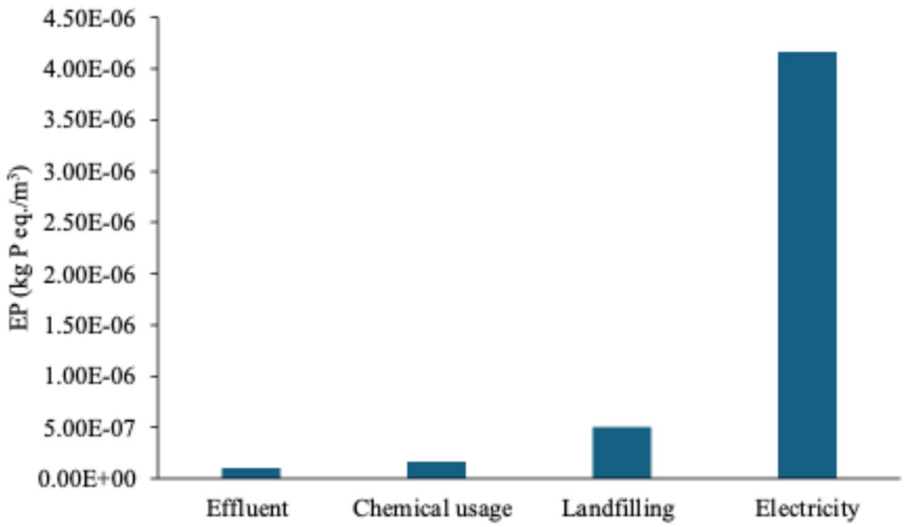


Fig. 8.4 EP of the leachate plant

The results of this study show lower GWP and EP values compared to other leachate treatment studies (Di Maria and Sisani, 2017), primarily due to lower influent COD concentrations, differences in treatment configurations, and site-specific geological conditions.

Despite providing valuable insights into the environmental performance of leachate treatment systems under Indian conditions, the present study has certain limitations that should be considered while interpreting the results. The assessment is site-specific and based on operational data obtained from the Bellahalli leachate treatment plant in Bengaluru. Leachate composition, treatment efficiency, operational practices, and energy requirements can vary significantly across landfill sites due to differences in waste composition, landfill age, climatic conditions, and management practices. Therefore, the results may not be directly generalizable to all Indian leachate treatment facilities. The inventory data were derived primarily from annual average operational records and field observations. Short-term fluctuations in leachate composition, hydraulic loading, membrane fouling, and operational upsets may not be fully captured within the present assessment. Consequently, the reported environmental impacts represent average operating conditions rather than dynamic real-time performance.

8.5 Practical Implications

Leachate management faces a critical convergence of technical, environmental, and economic hurdles. The challenges observed based on site visit and technology analysis are as follows:

- Leachate characteristics vary widely due to heterogeneous waste composition, rainfall variation, and poor segregation of waste at source. Resulting in high variation in COD, ammonia, TDS, and heavy metal concentrations over short time scales, making process control difficult and reducing the reliability of conventional treatment systems.

- Existing regulatory frameworks do not distinguish between young, medium, and mature landfill leachate, despite their different chemical profiles. This results in either over-designed treatment systems or underperformance of the system.
- Reverse osmosis (RO) has become the dominant treatment technology in Indian leachate treatment plants due to its ability to meet discharge standards. However, this shifts pollutants into a concentrated reject stream rather than eliminating them, creating long-term disposal challenges.
- RO reject contains high concentrations of salts, heavy metals, ammonia, and persistent organic pollutants. Common practices such as recirculation to landfills increase leachate strength and salinity over time, while alternatives like thermal evaporation or incineration are costly and carbon intensive.
- Biological processes are often underutilized or improperly designed due to shock loads, toxicity, and salinity stress. As a result, the potential for energy recovery through biogas generation and partial organic load reduction remains largely untapped.
- Seasonal rainfall causes sudden increases in leachate volume, leading to hydraulic overloading of treatment plants. It reduces treatment efficiency and increases energy consumption due to higher pumping and membrane operation requirements.
- Most leachate treatment systems in India follow a "treat-and-dispose" approach rather than a resource recovery model. Opportunities for nutrient recovery (e.g., ammonia), biogas generation, or conversion into liquid fermented organic manure are rarely explored at scale. The gaps, implications and the recommendation to address the gap is given in Table 8.3.

Table 8.3 Gaps in existing leachate treatment regulations and recommended improvements

No.	Identified Gap	Implications	Recommendations
1	Lack of age-specific leachate standards (young, intermediate, and aged landfill leachate)	• Inappropriate technology selection • Biological systems fail for aged leachate • Overdesign of treatment plants	• Introduce age-based leachate classification (young, mature, aged) • Define separate discharge norms for COD, BOD/COD ratio, NH_4^+-N, and refractory organics • Link technology selection guidelines to landfill age
2	Inadequate monitoring frequency (don't account variability in leachate quality, during monsoons)	• Shock organic and ammonia loads damage reactors • System instability and failures • Poor operational control	• Mandate high-frequency monitoring (weekly/online sensors for COD, NH_4^+, pH) • Introduce monsoon-specific monitoring protocols • Link monitoring data to adaptive process control
3	No limits for emerging contaminants (EC) (PFAS, microplastics, pharmaceuticals/personal care products)	• Long-term ecological and groundwater risks • Ineffective removal by conventional biological systems	• Introduce EC watch-list in leachate regulations • Pilot advanced oxidation and adsorption (biochar) unit
4	Unregulated RO reject (concentrate) management (no guidelines for reject handling)	• Recirculation of RO reject into landfill creates increased salinity and inhibitory effects on microbes • Escalating operational and maintenance cost	• Develop guidelines for RO reject disposal • Prohibit indefinite recirculation into landfills • Encourage thermal treatment, crystallisation, or co-processing in hazardous waste facilities
5	Over-reliance on membrane-based treatment systems	• High energy consumption and operational costs • Generation of secondary waste streams (e.g., RO concentrate), complicating the management	• Strengthen upstream treatment using advanced oxidation processes (AOPs) such as UV, ozone, or Fenton to reduce membrane load • Replace it with nature-based solutions, such as constructed wetlands, as tertiary polishing steps

8.6 Summary

The study utilizes LCA to identify environmental and operational hotspots within the LTP. Current frameworks predominantly advocate for “treatment for disposal”; however, a strategic shift is required toward “treatment for valorization,” where leachate is managed as a resource stream rather than a waste liability. Sustainable treatment strategies must prioritize nutrient recovery, water reuse, energy generation, and adaptive system design tailored to landfill age and leachate characteristics. Formal guidelines are needed to promote the reuse of treated effluent for non-potable applications such as dust suppression, industrial washing, or greenbelt irrigation to significantly reduce freshwater demand. For young and compost-derived leachate, anaerobic digestion presents a viable pathway for energy recovery, thereby lowering the net operational energy footprint. To enhance process efficiency, sustainable pretreatment methods, such as the addition of biochar or garbage enzymes can be integrated to improve biodegradability and minimize reliance on intensive chemical dosing. Conversely, for stabilized (aged) landfill leachate, the dependence on membrane systems should be reduced by strengthening upstream treatment through advanced oxidation processes like UV, ozone, or Fenton oxidation. Additionally, constructed wetlands offer a cost-effective tertiary polishing step, reducing treatment costs while enhancing the removal of nutrients and residual organics. Finally, continuous monitoring coupled with modular upgrades (e.g., adjustable biological stages or RO capacity) is essential to ensure system adaptability as leachate characteristics evolve over the landfill's lifecycle.

References

Di Maria, F., & Sisani, F. (2017). A life cycle assessment of conventional technologies for landfill leachate treatment. Environmental Technology & Innovation, 8, 411–422. https://doi.org/10.1016/j.eti.2017.07.002

El-Saadony, M. T., Saad, A. M., Fahmy, M. A., Mohammed, D. M., Salem, H. M., Abd El-Mageed, T. A., ... & AbuQamar, S. F. (2026). Hazardous landfill leachate: Integrated treatment strategies, regulatory frameworks, and circular economy perspectives. Ecotoxicology and environmental safety, 312, 119

Huijbregts, M. A. J., Steinmann, Z. J. N., Elshout, P. M. F., Stam, G., Verones, F., Vieira, M., Zijp, M., Hollander, A., & van Zelm, R. (2017). ReCiPe2016: A harmonised life cycle impact assessment method at midpoint and endpoint level. *The International Journal of Life Cycle Assessment, 22*, 138–147. https://doi.org/10.1007/s11367-016-1246-y

International Organization for Standardization (ISO). (2006a). Environmental management—Life cycle assessment—Principles and framework (ISO 14040:2006). ISO.

International Organization for Standardization (ISO). (2006b). Environmental management—Life cycle assessment—Requirements and guidelines (ISO 14044:2006). ISO.

Kurniawan, T. A., Lo, W. H., & Chan, G. Y. S. (2006). Physico-chemical treatments for removal of recalcitrant contaminants from landfill leachate. Journal of Hazardous Materials, 129(1–3), 80–100. https://doi.org/10.1016/j.jhazmat.2005.08.010

Nalladiyil, A., Khuntia, H. K., Chanakya, H. N., & Babu, G. S. (2025). Treatment of ultra-high-strength compost leachate using an anaerobic biomass biofilm reactor. Bioresource Technology, 133774. https://doi.org/10.1016/j.biortech.2025.133774

Nalladiyil, A., Sughosh, P., Babu, G. S., & Ramaswami, S. (2024). Landfill leachate treatment using fungi and fungal enzymes: A review. Biodegradation, 35(3), 225–247. https://doi.org/10.1007/s10532-024-10089-7

Renou, S., Givaudan, J. G., Poulain, S., Dirassouyan, F., & Moulin, P. (2008). Landfill leachate treatment: Review and opportunity. *Journal of Hazardous Materials, 150*(3), 468–493. https://doi.org/10.1016/j.jhazmat.2007.09.077

Wang, J., & Qiao, Z. (2024). A comprehensive review of landfill leachate treatment technologies. Frontiers in Environmental Science, 12, 1439128.

Zhang, L., Bai, H., Zhang, Y., Wang, Y., & Yue, D. (2021). Life cycle assessment of leachate treatment strategies. Environmental Science & Technology, 55(19), 13264–13273. https://doi.org/10.1021/acs.est.1c03262

Zhou, J., Chang, V. W. C., & Fane, A. G. (2011). Environmental life cycle assessment of brackish water reverse osmosis desalination for different electricity production models. Energy & Environmental Science, 4(6), 2267–2278. https://doi.org/10.1039/C0EE00720J

Chapter 9

Landfill with and without Bioremediation

9.1 Preamble

The detailed LCA and economic analysis of MSW treatment in landfills by utilising landfill gas is discussed in this chapter. The study uses the SimaPro software to evaluate five landfill scenarios for the treatment of 1 ton of MSW:

- Open Dumping (OD/S1),
- Sanitary Landfilling with leachate treatment and passive gas venting (SLF_LT/S2),
- SLF with Leachate Recirculation and Flaring (SLF_LR_F/S3),
- SLF with electricity generation (SLF_LR_ELE/S4), and
- SLF with Bio-CNG production (SLF_LR_BCNG/S5)—. The BioCNG production scenario was subdivided into two sub-scenarios, utilising BioCNG as vehicle fuel (VF) and cooking fuel (CF), named as SLF_LR_BCNG_VF (S5a) and SLF_LR_BCNG_CF (S5b), respectively.

This chapter aims to quantify and compare the environmental impacts of each scenario under consistent functional units and system boundaries. This study examines the trade-offs and synergies between environmental burdens and resource recovery by incorporating energy recovery, emission control technologies, and recirculation techniques. The study also examines the economic implications of the scenarios under investigation. The capital expenditure (CAPEX), operating expenditure (OPEX), and revenue were calculated for each scenario. The revenue was also calculated for the carbon credits obtained in scenarios where global warming was reduced, compared to the base scenario (OD). Revenue collected as tax on household garbage processing is also considered in the present study.

9.2 Materials and Methods

In this study, both environmental and economic evaluations were performed. The scenarios are examined for their environmental impact using the LCA approach. The study began by defining the goal and scope. A total of six scenarios were evaluated for environmental impacts based on LFG utilisation. The functional unit was set to 1 ton of MSW treatment to ensure comparability across scenarios (Clasen et al., 2024; Serafini et al., 2025). The system boundaries were defined as cradle-to-grave, encompassing the collection, transport, treatment, LFG recovery for utilisation, and leachate handling. For OD and SLF, the focus was on traditional practices without energy recovery. In contrast, for SLF_LR_F, SLF_LR_ELE, SLF_LR_BCNG_VF, and SLF_LR_BCNG_CF, the system was extended to include leachate recirculation, thereby enhancing gas generation and resource recovery. The economic analysis of each scenario, except open dumping, was conducted by incorporating data from the literature to assess its economic implications.

9.2.1 Estimation of methane from OD and SLF

Methane emission estimation is essential for quantifying atmospheric releases from open dumping (OD) and sanitary landfills (SLF). In this study, methane generation was estimated using the multicomponent multiphase methane generation model (MCMP-MGM), which accounts for component-specific degradation behaviour of biodegradable waste fractions (Kumar et al., 2026). Municipal solid waste (MSW) generation data over five years were derived for Bengaluru, India, assuming a per-capita waste generation rate of 0.43 kg and a population of 1.44 million growing annually at 2.67% (World Population Review, 2025). The yearly population growth and the MSW generated are given in Table 9.1. Based on current disposal practices, approximately 60% of the total MSW generated was assumed to be disposed of in OD or SLF. The overall biodegradable fraction of MSW was taken as 60%, further distributed as 60% food waste, 20% yard waste, 10% paper waste, and 10% textile waste. Methane generation was calculated using annual MSW deposition rates. The MCMP-MGM formulation is provided in Eq. 1. For scenarios involving leachate recirculation, decay rates were assumed to be three times those under conventional landfill conditions.

$$Q_{CH_4} = \sum_{c=1}^{4} \sum_{i=0}^{t_{1c}} \sum_{j=0}^{0.9} \frac{M_{i,c}}{10} k_{c,1} L_{0,c} e^{k_{c,1} t_{i,j}} + \sum_{c=1}^{4} \sum_{i=t_{1c}}^{t_{2c}} \sum_{j=0}^{0.9} \frac{M_{i,c}}{10} k_{c,2} L_{0,c} e^{-k_{c,2} t_{i,j}} + \sum_{c=1}^{4} \sum_{i=t_{2c}}^{t_{3c}} \sum_{j=0}^{0.9} \frac{M_{i,c}}{10} k_{c,3} L_{0,c} e^{-k_{c,3} t_{i,j}} \quad (9.1)$$

Table 9.1 Population growth and the MSW landfilled for 5 years.

Year	Population (G_r @ 2.67)	MSW (tons)
1	14400000	1356048
2	14784480	1392254
3	15179225	1429428
4	15584510	1467593
5	16000617	1506778

Year	Population (G_r @ 2.67)	MSW (tons)
Total		71,52,102

9.2.2 Estimation of leachate generation

Besides methane emissions, leachate emissions from OD or SLF are also crucial in analysing the environmental impact of OD or SLF. The estimation of leachate volume is based on the rainfall and landfill area. OD and SLF's infiltration coefficient (C) are 0.5 and 0.3, respectively (Abunama et al., 2021; Aljaradin, 2013; Fellner & Brunner, 2010). The area (A) of the landfill is calculated based on the average height and density of MSW in Bengaluru, which are approximately 20 m and 850 kg/m³, respectively. Bengaluru's average annual rainfall (P) is around 900 mm (Karthik et al., 2024). Table 9.2 shows the leachate generated per year from OD and SLF. Eq. 2 is used to calculate the annual leachate volume generated for OD and SLF.

$$V_L = \frac{P * A * C}{1000} \tag{9.2}$$

Table 9.2 The leachate generated per year from OD and SLF

	OD	SLF_LT	SLF_LR
Leachate generation (m^3/year)	189303	180596	180596
Leachate generated (L/ton)	450	430	227

9.2.3 Life Cycle Assessment (LCA)

The LCA is a data-driven methodology that follows the ISO 14040 and ISO 14044 standards, ensuring a systematic and standardised approach (ISO, 2006) for evaluating the environmental impact of a product or process throughout its life cycle. The LCA involves four key phases: goal and scope definition, inventory analysis, impact assessment, and interpretation.

9.2.3.1 Goal and scope

One of the study's goals was to estimate the environmental impact of various scenarios for MSW disposal in open dumps or sanitary landfills, with or without LFG utilisation as a by-product of anaerobic digestion of OFMSW. Specifically, six scenarios were considered based on the most common MSW disposal practice in OD and SLF in India:

- **Scenario 1:** Open Dump
- **Scenario 2:** Sanitary landfill with leachate treatment
- **Scenario 3:** Sanitary landfill with leachate recirculation and LFG flaring

- **Scenario 4:** Sanitary landfill with leachate recirculation and electricity generation from LFG
- **Scenario 5a:** Sanitary landfill with leachate recirculation and bioCNG (BCNG) used as vehicle fuel
- **Scenario 5b:** Sanitary landfill with leachate recirculation and bioCNG (BCNG) used as cooking fuel

The analysis was performed using SimaPro software (version 10.2.0.2), a widely recognised tool for LCA studies that integrates comprehensive databases, such as Ecoinvent v3.11, and utilises impact assessment methods like ReCiPe 2016 (H). The Life Cycle Assessment (LCA) was conducted to evaluate and compare the environmental impacts of six different waste management scenarios. The system boundary of treatment is shown in Fig. 1, which follows a cradle-to-grave approach. Credits were applied for the substitution of conventional sources of energy, such as coal-based electricity, the use of diesel as vehicle fuel, and the use of LPG as cooking fuel.

9.2.3.2 Scenario description

- ***Open Dumping (S1)***

The supply chain begins with the collection and transportation of MSW to the open dumpsite area. The LFG generated is calculated using the multicomponent multiphase methane generation model (MCMP-MGM), which considers different biodegradable waste components of MSW. The LFG generated in the scenario is completely released into the atmosphere. The leachate generated in the landfill is also assumed to be released into the groundwater in this scenario. The leachate volume is calculated based on the average rainfall data and the infiltration coefficient. The OD is the worst-case scenario in the present study. All the comparisons are made with respect to this scenario. The relevant inventory data of this system are presented in Table 9.3. Fig. 9.1a shows the system boundary of the open dumpsite facility.

- ***Sanitary landfills with leachate treatment (SLF_LT) (S2)***

Sanitary landfills (SLF) are scientifically designed to isolate the disposed MSW from the ground surface and the atmosphere. The barriers isolate the waste in this scenario at the base and top of the landfills. In this scenario, LFG produced is calculated using the same method as in the OD scenario, and the amount of LFG produced is the same. The methane generated in this scenario is vented using the passive venting system. Some of the LFG is oxidised in the landfill covers of SLF. The oxidation (OX) percentage is assumed to be 10% in the current analysis. Fig. 9.1b represents the boundary system diagram for S2. The leachate generation in the SLF is drastically reduced due to the presence of the landfill cover at the top, which reduces the infiltration of rainwater into the waste, resulting in less volume of leachate generation. The infiltration coefficient for SLF is taken to be 0.3. The quality of leachate generated is also different from that of OD leachate, as shown in Table 2. The generated leachate is assumed to be treated to the safe disposal limit in a water body. The electricity requirement for treating leachate is factored into the analysis. Even with the best base liners, over time, punctures appear in the liner system of SLF, allowing a considerable volume of leachate to leak through these puncture holes. The leachate leakage through the puncture is assumed to be 10% of the volume of leachate generated in the current analysis. The relevant inventory data for this scenario are presented in Table 9.3.

- ***Sanitary landfill with leachate recirculation and landfill gas flaring (SLF_LR_F) (S3)***

The supply chain begins with the collection and transportation of MSW to the sanitary landfill facility. In this scenario, the leachate generated in the landfill is recirculated back into the landfill to enhance the degradation process. This method of rapidly decomposing MSW is termed bioremediation of landfills. The decay rates of different biodegradable waste components are assumed to be 4-5 times the usual case for calculating methane generated. The generated methane is directly transported via a basic piping system to a flaring unit. The LFG recovery efficiency is assumed to be 80%, and surface emission is considered to be 10% for this analysis. The system boundary of S3 is illustrated in Fig. 9.1c. The leachate volume generated in sanitary landfills is assumed to be constant across all scenarios. The leachate leakage is considered to be at 5% for analysis in this scenario. While this approach does not utilise the energy potential of the biogas, it serves as a method for reducing waste volume, controlling odours, and mitigating the environmental impact of methane emissions by converting them to carbon dioxide. The relevant inventory data of this system are presented in Table 9.3. This list did not include all the materials used. Some materials were neglected due to a lack of background information in databases or the small amount consumed.

- ***Sanitary Landfill with leachate recirculation and electricity generation (SLF_LR_ELE) (S4)***

In this scenario, LFG produced from landfill is converted into electricity using internal combustion engines. This scenario is also based on the bioremediation process. Fig. 9.1d shows the system boundary of S4. The relevant inventory data for this scenario are presented in Table 3. A key assumption for Scenario 4 is that the electricity generated from LFG is supplied to the grid, replacing an equivalent amount of electricity that would otherwise be produced from coal-based power plants. This substitution forms the basis for the environmental credits applied in this scenario. All other processes remain as in scenario 3.

- ***Sanitary Landfill with leachate recirculation and BioCNG generation (SLF_LR_BCNG) (S5a & S5b)***

In this scenario, the LFG generated from landfilled MSW is collected, which then undergoes purification and compression to create bio-compressed natural gas (BCNG). This BCNG can subsequently be utilised as a) vehicle fuel (VF) or b) cooking fuel (CF) (Fig. 9.1). The system boundary of S5 is shown in (Fig. 9.1e). Scenario 5 is divided into two sub-scenarios, S5a and S5b, based on BCNG utilisation as VF or CF, respectively. The key environmental advantage of these scenarios is the replacement of diesel and LPG for S5a and S5b, respectively. This substitution directly contributes to reduced reliance on fossil fuels and lower associated emissions. The relevant inventory data for this scenario are presented in Table 9.3.

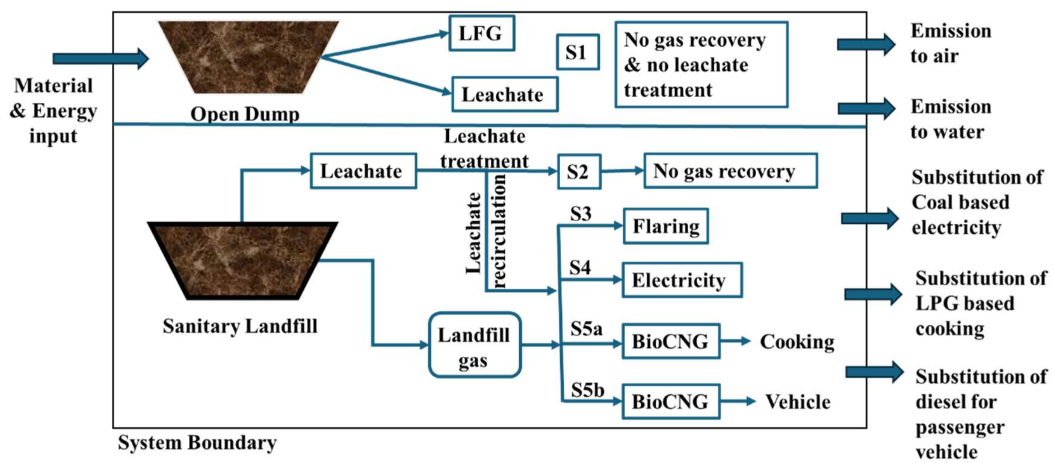


Fig. 9.1 System boundary of the different scenarios for life cycle assessment, a) Open dumping, b) Sanitary landfill with leachate treatment, c) Sanitary landfill with leachate recirculation and LFG flaring, d) Sanitary landfill with leachate recirculation and electricity generation from LFG, e) Sanitary landfill with leachate recirculation and bioCNG (BCNG) used as vehicle fuel or as cooking fuel

Table 9.3 Inventory data for emissions from different landfilling scenarios of MSW for LCA analysis (per functional unit) (S1: Open dump; S2: Sanitary landfill with leachate treatment, S3: Sanitary landfill with leachate recirculation with LFG flaring, S4: Sanitary landfill with leachate recirculation with electricity production, S5a: bio-CNG production for vehicle fuel, S5b: Bio-CNG production for bottled cooking fuel)

Input	**Units**	**S1**	**S2**	**S3**	**S4**	**S5a**	**S5b**	**Comments**
Raw material	tons	1	1	1	1	1	1	
Transportation	km	25	25	25	25	25	25	
Electricity	kWh/m^3	-	0.3	0.3	0.3	0.3	0.3	Leachate treatment or recirculation
Outputs								
Methane	m^3	42.1	42.1	46.4	46.4	46.4	46.4	Calculated using MCMP-MGM (*Kumar et al., 2025*)
Leachate	L	450	429	227	227	227	227	Calculated for 17 years for S1 and S2, and for a period of 9 years for all other scenarios, for an average rainfall of 900 mm.
Emissions to the air								
Surface emission from Landfill								
Methane	kg	27.6 5	24.89	3.05	3.05	3.05	3.05	10% oxidation of CH_4 in cover (*Chanton et al., 2009),* except for S1 and 80% of gas recovery for cases S3, S4, S5a and S5b
From biogas flaring								
Methane (CH_4)	kg	-	-	1.22	-	-	-	Flare efficiency to be 99.5% (Aereon, 2022)
Carbon dioxide (CO_2)	kg	-	-	63.75	-	-	-	Considered to be biogenic

From biogas combustion for electricity								
Methane (CH_4)	kg	-	-	-	0.102	-	-	CH_4 emission of 1.16 g/kWh (Kristensen et al., 2004)
Carbon dioxide (CO_2)	kg	-	-	-	90	-	-	Considered to be biogenic
Carbon monoxide (CO)	kg	-	-	-	0.09	-	-	CO emission of 1 g/kWh (Kristensen et al., 2004)
Dinitrogen monoxide (N_2O)	mg	-	-	-	0.15	-	-	N_2O emission of 0.0025 g/kWh (Kristensen et al., 2004)
From the Purification and compression unit								
Methane (CH_4)	kg	-	-	-	-	1.6	1.6	Purification loss: 7% *(based on survey taken from experts working in the field);* and 0.075% loss from compression unit (Singh and Kalamdhad, 2022a)
From the Fuel station								
Methane (CH_4)	kg					0.002		Assuming 0.01% loss from the Fuel station (Singh and Kalamdhad, 2022a)
From bio-CNG usage as a vehicle fuel (Tailpipe emission)								

Methane (CH_4)	kg					0.102		Assuming tailpipe emission to be 0.48% (Singh and Kalamdhad, 2022a)
Emission to water								
COD	kg/m^3	8	4	4	4	4	4	
BOD	kg/m^3	4.5	0.8	0.8	0.8	0.8	0.8	
NH_3	kg/m^3	0.4	1.5	1.5	1.5	1.5	1.5	
NO_3	kg/m^3	0.1	0.08	0.08	0.08	0.08	0.08	
PO_4	kg/m^3	0.05	0.007	0.007	0.007	0.007	0.007	
Cl	kg/m^3	4	2	2	2	2	2	*Lindamulla et al., 2022, Hussain et al., 2025*
Cr(vi)	kg/m^3	0.002	0.0005	0.0005	0.0005	0.0005	0.0005	
VOC	kg/m^3	0.004	0.0015	0.0015	0.0015	0.0015	0.0015	
<u>Offset</u>								
Fuel Replacement								
Coal-based electricity	kWh	-	-	-	88	-	-	Emission loss is to taken as 2%, engine efficiency as 25%, LHV of biogas as 5.56 kWh/m^3 (Hakawati et al., 2017; Singh and Kalamdhad, 2022b)
Cooking Fuel (LPG)	kg	-	-	-	-	-	23	Assuming 1 m^3 of biogas is equivalent to 0.45 kg of LPG (Cañote et al., 2021). LPG

								is 35% propane and 65% butane (Elgas, 2023)
Diesel	L	-	-	-	-	26.2	-	Bio-CNG available: 22 kg *(calculated)*; Fuel efficiency - Bio-CNG: 24 km/kg. (Singh and Kalamdhad, 2022a)
Emission savings during LPG usage								
Propane	kg	-	-	-	-	-	0.02	Assuming unburnt propane during use is 0.03% *(calculated)*
Butane	kg	-	-	-	-	-	0.05	Assuming unburnt butane during use is 0.03% *(calculated)*
Carbon dioxide (CO_2)	kg	-	-	-	-	-	68.77	1 kg of LPG combustion releases 2.99 kg of CO_2 *(calculated)*
Emission savings during diesel usage								
Methane (CH_4)	gm	-	-	-	-	2.84	-	CH_4 emission of 0.13 g/kg (Singh and Kalamdhad, 2022a)
Carbon dioxide (CO_2)	kg	-	-	-	-	70	-	CO_2 emission of 3186 g/kg (Singh and Kalamdhad, 2022a)
Dinitrogen monoxide (N_2O)	gm	-	-	-	-	0.57	-	N_2O emission of 0.26 g/kg (Singh and Kalamdhad, 2022a)

9.2.3.3 Life cycle inventory (LCI)

Inventory data were collected from site-specific studies, government reports, literature sources, and primary data from plant operators. These included waste composition, energy consumption, leachate generation and treatment data, flare gas composition, engine efficiency, electricity grid mix, and bio-CNG production rates. Background data for processes were obtained from the ecoinvent 3.11 database.

9.2.3.4 Life cycle impact assessment (LCIA)

In SimaPro, each scenario was modelled using process networks to reflect the waste flow, emissions, material and energy inputs, and recovery pathways. OD was modelled with high methane and leachate emissions due to anaerobic degradation. SLF_LT included engineered barriers and gas capture systems for passive venting. SLF_LR_F assumed improved methane recovery with flaring, whereas SLF_LR_ELE and SLF_LR_BCNG models incorporated energy recovery units that produced electricity or bio-CNG, respectively. For the impact assessment phase, the ReCiPe 2016 method was selected due to its robust midpoint indicators across environmental categories, including climate change, terrestrial acidification, freshwater eutrophication, and fossil depletion (Huijbregts et al., 2017). The mid-point impact categories considered in this study are global warming potential (GW), terrestrial acidification (TA), freshwater eutrophication (FE), terrestrial ecotoxicity (TE), freshwater ecotoxicity (FET), human carcinogenic toxicity (HCT), human non-carcinogenic toxicity (HNCT), mineral resource scarcity (MRS), and fossil resource scarcity (FRS). The endpoint impact assessment was performed using the ReCiPe 2016 Endpoint (H) v1.11 method with the World (2010) H/A perspective. This method converts midpoint results into damage categories corresponding to three areas of protection: human health, ecosystem quality, and resource scarcity. Under this framework, normalisation expresses the quantified damage in each category relative to the global per-capita environmental burden for the year 2100. Subsequently, weighting factors—400 for human health, 400 for ecosystem quality, and 200 for resource scarcity—are applied to aggregate the normalised damages into a single endpoint score, expressed in points (Pt). The results were visualised through comparative bar charts and contribution analyses.

9.2.4 Economic Assessment

The section outlines the methodologies for conducting the economic analysis of all scenarios. The current work adapts the approach commonly used for performing economic assessment of process plants (Peters et al., 2003). The key indicators included net present value (NPV) (eq.

(3)), internal rate of return (IRR) (eq. (4)), and payback period (eq. (5)), calculated over the lifespan of the project based on 90% cumulative gas generation time with a 15% discount rate (Pasciucco et al., 2023; Singh & Kalamdhad, 2022a). The economic analysis evaluated all scenarios except open dumping, including various economic components such as land requirements, site construction and operation, transportation of MSW to the site, leachate treatment, Leachate recirculation, gas collection, flaring, electricity generation, bio-CNG production, and upgradation. Revenue streams included electricity generation in S4 and bio-CNG used as VF and CF in S5a and S5b, respectively. The capital expenditure (CAPEX) and operational expenditure (OPEX) data for various components are calculated in accordance with the literature. The capital cost is calculated using the cost scaling factor based on the capacity method considered in the present work. The detailed economic analysis approach employed in Mehta et al. (2018) is applied in the present work to calculate the economics of different components for five scenarios, excluding the open dumping scenarios. The estimated cost is adjusted for inflation, based on the base year of 2016, as reported by Mehta et al. (2018). All produced quantities of electricity and BCNG are assumed to be fully sold. The financial analysis assumes a BCNG procurement price of ₹77.4/kg (US $0.87/kg) for gas purified to IS 16087:2016 specifications and compressed to 250 bars, excluding GST as vehicle fuel, which aligns with a retail price band of ₹80.01–₹85/kg as reported by MoPNG (2025). The procurement cost of BCNG as cooking fuel is assumed to be equivalent to that of PNG at ₹68.75/kg, excluding GST (PNGRB 2025). The rate of electricity is taken as ₹7/kWh. The revenue is also generated for households or firms in the form of a garbage tax. These taxes vary depending on the size and type of establishment, ranging from INR 10 to INR 400 per month for household areas of 600 sqft to 4000 sqft (The New Indian Express, 2025). The yearly estimated revenue collection is at INR 7000 million (Angel One / Deccan Herald, 2025). The revenues in the form of taxes are used towards the development of a landfill energy project. A 50% tax utilisation is assumed for energy project scenarios, while 30% and 20% of the total tax are assumed for flaring (S3) and sanitary landfill with leachate treatment (S2) scenarios, respectively. The revenue from the sale of carbon credits resulting from the reduction of GW compared to OD is also included in the economic analysis. The rate of carbon credit was set at INR 880/ ton CO_2, which aligns with average voluntary carbon market rates often cited in sustainability and agricultural systems research (Elwakeel et al., 2025). The reduction in GW from each case was used to calculate the revenue from carbon credits. Finally, the total cost is calculated per ton of MSW by subtracting total revenue from the total investment for each scenario. The data for economic analysis are presented in Table 9.4.

Table 9.4 Data for economic analysis of different landfilling Scenarios for 1-ton MSW

Scenarios	**S2**	**S3**	**S4**	**S5a**	**S5b**
Components Cost (INR /ton MSW)					
Land	69	69	69	69	69
Construction and Operation	234	234	234	234	234
Transportation of MSW	324	324	324	324	324
Leachate Treatment	626	-	-	-	-
Leachate recirculation	-	553	553	553	553
Flaring	-	765	-	-	-
Electricity	-	-	1238	-	-
BioCNG Upgradation	-	-	-	3021	3021
Revenue Details					
Garbage tax (INR /ton MSW)	978	1468	2447	2447	2447
Electricity Production capacity (kWh/ton MSW)	-	-	152	-	-
BioCNG Production (kg//ton MSW)	-	-	-	30	30
Cost of electricity (₹/kWh)	-	-	7	-	-
Cost of BioCNG as Vehicle Fuel (INR/kg)	-	-	-	77.40	-
Cost of BioCNG as Cooking Fuel (INR/kg)	-	-	-	-	69
Carbon Credit (INR/t CO_2-eq)	880	880	880	880	880
CO_2 reduction from S1 (t CO_2-eq)	0.12	1.4	1.5	1.4	1.4
Total cost_w/o tax_w/o_CC	1253	1945	1356	1863	2125
Total cost_w/o tax_w_CC	1113	760	45	647	911
Total cost_w_tax_w/o_CC	274	476	-1091	-583	-322
Total_w_tax_w_CC	134	-708	-2402	-1800	-1536

$$NPV = -initial\ cost + \sum_{i=1}^{n} \frac{Net\ cash\ flow}{(1+r)^i} \quad (3)$$

$$NPV = 0 = -initial\ cost + \sum_{i=1}^{n} \frac{Net\ cash\ flow}{(1+IRR)^i} \quad (4)$$

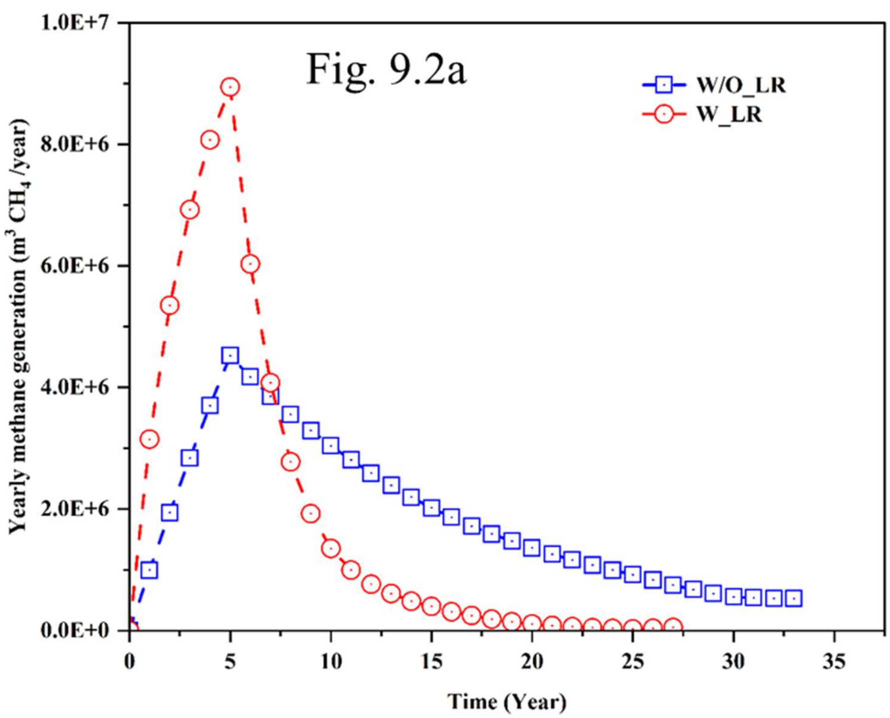
$$Payback\ period = \frac{Total\ initial\ investment}{Yearly\ cash\ flow} \quad (5)$$

Where r is the discount rate (taken as 15%), n is the lifespan in years (taken as 17 years for S2 and 9 years for all other scenarios), and IRR is the internal rate of return

9.3 Result and Discussion

9.3.1 Methane gas generation

(Fig. 9.2a) shows the yearly methane gas generation for OD or SLF_LT and SLF with leachate recirculation. The peak methane generation for OD and SLF_LT is 4.34E06 m^3/year, and for SLF_LR, it is 9.23E06 m^3/year. The peak gas generation occurs next to the final year of waste placement for both cases. The peak methane generation in leachate recirculation scenarios is almost 2.27 times that of scenarios with no leachate recirculation due to the high degradation rate in bioremediated landfills.



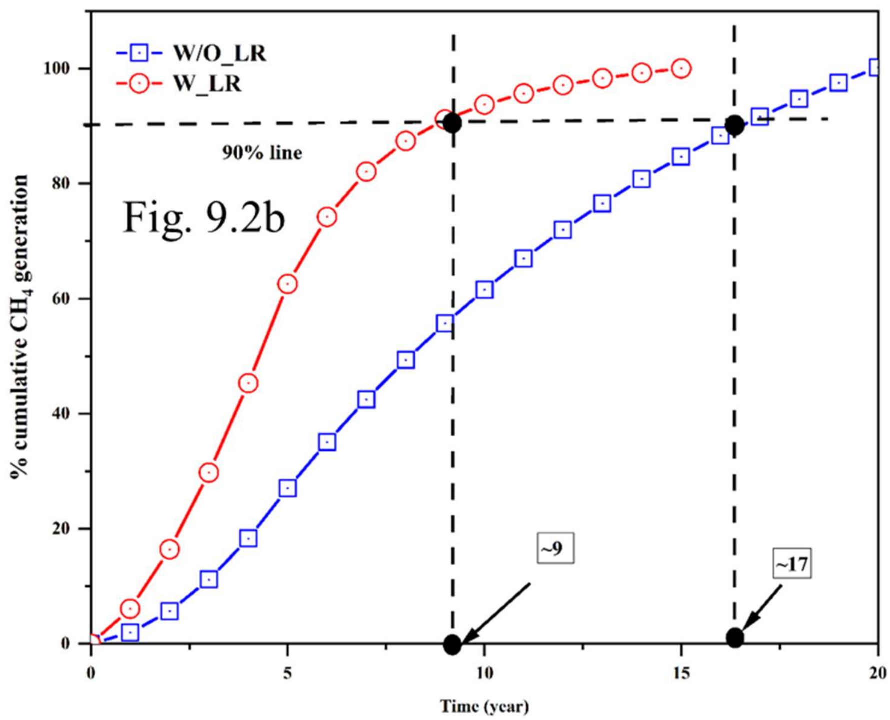


Fig. 9.2 Methane generation from OD (W/O_LR) and SLF (W_LR), a) Yearly methane generation rate, b) Cumulative percentage methane generation

(Fig. 9.2b) shows the cumulative methane generation for the scenarios without LR (S1 and S2) and with LR (S2, S4, S5a and S5b). The cumulative methane generation over 17 years is 3.17E07 m^3 for S1 and S2, representing 90% of the cumulative methane generation. For scenarios without LR, 90% of cumulative methane generation is approximately 3.55E07 m^3 over a period of 9 years. For the LCA computation, the 90% cumulative gas generation is considered to estimate methane for all the scenarios. In Fig. 9.2b, the horizontal dotted line shows the 90% cumulative methane generation. 90% of the cumulative methane is generated within 9 years for scenarios with LR and in 17 years for scenarios without LR. The operational period of the facilities is based on a 90% cumulative methane generation.

9.3.2 Leachate generation

The volume of leachate generated for OD and SLF per year is calculated using Eq. 9.2 and is given in Table 9.2. In the OD (S1) case, the complete volume of leachate generated is assumed to be emitted to water due to the absence of a base liner at the disposal site. In the case of sanitary landfills, the leachate volume generated is either treated (S2) or recirculated back into the landfills (S3, S4, S5a and S5b). In the case of SLF, leachate leakage from the base liners, due to punctures and tears, also accounts for 10% of the volume generated by emissions to water sources.

9.3.3 Life cycle assessment (LCA)

9.3.3.1 Global warming

The global warming (GW) of an open dumpsite facility (S1) is presented in (Fig. 9.3a). The results highlight the main contributions of various activities, with surface emissions making the most significant contribution to gross emissions (or total without credit). Transportation activity contributes significantly less than surface emissions from the dumpsite. The individual process contribution stands at 6.5 kg CO_2-eq and 1,513.5 kg CO_2-eq for the transportation of MSW and surface emission, respectively. Ultimately, the gross GW for scenario 1 stands at 1520 kg CO_2-eq/ton MSW (represented as total without credit) in (Fig. 9.3a). As there are no mitigation strategies adopted, this scenario represents the worst case.

In the case of a sanitary landfill with leachate treatment (S2), there are three modes of GW emission: the transportation of MSW to the site, surface emissions from passive methane venting, and the electricity used in leachate treatment. It is assumed that the leachate is treated to its safe limit for disposal on land or any water bodies. The GW contributions from each process are 6.5 kg CO_2-eq, 1353.4 kg CO_2-eq, and 1.04 kg CO_2-eq, respectively, and are presented in (Fig. 9.3b). The surface emission of methane still contributes the most to the GW. The gross GW for scenario 2 is 1361 kg CO_2-eq without any credit for GW reduction. This option of handling MSW has a similar extent of GW compared to S1.

In scenario 3, the LFG produced is flared using the flaring system, and the leachate generated is now recirculated back to the landfill for enhanced degradation and reduced leachate treatment costs. There are four modes of GW emission: surface emission of methane from cracks and fissures, transportation of MSW to the site, flaring methane, and the electricity used in the leachate recirculation. The GW contribution from each process stands at 167 kg CO_2-eq, 6.5 kg CO_2-eq, 6.68 kg CO_2-eq and 0.05 kg CO_2-eq, respectively. (Fig. 9.3c) shows the contribution from different modes towards the GW calculation in scenario 2. The gross GW for scenario 2 stands at 127.5 kg CO_2-eq. The electricity used for LR is negligible compared to the overall greenhouse gas emissions from other processes. The GW reduces drastically from 1520 kg CO_2-eq for S1 to just 174 kg CO_2-eq for the current scenario, which involves flaring as the mitigation strategy.

In scenario 4, the LFG is used to produce electricity. There are five modes of GW emission: surface emission of methane from cracks and fissures, transportation of MSW to the site, emissions from internal combustion engines, electricity used in leachate recirculation, and the offset from replacing coal-based electricity. The GW contribution from each process stands at 167 kg CO_2-eq, 6.5 kg CO_2-eq, 4.01 kg CO_2-eq, 0.05 kg CO_2-eq and -141.0 kg CO_2-eq, respectively. (Fig. 9.3d) shows the contribution from different modes to the GW calculation in scenario 2. The total GW without credit stands at 177.6 kg CO_2-eq, which is very comparable to the varying scenario where the total stood at 174 kg CO_2-eq. The gross GW for scenario 2 stands at 29.8 kg CO_2-eq (or Total). This near-neutral GW is primarily driven by the substantial "Electricity offset", which represents avoided emissions from coal-based thermal power plants. The considerable offsets from replacing fossil fuels ensure that the overall system is almost carbon-neutral, highlighting its potential for sustainable waste management and decarbonization of transport. This scenario can be made much more carbon-neutral or even carbon-negative if the surface emissions can be further reduced by providing better final landfill cover.

The result shown in (Fig. 9.3e) is the GW of a sanitary landfill with leachate recirculation, where landfill gas is upgraded to bio-compressed natural gas (bio-CNG) for application as vehicle fuel (scenario 5a). The total gross GW from the scenario is approximately 138 kg CO_2-eq (or Total). In this scenario, there are also five modes of GW emission, namely surface emission of methane from cracks and fissures, transportation of MSW to the site, emissions from BCNG upgradation and compression, the electricity used in the leachate recirculation and the negative GW contribution by the diesel offset by using BCNG as vehicle fuel. The GW contributions from each process are 167 kg CO_2-eq, 6.5 kg CO_2-eq, 124.9 kg CO_2-eq, 0.05 kg CO_2-eq, and -155 kg CO_2-eq, respectively. Like scenario 4, the significant positive contribution in this scenario is from "surface emission". This significant reduction in GW is primarily driven by the substantial "vehicle fuel offset", which represents avoided emissions from displacing diesel fuel-based vehicles with bio-CNG (resulting in savings of 26 L diesel). The considerable offsets from replacing fossil fuels ensure that the overall system is almost carbon-neutral, highlighting its potential for sustainable waste management and decarbonization of transport.

The result shown in (Fig. 9.3f) is the GW of a sanitary landfill with leachate recirculation, where landfill gas is upgraded to bio-compressed natural gas (bio-CNG) for use as cooking fuel (scenario 5b). The total gross GW from the scenario, including credits, is approximately 141 kg CO_2-eq. In this scenario, there are also five modes of GW emission, namely surface emission of methane from cracks and fissures, transportation of MSW to the site, emissions from BCNG upgradation and compression, the electricity used in the leachate recirculation and the negative GW contribution by the LPG offset by using BCNG as cooking fuel. The GW contributions from each process are 167 kg CO_2-eq, 6.5 kg CO_2-eq, 124.9 kg CO_2-eq, 0.05 kg CO_2-eq, and -151.3 kg CO_2-eq, respectively. Like scenario 4, the significant positive contribution in this scenario is from “surface emission”. This significant reduction in GW is primarily driven by the substantial "LPG offset", which represents avoided emissions from displacing LPG-based cooking with bio-CNG. The considerable offsets from replacing fossil fuels ensure that the overall system is almost carbon-neutral, highlighting its potential for sustainable waste management and decarbonization of household cooking.

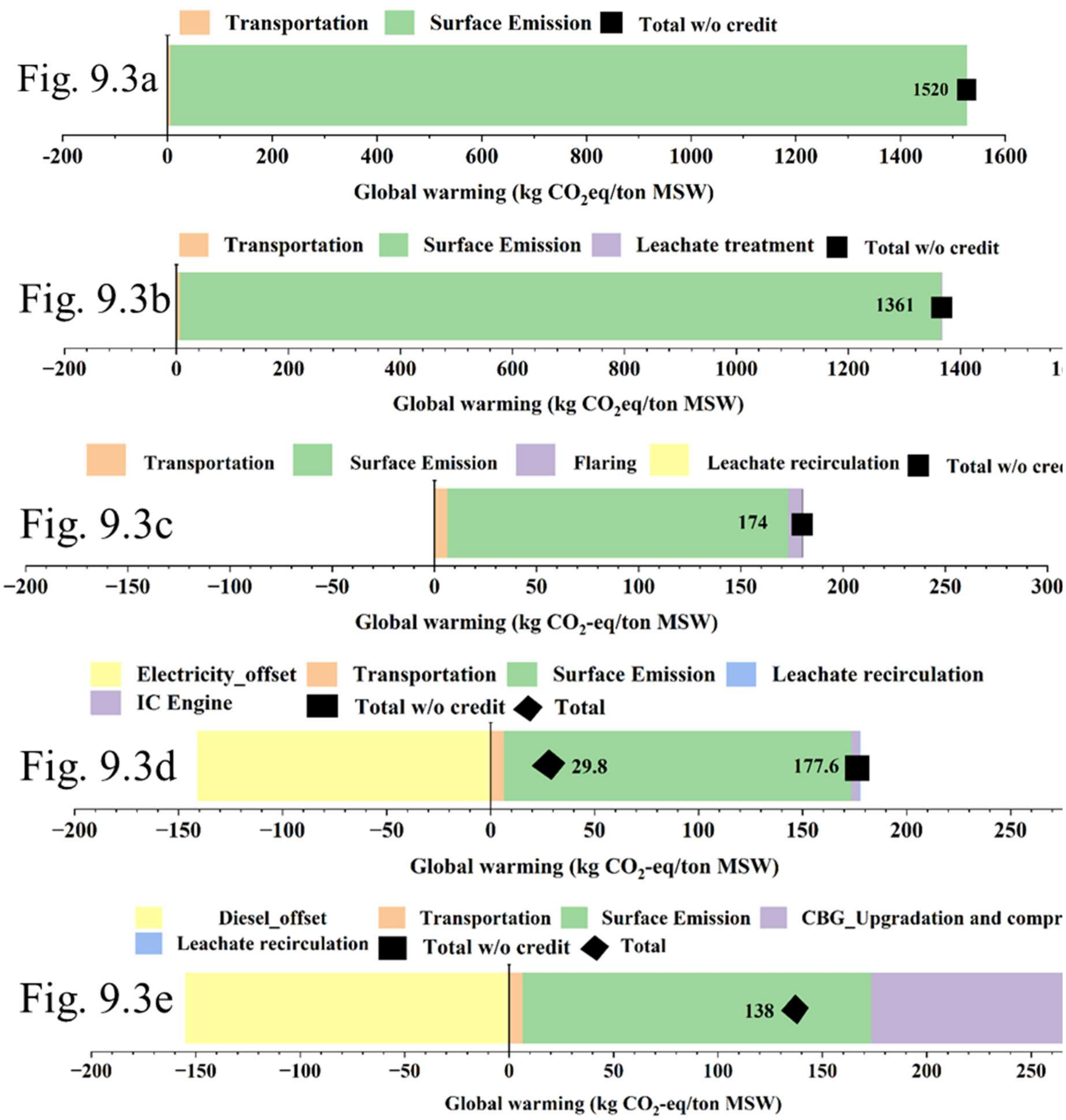


Fig. 9.3f

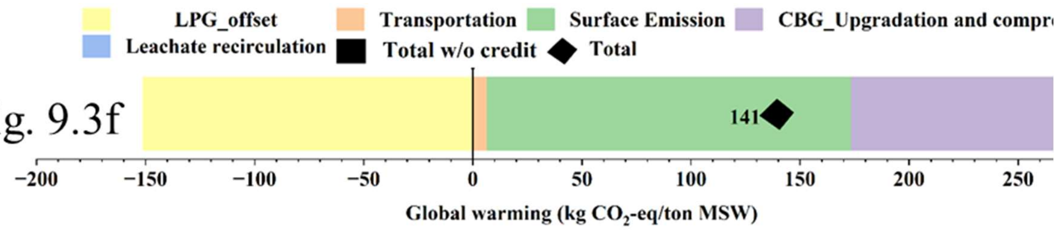


Fig. 9.3 Impact on global warming from different landfilling scenarios a) Open dumping, b) Sanitary landfill with leachate treatment, c) Sanitary landfill with leachate recirculation and LFG flaring, d) Sanitary landfill with leachate recirculation and electricity generation from LFG, e) Sanitary landfill with leachate recirculation and bioCNG (BCNG) used as vehicle fuel, f) Sanitary landfill with leachate recirculation and bioCNG (BCNG) used as cooking fuel

The result shown in (Fig. 9.4) provides a comparative analysis of the GW for different municipal solid waste landfilling scenarios. It clearly shows that all these scenarios result in a net positive GW. The reason behind the net positive GW for scenarios utilising LFG as an energy source is due to the high surface emission of methane from the landfill sites. The GW can be brought down to zero or even negative if the landfill cover provided works efficiently to check fugitive surface emissions. The percentage in Fig. 9.4 represents the reduction in GW of the individual scenarios compared to scenario 1, which serves as the base scenario for comparison. Scenario 2 reduces the GW by 10% compared to scenario 1. The maximum reduction in greenhouse gas emissions is achieved by adopting scenario 4, where landfill gas is directly used to generate electricity. A reduction of around 98% in GW is achieved by adopting scenario 4. It is worth noting that even scenario 5 is a better option in terms of GW reduction compared to scenario 1. The decrease in GW is around 80.9%. The lower reduction achieved in scenario 5 is due to the energy-intensive process of BCNG upgradation and compression. The most significant GW reduction is achieved when biogas is converted to electricity and displaces coal-based electricity, leading to a net GW of 29.8 kg CO_2-eq. Utilising LFG as vehicle fuel gives a GW of 138 kg CO_2-eq, significantly less than that of open dumping. It should be noted that the ability to purify and compress the LFG as BCNG opens avenues for commercial distribution to areas, creating a high-value, marketable product that improves energy access. Furthermore, this comparison highlights that energy recovery and fossil fuel displacement are crucial for maximising the climate change mitigation potential of anaerobic digestion plants, with electricity generation offering the highest greenhouse gas reduction.

The findings of the current study can be compared with those of various previous similar studies, such as Babu et al. (2014), Sharma and Chandel (2017), and Mehta et al. (2018). Since the results are highly dependent on the waste composition and various regional factors, a direct comparison with the results from other countries may not be appropriate. Sharma and Chandel (2017) focused solely on the LCA, whereas Mehta et al. (2018) also examined the LCA in conjunction with the economics of the various scenarios. They both reported the GW for OD (or a similar scenario) as 1000 kg CO_2-eq and 1240 kg CO_2-eq, respectively, compared to the 1520 kg CO_2-eq calculated here. The difference can be attributed to the fact that the decay rates were assumed to be the same for OD and SLF when calculating the methane generation. Additionally, the results reported in Babu et al. (2014) differ significantly from those of the current study. The reported GW stood at 16964 kg CO_2-eq for OD as compared to just 1520 kg CO_2-eq in the present analysis. One key difference lies in the calculation of GW for just 20 years as compared to 100 years in the present study. Mehta et al. (2018) have also considered the S3 presented in the current study. The GW reported value was 844 kg CO_2-eq, compared to 174 kg CO_2-eq in the present study. The high difference can be attributed to the fact that Mehta et al. (2018) included biogenic CO_2 emissions due to CH_4 conversion during flaring in their calculation, which resulted in very high GW values. Additionally, the present study assumes only 90% of the cumulative methane is generated by the end of the facility's life, resulting in a lower total cumulative methane generation compared to previous studies.

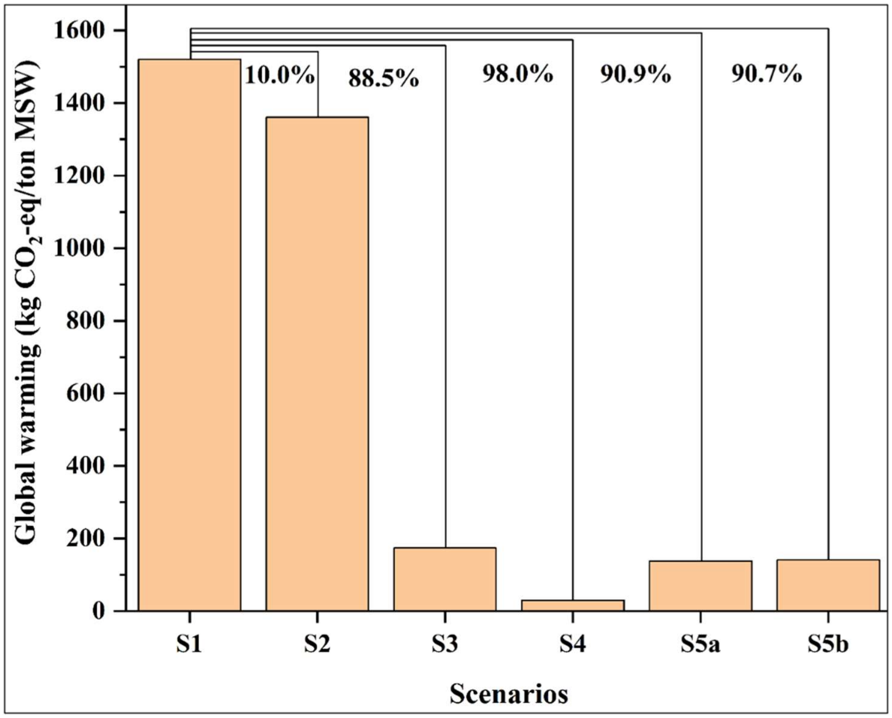


Fig. 9.4 Comparison of global warming of different treatment scenarios of municipal solid waste in dumpsites/landfills

A direct, one-to-one comparison of final impact values across different LCA studies is not only difficult but can also lead to misleading conclusions. LCA results are not universal facts; they reflect the specific assumptions, system boundaries, and contextual conditions defined in each assessment (Ferreira et al., 2019). Because no two LCAs are ever exactly alike, their comparability is inherently constrained (Jayawickrama et al., 2024). Differences in methodological choices such as the functional unit, system boundaries, inventory databases, software tools, and the selected LCIA method mean that even slight variations can result in studies effectively examining different systems or addressing different questions. Consequently, directly comparing outcomes between studies is not methodologically valid (Jayawickrama et al., 2024).

9.3.3.2 Mid-point scores

A consistent trend observed across most impact categories is that energy recovery from landfill gas significantly outperforms straightforward open dumping or passive venting of LFG in sanitary landfills, often leading to better environmental benefits the displacement of conventional energy sources (coal-based electricity, diesel-based vehicle fuels).

Regarding GW, open dumping (S1) has a net positive impact of 1520 kg CO_2-eq., making it the least environmentally favourable option. In contrast, all other energy recovery scenarios yield substantially lower GW values, indicating a significant benefit in mitigating climate change. Landfill gas conversion to electricity, displacing coal-based electricity (S4), demonstrates the most profound reduction, with a remarkable net reduction of -141 kg CO_2-eq in GW. This is primarily due to the high carbon intensity of the coal-based electricity it replaces. Utilisation of BCNG for vehicle fuel (S5a) and cooking fuel also offers considerable benefits of -155 kg CO_2-eq and -151.3 kg CO_2-eq, respectively. Both S5a and S5b scenarios significantly reduce GW compared to open dumping or a simple sanitary landfill. The gross GW reduction in S5a and S5b is less pronounced compared to S4 due to methane losses and the additional energy required for purification and compression processes.

Similar patterns are evident for terrestrial acidification and freshwater eutrophication. Open dumping, sanitary landfill and flaring remain the only scenarios with a net positive contribution to terrestrial acidification (0.010 kg SO_2-eq, .0003 kg SO_2-eq and 0.105 kg SO_2-eq, respectively). In contrast, all energy recovery options result in net benefits, with electricity generation showing the most significant reduction (-0.050 kg SO_2-eq and -0.003 kg SO_2-eq for S4, S5a & S5b, respectively). For freshwater eutrophication, landfill gas-to-electricity generation again exhibits a significant net benefit (-0.01 kg P eq.), while open dumping, sanitary landfill, flaring, and BCNG generation scenarios show minor net positive impacts. This suggests that while energy recovery is broadly beneficial, the specific method and displaced product determine the magnitude of these benefits in relation to different environmental concerns.

For toxicity categories (terrestrial ecotoxicity, freshwater ecotoxicity, human carcinogenic toxicity, human non-carcinogenic toxicity), as well as mineral resource scarcity and fossil resource scarcity, the first two scenarios, including open dumping and sanitary landfill, yield net positive impacts. The freshwater ecotoxicity remains positive for scenarios 3, 4, 5a & 5b, with S4 showing the least freshwater ecotoxicity. All other toxicity parameters remain negative for these three scenarios, indicating the environmental benefits of flaring, electricity generation, and BCNG generation. This widespread benefit across toxicity and resource scarcity indicators is primarily driven by the significant negative contributions from the "energy offset" from electricity or diesel replacement. Among the energy recovery options, electricity generation consistently demonstrates the most critical net benefits compared to the BCNG, reinforcing its overall environmental superiority.

In conclusion, the analysis demonstrates that maximising the environmental benefits of MSW treatment in dumpsites and landfills hinges on effective energy recovery. While all energy recovery scenarios significantly mitigate GW compared to open dumping, the conversion of Landfill gas to electricity offers the most comprehensive environmental benefits across a broad spectrum of mid-point impact categories due to the high environmental burden of the displaced coal-based electricity. Even with additional processing, utilising landfill gas as a purified vehicle fuel still provides substantial environmental advantages by displacing fossil-based alternatives, albeit sometimes with slightly reduced benefits compared to direct utilisation or electricity generation.

9.3.3.3 Endpoint score

This endpoint category analysis provides a crucial perspective on the environmental damages associated with different scenarios considered in the present study, expressed in points (Pt). Unlike midpoint indicators that quantify problem-oriented impacts (e.g., GW, acidification, toxicity, and others), endpoint categories translate these into tangible impacts on human health, ecosystems, and resources as shown in (Fig. 9.5).

The results highlight that electricity generation (scenario 4) is the only scenario consistently leading to a net environmental benefit across all aggregated categories, with a total impact of -4.94 Pt. This benefit is predominantly driven by its substantial negative impact on human health, indicating direct positive effects on human well-being. A small negative impact on ecosystems is also observed.

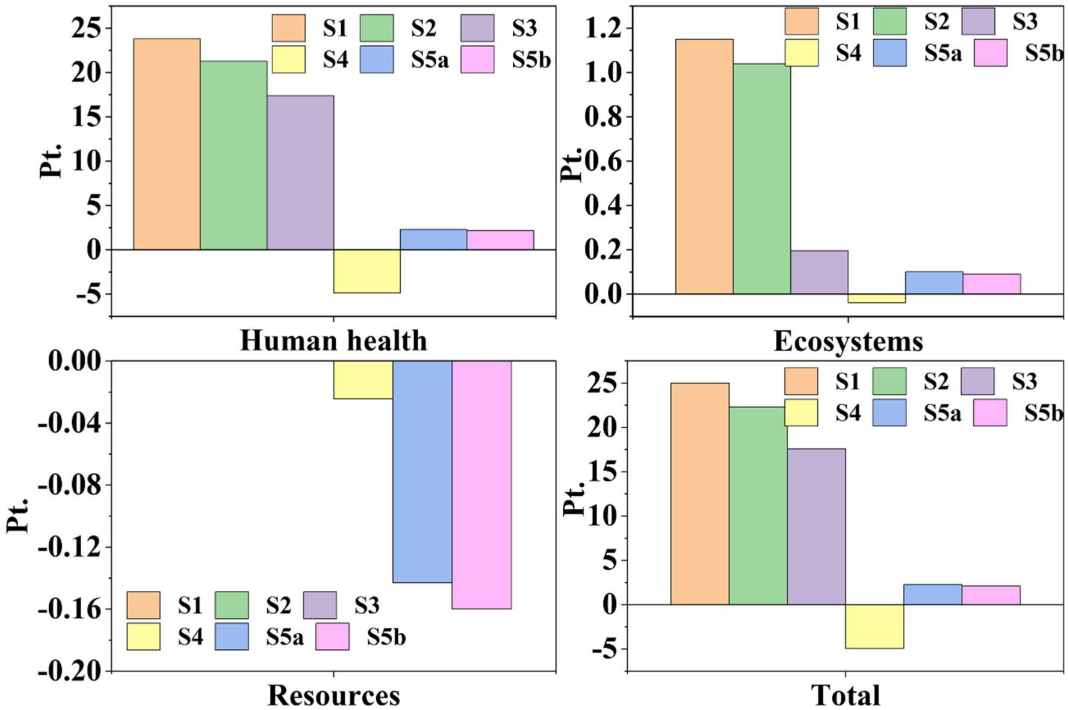


Fig. 9.5 Damage category and single point score of different landfill scenarios

In contrast, all other scenarios yield significant net environmental damage, as indicated by their positive point scores. Open dumping (Scenario 1) emerges as the most environmentally damaging option, demonstrating the most significant overall damage with a total score of 25 Pt. The damage is consistent across all three categories, providing the most substantial impact on human health (23.8 Pt) and ecosystems (1.15 Pt), primarily due to the significantly high-impact emissions from open dumping. Utilising landfill gas as vehicle fuel (scenario 5) also results in net environmental damage (2.12 Pt total), with impacts on human health (2.3 Pt) and ecosystems (0.10 Pt). While this scenario is damaging, its overall performance is less damaging than the first three.

For the resources category, scenarios 4, scenario 5a and 5b, which are energy recovery scenarios, demonstrate net benefits, with landfill gas to BCNG production for cooking fuel (Scenario 5b, -0.16 Pt) showing the highest resource savings, marginally outperforming BCNG production for vehicle fuel generation (scenario 5a, -0.143 Pt), which also contributes to resource savings. S4 shows a net resource saving of 0.03 Pt, which is the least of all the energy recovery scenarios. This divergence from other categories, where electricity was dominant, might reflect the specific resource intensity of the displaced fuels (e.g., diesel vs. LPG vs. coal). In summary, the endpoint analysis highlights the crucial importance of recovering energy from MSW landfills to prevent substantial environmental impacts, especially those affecting human health. Although all energy recovery options provide environmental advantages, electricity generation delivers the most significant overall mitigation, followed by the production of BCNG from purified landfill gas. This highlights that the selected end-use pathway has a considerable influence on the final environmental performance. Ultimately, the positive outcomes stem from the displacement of conventional, more polluting energy sources.

9.3.4 Economic analysis

Open dumping is not considered in this analysis, as it represents the worst-case scenario from an environmental perspective. (Fig. 9.6a) compares the five scenarios from an economic perspective in the current study, considering various revenue sources. The primary revenue sources were taxes, energy sales, and carbon credits. The sale of energy is always included wherever applicable (S4, S5a, and S5b). The cases were studied with and without tax and carbon credit. Scenario 2 illustrates the net revenue deficit condition for all four cases, with a maximum deficit of INR 1,253 per ton of MSW for the case without tax and carbon credit, and a minimum deficit of INR 134 per ton of MSW for the case with tax and carbon credit. As shown in Figure 6, the flaring scenario (S3) yields the highest total cost, approximately INR 1,945 per ton of MSW, when neither the carbon credit nor the tax is considered. In the same scenario, S3 becomes profitable at INR 708 per ton of MSW, considering both tax and carbon credit. Meanwhile, the economics of S4, which include the costs of landfill construction, LFG recovery, and electricity generation, show a revenue surplus of INR 1091 without CC and a surplus of INR 2402 with CC per ton of MSW, with tax included for both cases. Scenario 5a performs better than 5b because of the difference in the rate of the BNG as vehicle fuel (VF) and cooking fuel (CF). BCNG as VF is sold slightly higher at INR 77.4 per kg compared to cooking fuel, which is sold at just INR 68.8 per kg. After accounting for the revenue from carbon credits, all energy recovery scenarios become more economical, with S4 becoming the most profitable scenario, yielding a profit of INR 1,091 per ton of MSW without CC and INR 2,402 per ton of MSW with CC. Without taking carbon credits, none of the energy recovery scenarios from LFG can be profitable.

Fig. 9.6a

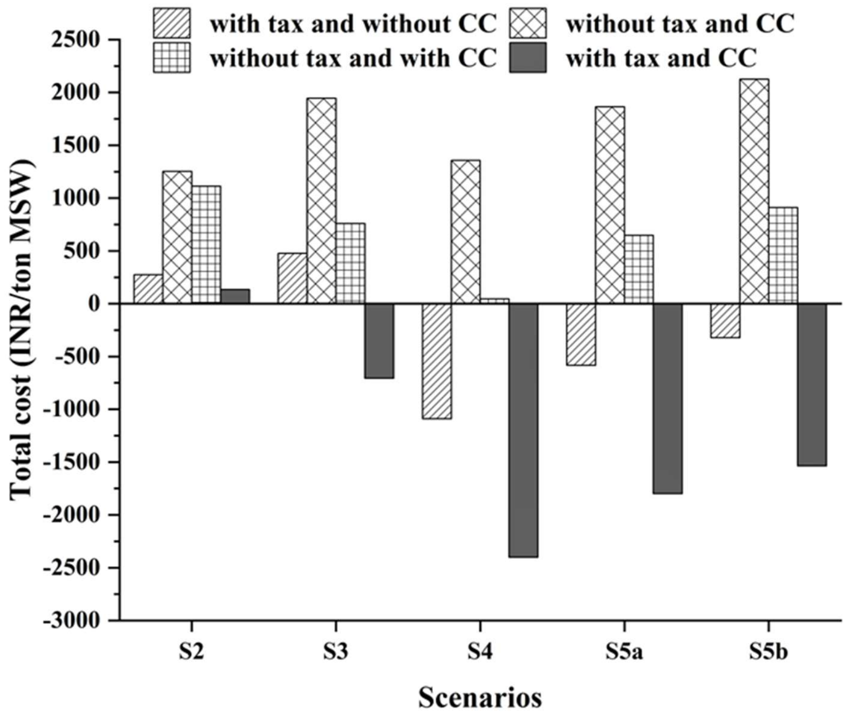


Fig. 9.6b

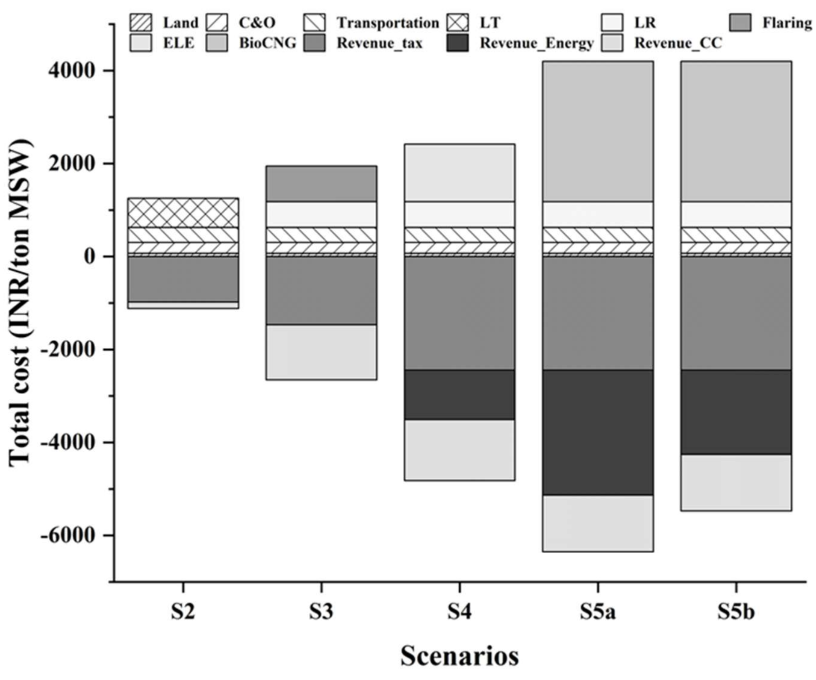


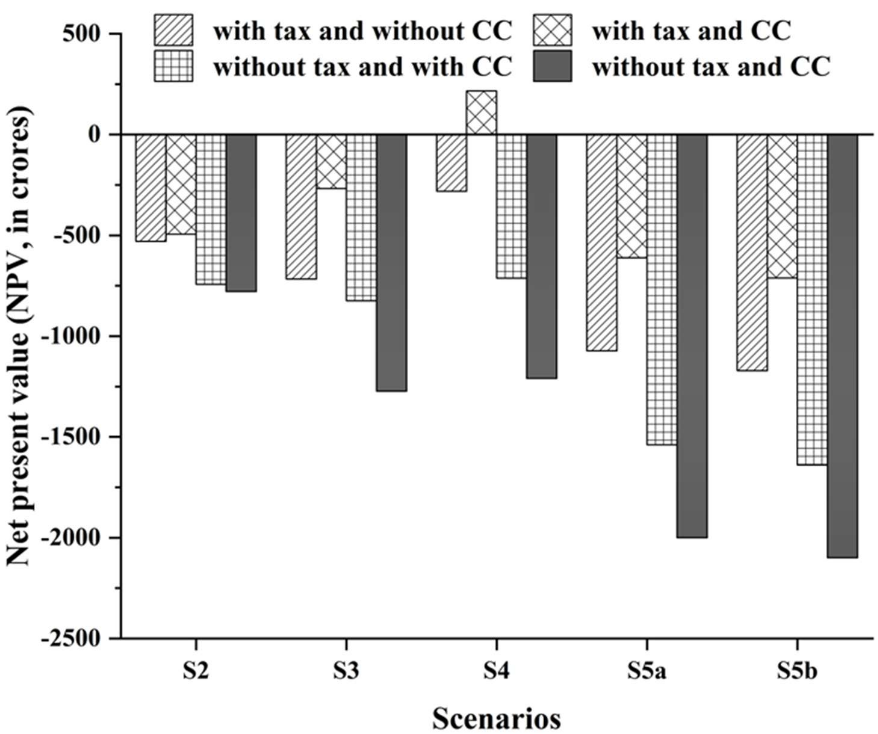
Fig. 9.6 Comparison of the total cost for the management of 1 ton of MSW for six different scenarios, considering different revenue sources (a), Distribution of the cost between components of different landfilling scenarios (b)

It is also essential to understand the distribution of the total cost for each scenario to gain a more detailed picture of the economic trade-off for each scenario. (Fig. 9.6b) shows the distribution of the total cost of each scenario. There are various components for which the cost has been calculated for each scenario, as shown in (Fig. 9.6b). The land acquisition contributes the least of all. The land required for OD was 104 acres compared to 165.3 acres for sanitary landfills. The cost of land for all the sanitary landfill scenarios was INR 69 per ton of MSW, respectively. The transportation cost of MSW remains constant at INR 324 per ton of MSW across all scenarios. In the S2 scenario, leachate treatment accounts for approximately 50% of the total cost at around INR 626 per ton of MSW. Similar studies by Damgaard et al. (2011) and Mehta et al. (2018) demonstrate that leachate treatment accounts for approximately 40% of the total cost. In scenario S3, the flaring unit incurs a significant capital expenditure for its construction, which amounts to approximately INR 765 per ton of MSW. The high cost of the flaring unit is attributed to the shorter operational time in the present study, compared to the longer operation duration reported in the literature (Mehta et al., 2018). The electricity generation facility in S4 accounts for 51% of the total cost. The revenue from the sale of electricity at a rate of INR 7/kWh amounts to approximately INR 1,062 per ton of MSW. The revenue calculated from the reduction of GW by taking carbon credit stood at around INR 1311 per ton of MSW, which is even higher than the revenue from the sale of electricity. Scenarios 5a and 5b are high-energy-demanding scenarios due to the presence of a compression and upgradation unit, which converts LFG to BCNG. The share of the compression and upgradation unit accounts for approximately 72% of the total initial cost, excluding revenue considerations. The revenue generated from selling BCNG as VF and CF stands at INR 2337 and INR 2076 per ton of MSW. There is approximately 12.6% less revenue generated when BCNG is sold as CF compared to VF, due to the high market price of VF. The cost of leachate recirculation was taken at 50% of the leachate treatment cost for the scenarios considered. The tax collection from households and firms, such as the garbage tax, contributes highly towards total revenue. The revenue from the CC for S5a and S5b stands at INR 1216 and INR 1213 per ton of MSW, respectively. The revenues from CC are similar because both scenarios reduce the GW by approximately 90%.

(Fig. 9.7) compares the net present values (NPV) and the payback period for different scenarios under various revenue sources. It is clear from (Fig. 9.7a) that the NPV of S4, considering revenues from taxes, CC, and the sale of fuel, yields a positive NPV of INR 216 crores, indicating the project's viability. All remaining scenarios, regardless of revenue consideration, yield a negative NPV, rendering the project unviable. The next viable option from the NPV perspective is S3, which has an NPV value of INR -267 crores, but at the cost of energy loss.

(Fig. 9.7b) represents the payback period for different scenarios with different revenue sources. Scenario S4 shows the shortest payback period of approximately 4.2 years for the investment, considering all sources of revenue. The same scenario can take up to 9 years to return on payment if tax revenue is neglected. The payback period for S3 can go up to 132 years if only CC is considered, excluding the tax revenue. With tax and CC revenues, S3 will require approximately 16.5 years to recover its investment. The internal rate of return (IRR) was also calculated for each scenario, taking into account all revenue sources. The IRR of all scenarios except S4 was less than the discount rate used in the calculation. The IRR for S4 was approximately 19%, resulting in a positive NPV for this scenario, making it the most viable energy project among all. The analysis shows that the revenue collected as the garbage tax, if used for the energy recovery project from landfill, can yield a positive NPV and a much lower payback period on the investment.

Fig. 9.7a



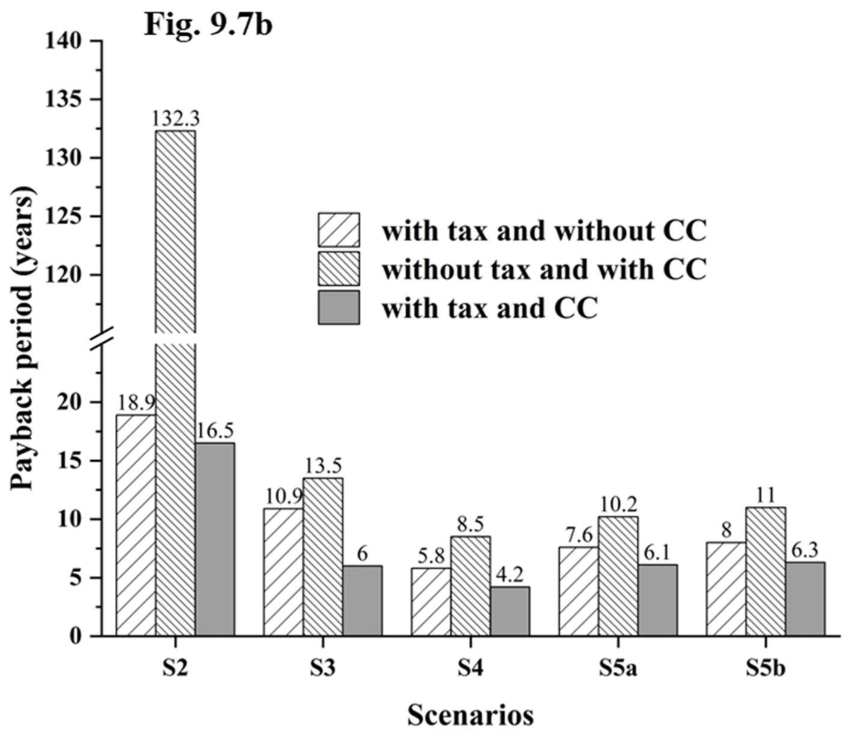


Fig. 9.7 Comparison of net present value (a) and payback period (b) for different landfilling scenarios

9.4 Practical implications

Based on the findings, the following key points should be adopted to enhance the effective use of methane as a renewable energy source from landfills.

- **Avoid open dumping and simple passive venting of LFG from sanitary landfill:** The MSW generated should be disposed of in a sanitary landfill as the first step towards reducing the environmental impact of waste. The LFG generated due to the biodegradation of organics should be tapped and mitigated efficiently. The focus should be on reducing the amount of organic material reaching the landfill site to minimise the LFG generation. The flaring of LFG should be the minimum requirement for reducing the environmental impacts of landfills.
- **Prioritise energy recovery:** Landfill gas flaring should be avoided as it consistently leads to net environmental damage, particularly in global warming (GW) and human health impacts. Instead, focus on energy recovery. While electricity generation offers the most significant overall environmental benefits, particularly in GW reduction and human health, utilising LFG to produce BCNG as vehicle fuel also provides substantial environmental

advantages by displacing fossil fuels. The choice of end-use should consider local energy demands and market conditions.

- **Efficient upgradation technologies of landfill gas:** The present analysis assumes an 8% methane loss during the bio-CNG purification process. Reducing these losses would yield direct environmental benefits while simultaneously improving economic performance by increasing the volume of methane available for sale as fuel. Establishing stringent regulatory limits within operational permitting frameworks is therefore essential. Such regulations should mandate investments in high-efficiency purification and compression technologies, along with regular third-party audits to monitor and minimise methane leakage throughout bio-CNG production and handling.

9.5 Summary

This study confirms that landfill-based energy recovery substantially enhances both the environmental and economic performance of municipal solid waste (MSW) management in India. Open dumping exhibits the highest global warming impact, whereas electricity generation from landfill gas reduces emissions from 1,520 to 29.8 kg CO_2-eq per ton of MSW through avoided coal-based power generation. Bio-CNG production for vehicle and cooking fuel also achieves significant emission reductions, although its environmental performance is lower than that of electricity generation due to the energy-intensive processes involved in upgrading and compression. Endpoint results show that electricity generation is the only scenario with an overall net negative environmental impact. Economic analysis further reinforces its superiority, as this option yields the highest revenue surplus (INR 2,402 per ton of MSW), the shortest payback period (4.2 years), and a positive net present value (INR 216 crore) when carbon credits and tax revenues are included. These findings highlight electricity generation as the most effective pathway for landfill decarbonization, underscoring the critical role of fiscal incentives in enabling sustainable, circular waste management systems in India.

References

Abunama, T., Othman, F., & Tengku Nilam, S. H. (2021). Comparison of landfill leachate generation and pollution potentials in humid and semi-arid climates. *International Journal of Environment and Waste Management, 27*(1), 79–92. https://doi.org/10.1504/IJEWM.2021.112688

Aereon. (2022). Retrofitting Air-Assisted Flares to Attain 99.5% Destruction Efficiency. https://aereon.com/retrofitting-air-assisted-flares-to-attain-99-5-destruction-efficiency/

Aljaradin, M. and Persson, K.M., 2013. Proposed water balance equation for municipal solid waste landfills in Jordan. *Waste management & research*, *31*(10), pp.1028-1034.

Angel One / Deccan Herald (2025). *Bengaluru collects ₹350 crore garbage tax in first two months, target ₹700 crore.* Angel One news, 12 Jun 2025. Available at: https://www.angelone.in/news/market-updates/bengaluru-collects-350-crore-garbage-tax-in-2-months-target-700-crore (Accessed 09 Jan 2026)

Babu, G.S., Lakshmikanthan, P. and Santhosh, L.G., 2014. Life cycle analysis of municipal solid waste (MSW) land disposal options in Bangalore City. In *ICSI 2014: Creating Infrastructure for a Sustainable World* (pp. 795-806).

Cañote, S. J. B., Barros, R. M., Lora, E. E. S., del Olmo, O. A., dos Santos, I. F. S., Piñas, J. A. V., Ribeiro, E. M., de Freitas, J. V. R., & de Castro e Silva, H. L. (2021). Energy and Economic Evaluation of the Production of Biogas from Anaerobic and Aerobic Sludge in Brazil. Waste and Biomass Valorization, 12(2), 947–969. https://doi.org/10.1007/s12649-020-01046-w

Chanton, J.P., Powelson, D.K. and Green, R.B., 2009. Methane oxidation in landfill cover soils, is a 10% default value reasonable?. *Journal of environmental quality*, *38*(2), pp.654-663.

A Strategic Analysis and Planning Responses Applicable to Algeria. *Sustainability*, *16*(16), p.6930.

Clasen, A. P., Agostinho, F., Almeida, C. M. V. B., Liu, G., & Giannetti, B. F. (2024). Advancing towards circular economy: Environmental benefits of an innovative biorefinery for municipal solid waste management. *Sustainable Production and Consumption*, *46*, 571–581. https://doi.org/10.1016/j.spc.2024.03.015

Damgaard, A., Manfredi, S., Merrild, H., Stensøe, S. and Christensen, T.H., 2011. LCA and economic evaluation of landfill leachate and gas technologies. *Waste management*, *31*(7), pp.1532-1541.

Elgas. (2023). LPG Gas Composition: LPG Gas Mixture of Propane & Butane. https://www.elgas.com.au/elgas-knowledge-hub/residential-lpg/lpg-composition/

Elwakeel, A.E., El-Mesery, H.S., Elbeltagi, A., Salem, A., Sabry, A., Saleh, D.I., Moustapha,

Fellner, J., & Brunner, P. H. (2010). Modeling of leachate generation from MSW landfills by a two-dimensional two-domain approach. *Waste Management, 30*(11), 2084–2095. https://doi.org/10.1016/j.wasman.2010.05.019

Ferreira, S. F., Buller, L. S., Berni, M., & Forster-Carneiro, T. (2019). Environmental impact assessment of end-uses of biomethane. Journal of Cleaner Production, 230, 613–621. https://doi.org/10.1016/j.jclepro.2019.05.034

Hakawati, R., Smyth, B. M., McCullough, G., De Rosa, F., & Rooney, D. (2017). What is the most energy efficient route for biogas utilization: Heat, electricity or transport? Applied Energy, 206, 1076–1087. https://doi.org/10.1016/j.apenergy.2017.08.068

Huijbregts, M.A.J., et al. (2017). "ReCiPe 2016: a harmonised life cycle impact assessment method at midpoint and endpoint level." *International Journal of Life Cycle Assessment*, 22, 138–147.

Hussain, A., Deshwal, A., Priyadarshi, M., Pathak, S., Sambandam, G., Chand, S. and Shukla, A.K., 2025. Landfill leachate analysis from selected landfill sites and its impact on groundwater quality, New Delhi, India. *Environment, Development and Sustainability*, *27*(6), pp.12537-12562.

ISO. (2006). *ISO 14040 and ISO 14044: Environmental management–Life cycle assessment–Principles and framework; Requirements and guidelines*. International Organization for Standardization.

Jayawickrama, K., Ruparathna, R., Seth, R., Biswas, N., Hafez, H., & Tam, E. (2024). Challenges and Issues of Life Cycle Assessment of Anaerobic Digestion of Organic Waste. *Environments*, *11*(10), 217. https://doi.org/10.3390/environments11100217

Karthik, V.C., Samuel, B.N. and Hanji, S.S., 2024. Rainfall Trend Analysis in Mysuru and Bengaluru Districts of Karnataka, India. *International Journal of Environment and Climate Change*, *14*(9), pp.139-148.

Kristensen, P. G., Jensen, J. K., Nielsen, M., & Illerup, J. B. (2004). Emission factors for gas fired CHP units < 25 Mw. International Gas Research Conference Proceedings.

Kumar, P., Babu, G.S. and Rao, L., 2026. Improved Methane Estimations from Landfills Using a Multicomponent Multiphase Methane Generation Model Based on Three-Phase Degradation Kinetics. *Journal of Hazardous, Toxic, and Radioactive Waste*, *30*(1), p.04025044.

Lindamulla, L., Nanayakkara, N., Othman, M., Jinadasa, S., Herath, G. and Jegatheesan, V., 2022. Municipal solid waste landfill leachate characteristics and their treatment options in tropical countries. *Current pollution reports*, *8*(3), pp.273-287.

Mehta YD, Shastri Y, Joseph B. Economic analysis and life cycle impact assessment of municipal solid waste (MSW) disposal: A case study of Mumbai, India. *Waste Management & Research: The Journal for a Sustainable Circular Economy*. 2018;36(12):1177-1189. doi:10.1177/0734242X18790354

Pasciucco, F., Francini, G., Pecorini, I., Baccioli, A., Lombardi, L., & Ferrari, L. (2023). Valorization of biogas from the anaerobic co-treatment of sewage sludge and organic waste: Life cycle assessment and life cycle costing of different recovery strategies. Journal of Cleaner Production, 401, 136762. https://doi.org/10.1016/j.jclepro.2023.136762

Petroleum and Natural Gas Regulatory Board (PNGRB). "DPNG & CNG Prices." PNGRB, Government of India, 2025. Available at: **https://pngrb.gov.in.**

Serafini, L. F., Praça, P. J. G. M., González-Andrés, F., & Gonçalves, A. (2025). Life cycle approach as a tool for assessing municipal biowaste treatment units: A systematic review. *Waste Management & Research: The Journal for a Sustainable Circular Economy*. https://doi.org/10.1177/0734242X251326866

Sharma, B.K. and Chandel, M.K., 2017. Life cycle assessment of potential municipal solid waste management strategies for Mumbai, India. *Waste Management & Research*, *35*(1), pp.79-91.

Singh, P., & Kalamdhad, A. S. (2022a). Assessment of agricultural residue-based electricity production from biogas in India: Resource-environment-economic analysis. Sustainable

Energy Technologies and Assessments, 54, 102843. https://doi.org/10.1016/j.seta.2022.102843

Singh, P., & Kalamdhad, A. S. (2022b). Biomethane plants based on municipal solid waste and wastewater and its impact on vehicle sector in India — An Environmental-economic-resource assessment. Environmental Technology & Innovation, 26, 102330. https://doi.org/10.1016/j.eti.2022.102330

The New Indian Express (2025). *BBMP to implement solid waste management user fee from April 1*. March 30, 2025. Available at: https://www.newindianexpress.com/cities/bengaluru/2025/Mar/30/bbmp-to-implement-solid-waste-management-user-fee-from-april-1 (accessed 09 January 2026).

World Population Review. (2025). *Bangalore population 2025 (demographics, maps, graphs)*. Retrieved from https://worldpopulationreview.com/cities/india/bangalore

Chapter 10
Biomining

10.1 Preamble

This study provides a LCA of biomining processes within the Indian context. By integrating MFA, sensitivity analysis, and economic evaluation, the study assesses the feasibility of biomining across environmental, techno-economic, and policy dimensions. The primary objectives are:

- To evaluate and compare the environmental impacts of the current baseline scenario of biomining with a futuristic scenario optimized for enhanced material recovery from landfill mining.
- To identify hotspots within the biomining process and propose strategies to improve resource recovery efficiency and reduce greenhouse gas (GHG) emissions.

10.2 Methodology

The study employs a multi-disciplinary approach, integrating LCA, MFA, and techno-economic analysis to evaluate the performance and feasibility of biomining. The methodology is structured to capture material flows, quantify environmental impacts, assess economic viability, and evaluate system sensitivities under varying operational conditions.

10.2.1 Site description

The Mandur dumpsite consists of 135 acres (85 acres in the South and 50 acres in the North). The site received approximately 1700–1800 MT of mixed MSW per day from 2008 to November 2014 (Fig. 10.1). Biomining operations at Mandur landfill followed a structured process to recover useful materials from legacy waste. The process began with the excavation of compacted waste using front-end loaders. The excavated waste was then loaded onto trucks, weighed, and transported to designated areas for drying. To reduce the moisture content and improve the screening efficiency, the waste was spread in layers of about 50 -100 cm height. Once sufficiently dried, different size trommel screens were used to separate the waste into different fractions. The materials were grouped into RDF, non-recyclable rejects, fine soil-like material (SLM) (<4 mm), metals and others. The density of the excavated waste ranged between 1 and 1.5 t/m³, which influenced both processing efficiency and material recovery

(Nalladiyil et al., 2024). This was comparable with the waste characteristic reported in the literature (Devahi et al., 2022).

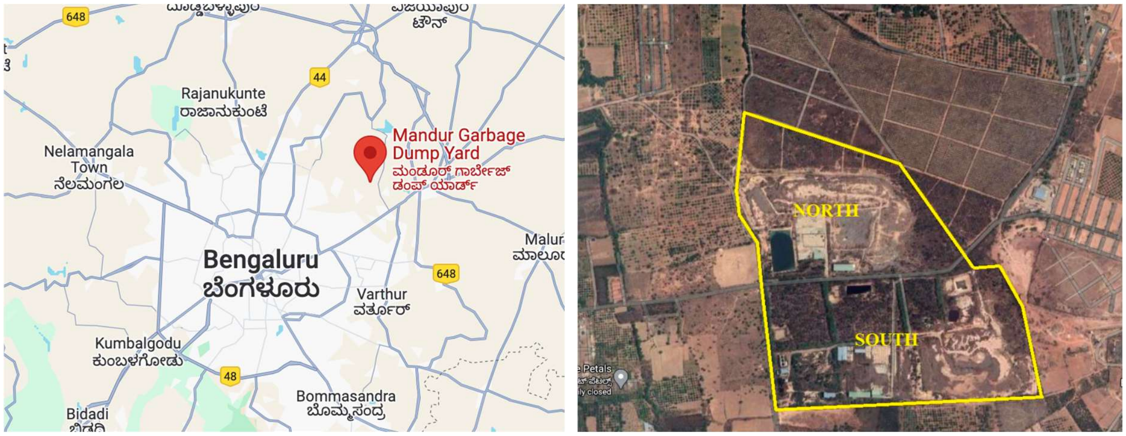


Fig. 10.1 a) Mandur dumpsite location w.r.t to Bengaluru city, b) Mandur biomining site

The composition of the mined waste showed that, 65% consisted of SLM, indicating that a large portion of the waste had already decomposed (Fig. 10.2). The refuse-derived fuel (RDF) fraction accounted for 14% and included combustible materials such as plastics, textiles, and paper, which could be used as fuel in industrial applications. Construction and demolition (C&D) waste made up 10% of the total and mainly comprised concrete and bricks. The inert fraction (8%) included materials such as stones and ceramics. Recyclables, including metals and glass, represented only 3% of the waste stream. However, improved sorting and recovery could still help reduce the demand for new raw materials.

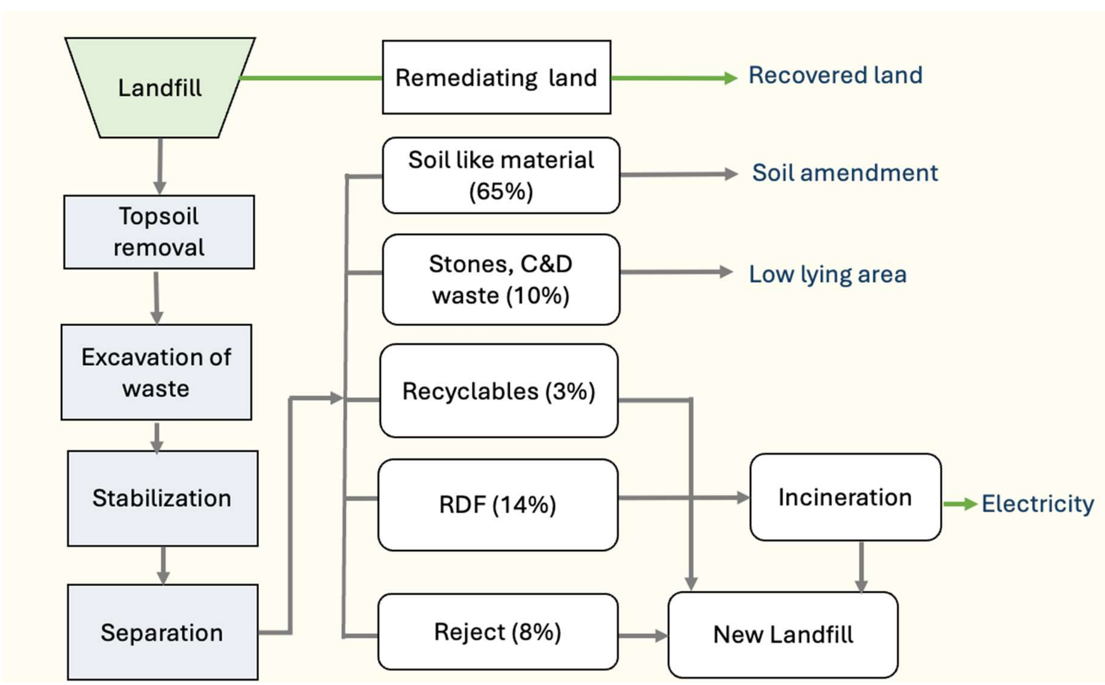


Fig. 10.2 Biomining process at Mandur site with recovered waste fraction

10.2.2 Life cycle assessment (LCA)

The LCA applied in this study followed the framework established by ISO 14040 and ISO 14044, enabling a systematic evaluation of inputs, outputs, and potential environmental impacts across the entire life cycle of the product system. The methodology is structured into four interconnected phases: goal and scope definition, life cycle inventory (LCI) analysis, life cycle impact assessment (LCIA), and interpretation of results.

10.2.2.1 Goal and scope

The primary goal is to quantify the environmental burdens and economic costs of biomining operations at Mandur biomining site. The functional unit is defined as the processing of 1 ton of legacy waste (Cheela et al., 2023). The system boundary is cradle-to-grave, consisting of excavation and stabilization, resource recovery (RDF, combustibles, and fine soil/inert fractions), transportation logistics for downstream utilization and final disposal of rejects. Two scenarios were considered based on the most common practices in India.

- Scenario 1: Current baseline scenario -biomining with SLM and RDF recovery
- Scenario 2: Enhanced biomining material recovery - recyclable fractions and ash from WTE plant

Credits were applied to account for the substitution of conventional resources by the byproducts.

10.2.2.2 Life cycle inventory (LCI)

For the inventory analysis, all material and energy inputs and outputs within the system boundary were quantified relative to the functional unit. Wherever possible, foreground data was sourced directly from the field visit and from academic literature. Background data for processes were obtained from the LCA for Expert professional database (see Table 10.1). The electricity demand for all unit processes was modelled using the Indian grid mix (2023–2027), consisting of: hard coal (59.3%), lignite (15.6%), hydropower (10.2%), nuclear (2.8%), natural gas (4.89%), wind power (2.89%), and others (4.32%).

Table 10.1 Lifecycle inventory data

	Unit	Scenario 1	Scenario 2	Reference
Input				
Legacy waste	t	1	1	
Excavation and sorting, diesel consumption	L/t	2.5	2.5	Field data
Transportation distance from biomining site to				
WTE plant	km	40	60 (utilization of ash also)	Field data
SLM utilization site	km	20	20	Field data
Recycling plant	km	-	200	Field data
Landfill	km	30	30	Field data
WTE plant				
Electricity used	kWh	55	55	Field data
Ammonia	kg	2.6	2.6	Field data
Hydrated lime	kg	19.1	19.1	Field data
Activated carbon	kg	0.23	0.23	Field data
Electricity generated	kWh	363	363	Field data

10.2.2.3 Scenarios studied

Scenario 1 (baseline)**:** In this scenario, the waste is excavated and stabilised. During the stabilisation phase, partial degradation and drying occurs, leading to a reduction in moisture content and an improvement in overall waste stability. The recovered SLM is stabilised on-site and transported for potential land application. A diesel consumption rate of 1.5 L per metric ton (MT) of mined waste was considered for excavation and sorting operations (Fig. 10.3). These processes were modelled separately using fuel-use and emission data collected from field measurements and literature sources. Excavation activities involve the use of a bulldozer equipped with a backhoe loader, excavator, and wheel loader. Transportation of excavated materials was carried out using 14–20 t capacity trucks. During stabilisation process of excavated waste, emissions were assumed to be 10–15% of those generated from composting fresh organic waste, owing to the partially stabilised nature of the material (Cheela et al., 2023). Diesel consumption for windrow turning operations was assumed to be 0.2 L/MT of excavated waste. The final SLM is applied as a soil amendment and transported 20 km for land application. It is assumed that metals present in the applied SLM remain in the soil and do not exceed permissible limits.

Based on the waste's physical characteristics and composition, an average separation efficiency of 83% was assumed. This implies that, per ton of excavated waste, 83% of the material is suitable for separation and valorization, only 8% is sent to the landfill for final disposal. RDF including mixed plastics, untreated wood, paper, paperboard, glass, textiles, and tires were routed to thermal treatment based on their calorific properties. SLM are transferred for use as a soil amendment after appropriate processing.

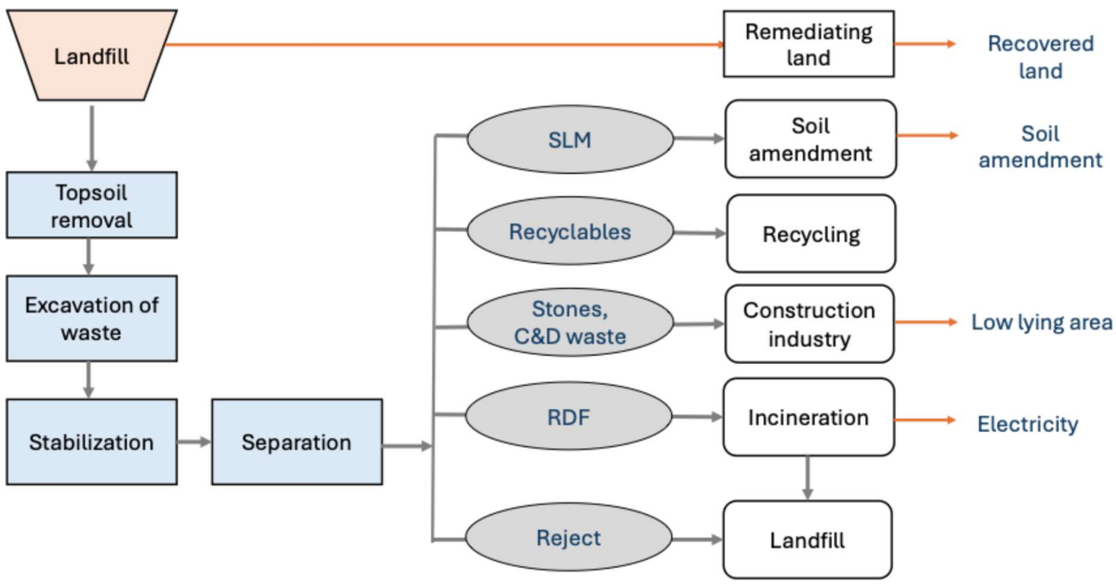


Fig. 10.3 System boundary of Biomining (Scenario 1)

Scenario 2: The excavation and recovery process in scenario 2 follows the same approach as scenario 1; however, additional material recovery pathways are incorporated, including the recovery of recyclables, construction and demolition (C&D) waste, and bottom ash (Fig. 10.4).

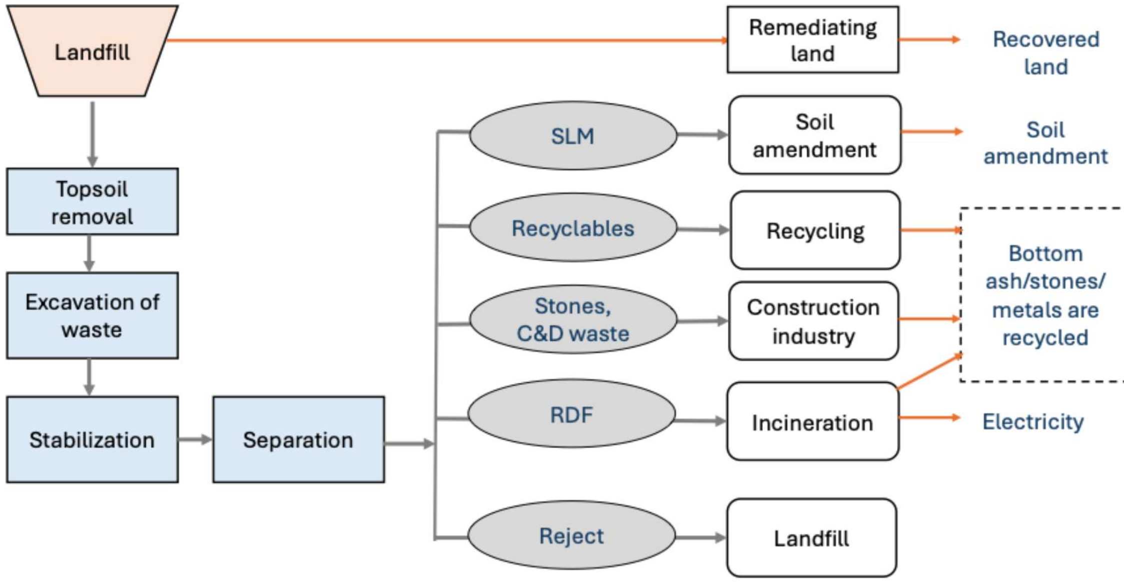


Fig. 10.4 System boundary of Biomining (Scenario 2)

Biomining at the Mandur site involved both mechanical and manual processes for waste excavation, separation, and material recovery. Equipment such as backhoe loaders, trommel screens, trucks, and compactors enabled efficient excavation, screening, and transportation of waste, but also contributed to capital, energy, and operational impacts within the system boundary. Mechanical screening improved the recovery of size-segregated fractions, while manual sorting was used to recover metals and recyclables with higher precision.

10.2.2.4 Life cycle impact assessment (LCIA)

The LCA was modeled using LCA for Experts (GaBi, version 10.9.0.31). Environmental impacts were evaluated using the ReCiPe 2016 methodology, applied at both midpoint and endpoint levels to provide a comprehensive view of environmental performance. The mid-point impact categories considered in this study are global warming (GW), terrestrial acidification (TA), freshwater eutrophication (FE), terrestrial ecotoxicity (TE), freshwater ecotoxicity (FET). The endpoint impact assessment was conducted using the ReCiPe 2016 Endpoint (H) H/A method. This approach aggregates midpoint results into three key areas of protection: human health, ecosystem quality, and resource scarcity.

10.2.3 Economic assessment

Techno-economic analysis (TEA) was conducted to evaluate the financial viability of the biomining scenarios. The assessment boundaries encompass the excavation, on-site stabilization, material separation, and final transportation of recovered fractions (SLM and

RDF). All costs and revenues are expressed in Indian Rupees (₹) per metric ton (T) of excavated waste.

$$\text{Total cost} = C_{CAPEX} + C_{OPEX} - \text{Revenues}$$

Where C_{CAPEX} represents capital expenditures amortized over the project life, C_{OPEX} denotes operational expenditures (fuel, electricity, labour, maintenance), and Revenues represents total revenue from recovered materials and reclaimed land value.

10.3 Results and discussion

10.3.1 Life cycle impact assessment

10.3.1.1 Global warming

The LCA analysis reveals that the scenario 1 operates as a net-carbon-negative system, primarily driven by energy recovery credits (Fig. 10.5). The positive contributions to GW were primarily associated with operational activities. Screening and sorting emerged as the highest contributor (7.49 kg CO_2 eq./t) attributed to the electricity and fuel consumption of the trommels and separating machinery. Excavation and stabilization followed closely (6.50 kg CO_2 eq/t), while the transportation of various fractions (waste to landfill, SLM transport, and RDF transport) contributed a combined total of 11.6 kg CO_2 eq./t The final disposal of inert and ash in the sanitary landfill, including the requisite leachate treatment, contributed to a minor burden of 3.93 kg CO_2 eq./t The combustion of RDF generated 202 MJ of electricity. By substituting an equivalent amount of grid electricity derived from hard coal, the system achieved a substantial avoided burden of -63.95 kg CO_2 eq./t. In results, environmental burdens are shown as positive values, while environmental benefits are represented as negative values.

When balancing the operational burdens against the energy recovery credits, the net GW for the legacy waste valorization scenario is significantly negative. This indicates that the environmental benefits of displacing fossil-fuel-based energy and recovering soil resources outweigh the emissions generated during excavation, processing, and transportation. The results suggest that integrating RDF utilization and SLM repurposing is vital for transforming legacy waste management from a pollution source into a sustainable, carbon-mitigating process.

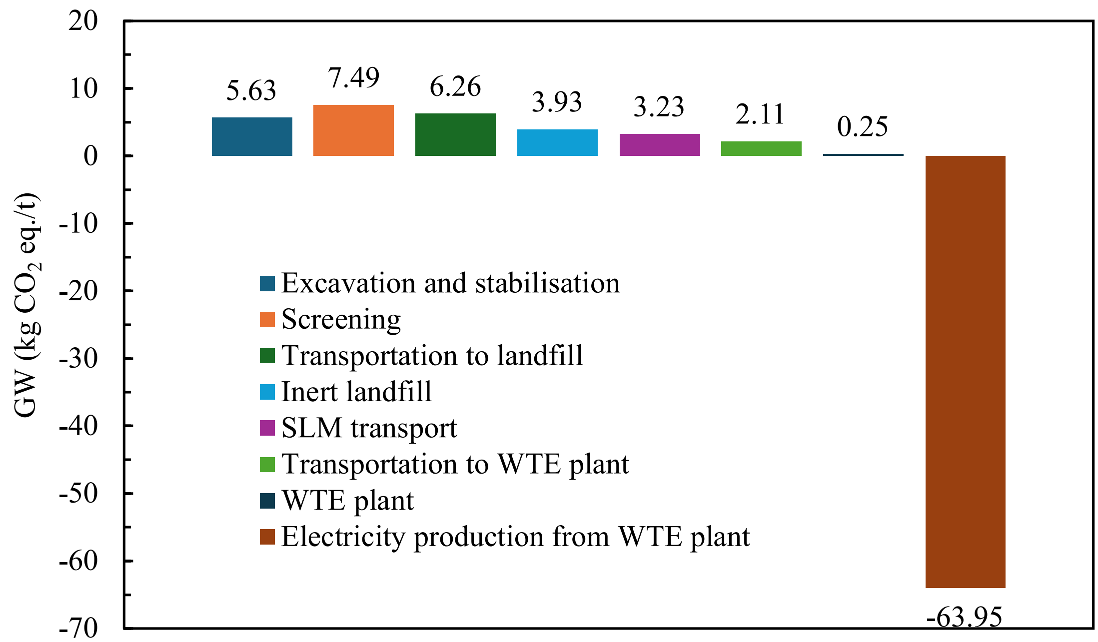


Fig. 10.5 Global warming of Biomining (Scenario 1)

In Scenario 2, the environmental credit achieved through system expansion, specifically through material recovery. The scenario achieves a net negative GW profile, largely driven by the electricity production from the WTE plant, which offers an offset of -63.95 kg CO_2 eq./t (Fig. 10.6). Material recycling provided additional, though smaller, environmental benefits. Recycling of scrap metals resulted in a credit of -4.54 kg CO_2 eq. Sand replacement utilizing the construction waste fraction provided a minor offset of -0.29 kg CO_2 eq., substituting virgin sand extraction. The high avoided burden from energy substitution (-63.95 kg CO_2 eq.) completely offsets the cumulative operational burdens of excavation, screening, and transportation (~24 kg CO_2 eq.). However, this benefit is sensitive to the energy mix being substituted; the displacement of coal-based power creates a "best-case" scenario for reduction.

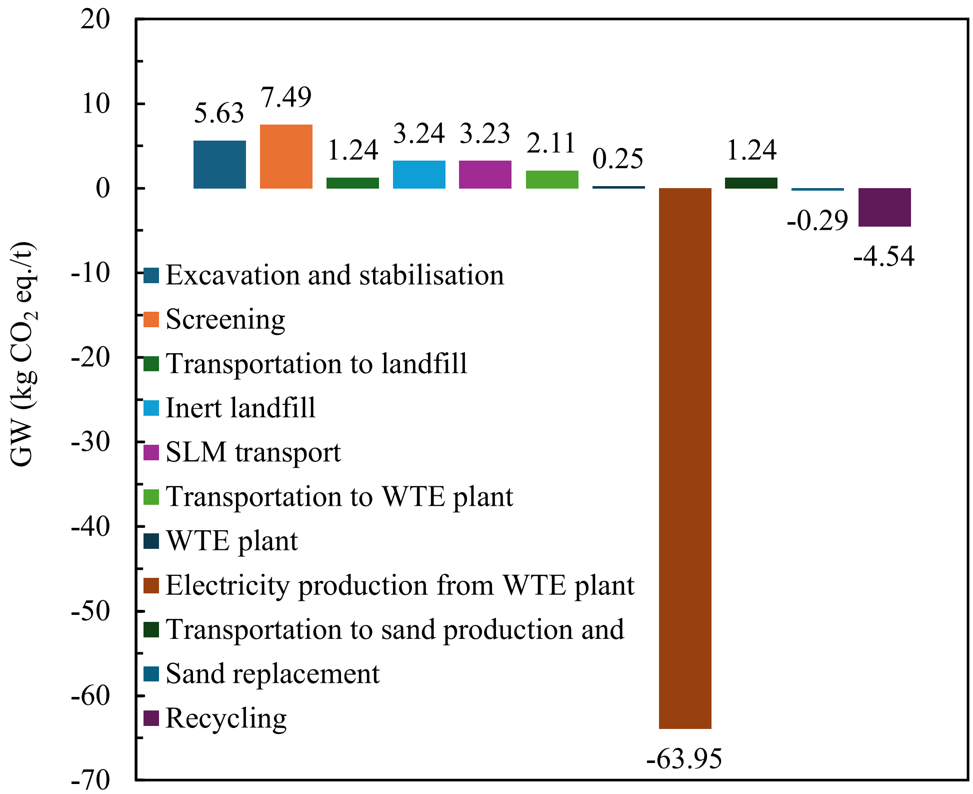


Fig. 10.6 Global warming of biomining (Scenario 2)

10.3.1.2 Midpoint impacts

Scenario S2 demonstrates a higher capacity for environmental credits, in GW as discussed. The same trend remains in fossil depletion, where S2 offers a credit of -8.38 kg oil eq. against S1's -6.62 kg oil eq. The deeper negative values in S2 suggest a more effective displacement of fossil-based energy or materials within the system boundary. Across different impact categories, Scenario S2 consistently outperforms S1 by either maximizing environmental credits or eliminating trace burdens. This is particularly evident in Human Toxicity (non-cancer), where S2 provides a credit of -6.09 kg 1,4-DB eq. compared to -5.81 kg 1,4-DB eq. for S1. These results indicate that Scenario S2 is the more sustainable configuration under the midpoint assessment, offering enhanced mitigation potential across atmospheric, aquatic, and terrestrial compartments. In scenario 2, the substitution of virgin metal with recovered metal from excavation avoided the impacts associated with primary metal extraction and processing which resulted in the higher positive credits in scenario.

10.3.1.3 Endpoint impacts

The endpoint results showed Scenario S2 as the more sustainable option across all the endpoint categories (Table 10.2). This indicate enhanced recovery of biomining is a more balanced mitigation strategy for protecting human health, natural ecosystems, and resource availability.

Table 10.2 Endpoint impacts for S1 and S2

Category	Unit	S1	S2
Resources	$	966.781	958.430
Human Health	DALY	0.018	0.014
Ecosystems	species.yr	5.27E-05	4.47E-05

10.3.1.4 Influence of RDF utilization pathways

The environmental feasibility of biomining is heavily dependent on the downstream utilization of the RDF fraction. The high avoided burden observed in Scenarios relies on the displacement of coal-based power, which creates a "best-case" scenario for GW reduction. The net-negative GW results are contingent upon the current carbon intensity of the Indian national grid. As of 2024-25, the power generation mix remains over 70% reliant on thermal energy (coal and lignite). While this maximizes the "avoided burden" credit for RDF, these results are sensitive to regional electricity variations. As the grid transitions toward higher shares of renewables, the net-negative benefit of RDF energy substitution will decrease, emphasizing the need for higher-efficiency co-processing in cement kilns over traditional WTE plants.

Legacy RDF recovered from old dumpsites typically exhibits high moisture content, heterogeneity, low and variable calorific value, and elevated ash and inert fractions, all of which adversely affect stable combustion and energy efficiency in WTE plants and often necessitate extensive pre-processing. Cement plants represent a more practical and environmentally robust option than WTE plants for the utilisation of legacy RDF, in the Indian context. In contrast, cement kilns are technically well suited to accommodate such variability, as they can co-process RDF as an alternative fuel while simultaneously incorporating its ash fraction into the clinker matrix, thereby eliminating secondary residues such as bottom ash and fly ash that require further disposal in WTE systems. The high operating temperatures and long residence times in cement kilns ensure complete destruction of organic contaminants and persistent pollutants, while achieving superior thermal efficiency through direct substitution of fossil fuels such as coal or petcoke. From a systems perspective, co-processing RDF in cement plants avoids the capital-intensive infrastructure and leverages existing industrial capacity and aligns more closely with circular economy principles by enabling both energy recovery and material recovery in a single process.

The environmental feasibility of substituting fossil fuels with RDF is fundamentally governed by the "energy-to-logistics" ratio. Replacing high-calorific fuels like Pet Coke requires a mass substitution ratio of nearly 2.5:1, which drastically increases the transport-related carbon footprint. Consequently, to maintain the same net environmental impact, RDF sourcing for Pet Coke replacement must be limited to a tight radius (<388 km), whereas replacement of lower-grade coal remains viable over significantly longer distances (~660 km) (Fig. 10.7). This demonstrates that the critical transport distance for RDF decreases systematically, rather than linearly as the energy density of the substituted fossil fuel increases.

The analysis reveals a critical breakeven distance a geographical threshold where the environmental cost of transporting outweighs its benefits. Therefore, a decentralized waste management strategy is recommended: for cement plants located within the immediate vicinity of the landfill or dumpsite, direct co-processing of loose RDF is preferable to avoid processing penalties.

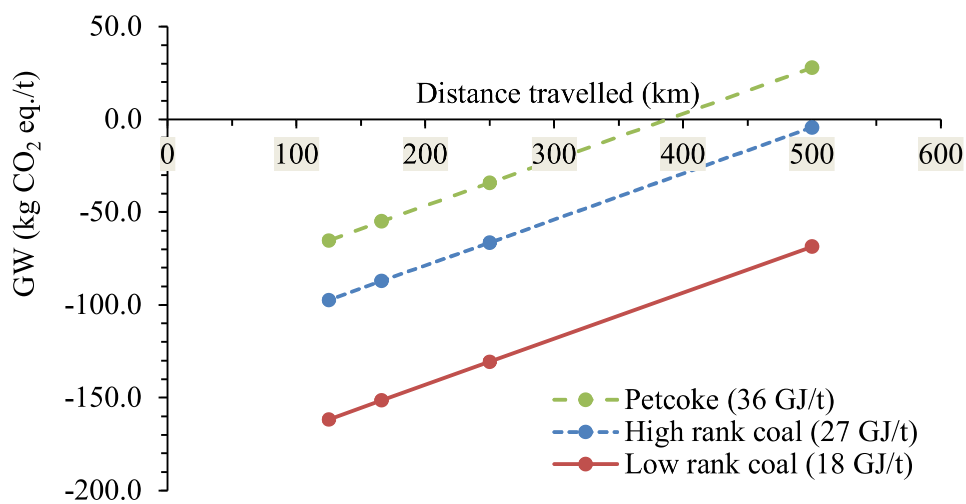


Fig. 10.7 Global warming when RDF (6.2 GJ/t) is replacing different type of fuel pet coke (36 J/t) High rank coal (27 GJ/t) and Low rank coal (18 GJ/t)

10.3.2 Sensitivity analysis - Influence of various parameters

A sensitivity analysis was conducted to determine the 'environmental breakeven grid factor' (Fig. 10.8). The analysis indicates that, for the stationary electric trommel to become carbon-competitive with the heavy-duty diesel variant, the grid emission factor must decrease below 0.08 kg CO_2/kWh. This threshold is substantially lower than the current Indian grid intensity (~0.9 kg CO_2/kWh) and even lower than that of many developed economies (e.g., UK ~0.2 kg CO_2/kWh). The results suggest that grid decarbonization alone is unlikely to make the currently assessed electric trommel system environmentally competitive in the near term. The relatively high specific energy consumption of the system (12 kWh/t) substantially amplifies emissions associated with electricity generation. Therefore, priority should be given to reducing the energy intensity of the trommel through process optimization and improved equipment efficiency, alongside the integration of dedicated on-site renewable energy systems.

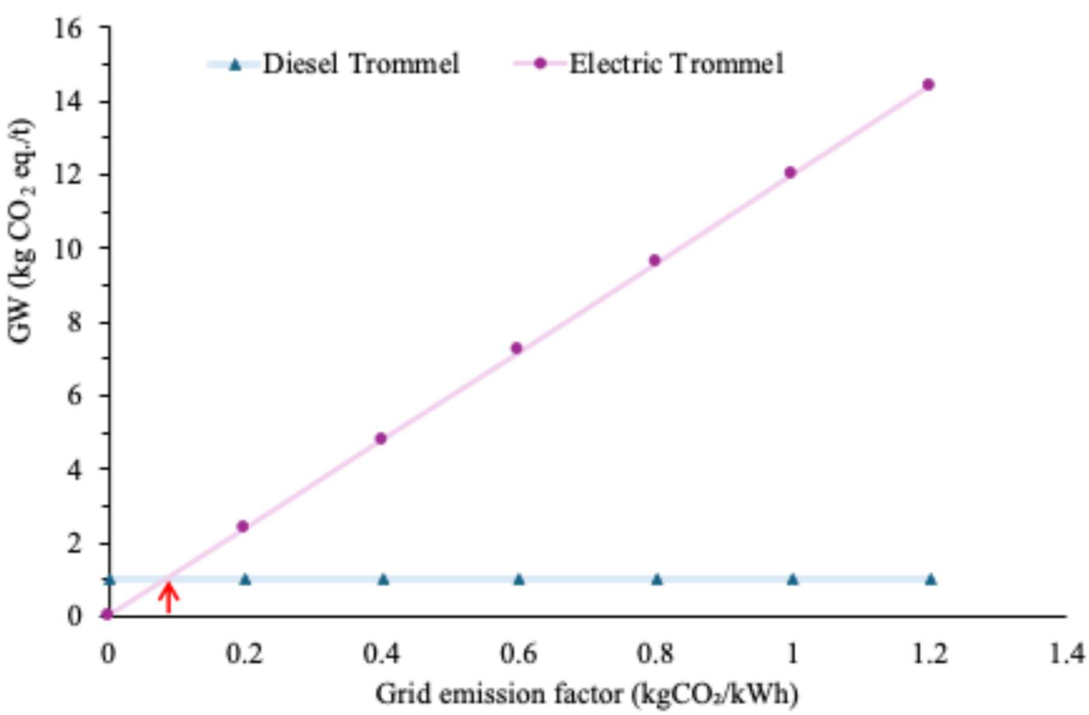


Fig. 10.8 Influence of grid emission factor on the GW of the stationary electric trommel

10.3.3 Renewable energy integration

To evaluate the potential of hybridization as a mitigation strategy, a sensitivity analysis was conducted by varying the energy mix of the stationary electric trommel from 100% grid dependency to a 60% solar/grid hybrid configuration (Fig. 10.9). The baseline scenario (100% Grid) exhibited the highest environmental impact with a GW of 12.99 kg CO_2 eq./t. The integration of solar photovoltaic (PV) energy demonstrated a linear reduction in carbon footprint. Displacing grid electricity with solar energy yielded a reduction rate of approximately 1.24 kg CO_2 eq./t for every 10% increase in renewable share. Consequently, the Hybrid-60% scenario (40% grid + 60% solar) achieved the lowest impact among the electric configurations, recording a GW of 5.56 kg CO_2 eq./t. This analysis assumes a linear displacement of grid electricity by solar power, which serves as a first-order approximation for steady-state operation. While factors such as inverter efficiency losses and partial load variations could introduce minor non-linearities, the linear model provides a clear benchmark for decarbonization potential. Furthermore, the environmental burden of the solar PV system (manufacturing lifecycle impacts) was excluded to focus purely on operational displacement. Despite the significant reduction achieved through 60% hybridization (a 57% decrease from baseline), the electric trommel remains considerably more carbon-intensive than the conventional heavy-duty diesel trommel (0.65 kg CO_2 eq./t). This disparity reinforces the earlier finding that the high specific energy consumption 12 kWh/t creates a carbon burden so large that partial decarbonization of the power supply is insufficient.

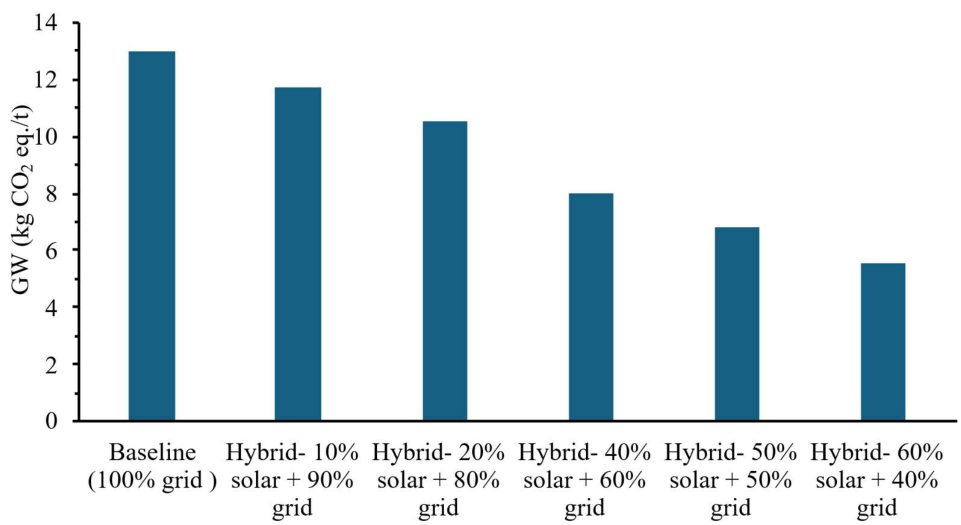


Fig. 10.9 Sensitivity analysis of GHG emissions with increasing shares of solar energy integration

10.3.4 Economic analysis

The direct processing cost was ₹918 per ton of excavated waste, driven primarily by diesel consumption (₹155/MT) and skilled labour (₹200/MT). In contrast, revenue from recovered materials remains marginal; the SLM is valued as low-grade (₹100/MT) (Table 10.3). Consequently, the analysis demonstrates that the project is financially unviable if relying solely on resource recovery (revenue < operation cost). The economic feasibility is strictly contingent on land reclamation credits. The economic model assumes that heavy metal concentrations in the SLM remain within permissible limits for land application. Exceedance of these toxicity limits would necessitate secure landfilling of the fine fraction, increasing the reject rate from 17% to 60% and rendering the project economically prohibitive due to elevated tipping fees and loss of diversion credits. The negative values in the economic model represent 'avoided costs' or savings. Specifically, the landfill cost (-₹240/t) represents the avoided tipping fees and long-term post-closure maintenance costs that would have been incurred if the waste remained un-mined. Similarly, the C&D cost (-₹20/t) reflects the savings from using recovered inert fractions as onsite backfill instead of purchasing virgin construction aggregates.

Table 10.3 Expenses and revenue of biomining project at Mandur

Expenses /Revenue		
Excavation and sorting	155	Rs/t
Stabilisation and drying	18	Rs/t
Transport	315	Rs/t
Electricity	96	Rs/t
Maintenance cost	14	Rs/t
Labour	200	Rs/t
Overhead (15%)	120	Rs/t
RDF revenue	-125	Rs/t
SLM revenue	-65	Rs/t
Recycling revenue	-108	Rs/t
C&D avoided cost	-20	Rs/t
Net cost	600	Rs/t

The environmental and economic efficiency of biomining is highly project-specific, varying based on material recovery types, the geographical location of the site and market demand.

10.3.4.1 Carbon credit based on landfill age

A strong negative correlation exists between landfill age and carbon credit potential due to the degradation of organic matter over time. In younger dumpsites, the high concentration of biodegradable waste leads to active methane generation; excavating these sites prevents future potent GHG emissions. While this study provides a conceptual framing of carbon potential, formal credit eligibility would be governed by established methodologies such as the Clean Development Mechanism (CDM) ACM0022 for 'Alternative waste treatment processes' or the Verra (VCS) VM0046 for 'Landfill Gas Destruction' or “Gold Standard for the global goals”.

Analysis shows that biomining is most carbon-efficient when applied to "young" legacy waste. As the site reaches 40+ years, the waste has largely stabilized, and the net emission from the energy-intensive excavation machinery may nearly equal the emissions saved (Fig. 10.10). leading to a "carbon-neutral" or even "carbon-positive" operation that wouldn't qualify for credits. Under such conditions, a site may reach a 'carbon-neutral' or 'carbon-positive' state, potentially failing the 'additionality' requirements of standard carbon accounting protocols. To achieve a verifiable carbon credit, the total emissions avoided primarily through methane avoidance and the displacement of fossil-fuel-based electricity must quantitatively exceed the operational emissions from fuel for excavators, electricity for trommel screens, and transport of segregated fractions.

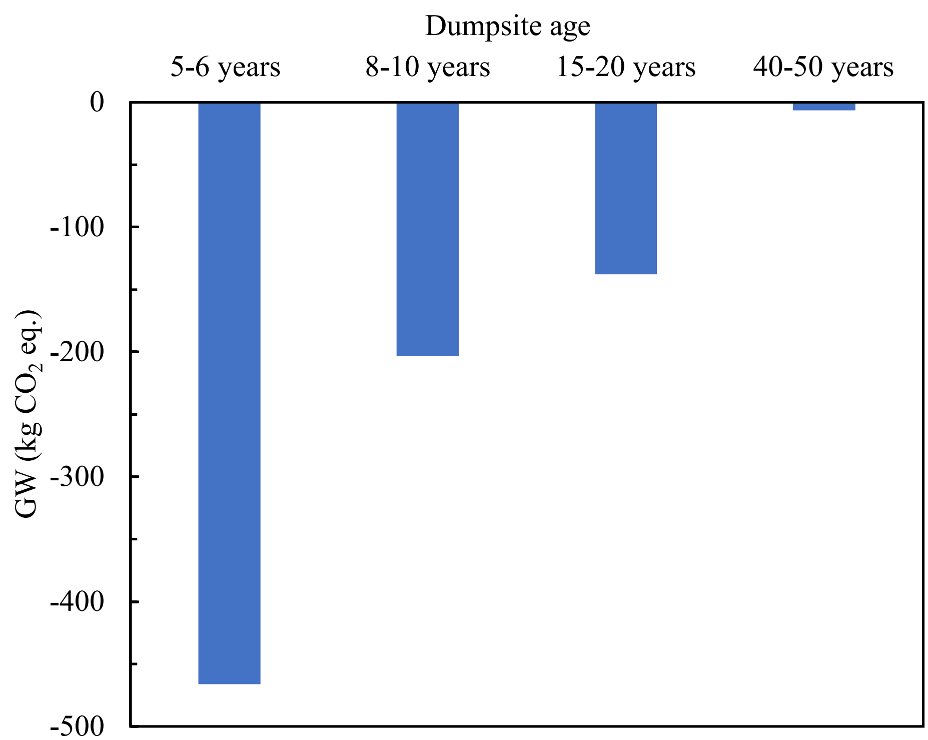


Fig. 10.10 Dumpsite age v/s carbon credit potential

To achieve a carbon credit, emission avoided (Methane avoidance and the displacement of coal (electricity generation) should be greater than emission from operations (fuel for excavators, electricity for trommel screens, and transport of segregated fractions (RDF, soil, recyclables). Combining the Carbon Credit value + the Real Estate Value of the reclaimed land might show that even if a 40-year-old site has zero carbon credits, it is still "profitable" due to land recovery. Revenue from recovered materials alone is often insufficient to offset excavation, processing, and transportation costs, making LFM financially dependent on external value streams such as land reclamation benefits and carbon credits. Furthermore, the eligibility of LFM projects for carbon credits is closely linked to landfill age and residual biodegradability, as older dumpsites may offer limited methane avoidance potential. These interdependencies highlight the need for an integrated assessment framework that simultaneously considers environmental performance, economic feasibility, and policy relevance.

10.4 Practical implications

The Central Pollution Control Board (CPCB) guidelines (2019) establish a necessary foundation for legacy waste handling. However, to move beyond ad hoc remediation, these guidelines must be transitioned into a regulatory framework with verifiable performance metrics. Currently, the lack of mandatory stabilization thresholds and recovery targets leads to sub-optimal environmental outcomes and "secondary dumping" of unprocessed fractions. By establishing quantifiable key performance indicators (KPIs), regulatory bodies like the State Pollution Control Boards (SPCBs) can ensure that dumpsite remediation contributes to a true circular economy. The major issues or gap in the guidelines and their corresponding recommendations are listed in Table 10.4.

Table 10.4 Issues or gap and proposed recommendation

Issues/Gap	**Recommendation**
Lack of formal standards for stabilization condition	Establish stabilization thresholds before further processing: Moisture < 25%, Organic content < 10%, Bulk density > 1.0 t/m³
Lack of defined drying period and operational conditions	Specify 8–12 weeks drying, depending on climate; mandatory aeration and periodic windrow-turning (Min 2 times/week) to ensure active stabilization
No standards for monsoon / rainy-season operations	Define rain-resilient operational protocols: temporary covered processing zones, storm-water diversion, rapid transfer to covered dryers
Lack of on-site air quality monitoring	Mandatory monitoring for methane, PM10 and PM2.5, and odor control; use of dust suppression systems
Absence of leachate management directives	Leachate collection, storage, and on-site treatment must be operational throughout remediation; groundwater protection monitoring required
No requirement for performance audits of processing machinery	Enforce quarterly performance audits: throughput capacity, breakdown frequency, emission norms for excavators/screens
No requirement of baling of RDF before transportation	Mandatory baling/compaction of RDF prior to transport; covered transportation to minimize litter and combustion risk

Low calorific value RDF fraction (<1500 kcal/kg) usage provision	Introduce pre-processing/blending standards to improve calorific value: drying, shredding etc.
Insufficient emphasis on resource recovery	Min. Recovery: >50% of total mined volume (by mass) diverted from landfills.
Weak enforcement and accountability	Convert guidelines into legally binding rules; impose penalties for delays, and incentive schemes for high-performing municipalities
Inadequate post-remediation land-use guidelines	Issue clear safe land-use certification criteria: prioritized use for green buffers, solar parks, industrial utilities; residential use only after long-term monitoring

Given the scale of legacy waste in Indian cities and its long-term environmental and social costs, India should upgrade its legacy-waste framework from guideline-based to regulation-based, embedding stabilization standards, resource recovery mandates, mandatory monitoring and reporting, and transparent stakeholder engagement. Simultaneously, the country should adopt circular-economy principles, drawing from international best practices not just eliminating waste but turning legacy waste into resources.

10.5 Summary

This chapter evaluated the environmental and operational feasibility of biomining through LCA and techno-economic analysis. By comparing baseline practices with optimized recovery scenarios, the study identifies critical hotspots like RDF quality in WTE plant and machinery energy consumption that dictate net sustainability. A central finding is the urgent need to transition from the CPCB (2019) guidelines to a mandatory regulatory framework. Without verifiable performance metrics, such as stabilization thresholds (Moisture < 25%, Organic content < 10%) and defined drying periods (8–12 weeks), biomining risks "secondary landfilling" and sub-optimal recovery. To achieve a true circular economy, the study recommends mandating a minimum resource recovery rate of >50% by mass and improving RDF quality through standardized pre-processing. Financial analysis at sites like Mandur reveals that biomining is not self-sustaining through material recovery alone. Economic feasibility is entirely contingent on land reclamation credits and avoided costs (e.g., tipping fees and long-term maintenance). Furthermore, carbon credit potential is highly sensitive to landfill age; younger sites offer significant methane avoidance, while sites over 40 years old may reach carbon-neutral states where operational emissions offset savings.

References

Cheela, V. R. S., John, M., Biswas, W. K., & Dubey, B. (2021). Environmental impact evaluation of current municipal solid waste treatments in India using life cycle assessment. *Energies, 14*(11), 3133. https://doi.org/10.3390/en14113133

Devahi, P., Rathod, D., & Muthukkumaran, K. (2022). Sustainable reuse potential of landfill mining waste retrieved from urban mining sites in South India. *Journal of Material Cycles and Waste Management, 24*(6), 2582–2597. https://doi.org/10.1007/s10163-022-01520-8

Goli, V. S. N. S., & Singh, D. N. (2023). Valorization of landfill mined plastic waste and soil-like fractions in polymer composites – A comprehensive solution for sustainable landfill mining. *Journal of Cleaner Production, 420*, 138349. https://doi.org/10.1016/j.jclepro.2023.138349

Hogland, W., Marques, M., & Nimmermark, S. (2004). Landfill mining and waste characterization: A strategy for remediation of contaminated areas. *Journal of Material Cycles and Waste Management, 6*(2). https://doi.org/10.1007/s10163-003-0110-x

Jones, P. T., Geysen, D., Tielemans, Y., Van Passel, S., Pontikes, Y., Blanpain, B., Quaghebeur, M., & Hoekstra, N. (2013). Enhanced landfill mining in view of multiple resource recovery: A critical review. *Journal of Cleaner Production, 55*, 45–55. https://doi.org/10.1016/j.jclepro.2012.05.021

Kaartinen, T., Sormunen, K., & Rintala, J. (2013). Case study on sampling, processing and characterization of landfilled municipal solid waste in the view of landfill mining. *Journal of Cleaner Production, 55*, 56–66. https://doi.org/10.1016/j.jclepro.2013.02.036

Kurian, J., Esakku, S., & Nagendran, R. (2007). Mining of compost from dumpsites and bioreactor landfills. *International Journal of Environmental Technology and Management, 7*, 317–325. https://doi.org/10.1504/IJETM.2007.015149

Nalladiyil, A., & Babu, G. S. (2024). Dumpsite remediation through landfill mining and rehabilitation: A circular economy perspective. *Journal of the Indian Institute of Science, 104*(2), 489–518. https://doi.org/10.1007/s41745-024-00444-5

Quaghebeur, M., Laenen, B., Geysen, D., Nielsen, P., Pontikes, Y., Van Gerven, T., & Spooren, J. (2013). Characterization of landfilled materials: Screening of the enhanced landfill mining potential. *Journal of Cleaner Production, 55*, 72–83. https://doi.org/10.1016/j.jclepro.2012.06.012

Singh, A., & Chandel, M. K. (2020). Effect of ageing on waste characteristics excavated from an Indian dumpsite and its potential valorisation. *Process Safety and Environmental Protection, 134*, 24–35. https://doi.org/10.1016/j.psep.2019.11.025

Wagner, T. P., & Raymond, T. (2015). Landfill mining: Case study of a successful metals recovery project. *Waste Management, 45*, 448–457. https://doi.org/10.1016/j.wasman.2015.06.034

Volume II

Development of Greenhouse Gas (GHG) Emission Calculator App

Office of the Principal Scientific Adviser
to the Government of India

Chapter 1
Introduction

1.1 Overview

The increasing environmental concerns associated with waste management highlight the need for scientifically robust tools capable of estimating greenhouse gas (GHG) emissions from different waste treatment pathways. Existing tools, such as the United States' Environmental Protection Agency Waste Reduction Model (EPA WARM) and the Institute for Global Environmental Strategies Emission Quantification Tool (IGES EQT), are widely used for GHG estimation. However, the direct application of these tools under Indian municipal solid waste conditions is often constrained by differences in waste composition, climatic conditions, treatment infrastructure, operational practices, and the lack of India-specific emission factors.

Life Cycle Assessment (LCA) provides a systematic framework for evaluating the environmental impacts associated with waste collection, transportation, treatment, recovery, and disposal activities. Integrating the LCA principles with GHG accounting enables a comprehensive assessment of waste management systems by considering both direct emissions and avoided emissions associated with material recovery and energy generation.

To address the limitations of existing assessment approaches and support climate-oriented decision-making, a web-based GHG Calculator platform is developed for municipal solid waste management systems. The developed platform estimates emissions associated with transportation, composting, anaerobic digestion, recycling, incineration, and landfill disposal within a life cycle assessment framework. In addition, the platform incorporates Material Flow Analysis (MFA), scenario comparison, avoided emission assessment, and dashboard-based visualization to facilitate urban local bodies (ULBs), corporations, consultants and city-planning authorities to , evaluate and plan sustainable waste management practices.

The GHG estimation methodology implemented in this project is primarily based on the Emission Quantification Tool (EQT) developed by the Institute for Global Environmental Strategies (IGES), which follows the 2006 Intergovernmental Panel on Climate Change (IPCC) Guidelines for greenhouse gas estimation in the waste sector. The developed framework can serve as a decision-support tool for municipal authorities, researchers, policymakers, and environmental planners in designing sustainable and climate-responsive municipal solid waste management systems. Fig. 1.1 illustrates the major MSW management pathways considered for the development of the web application.

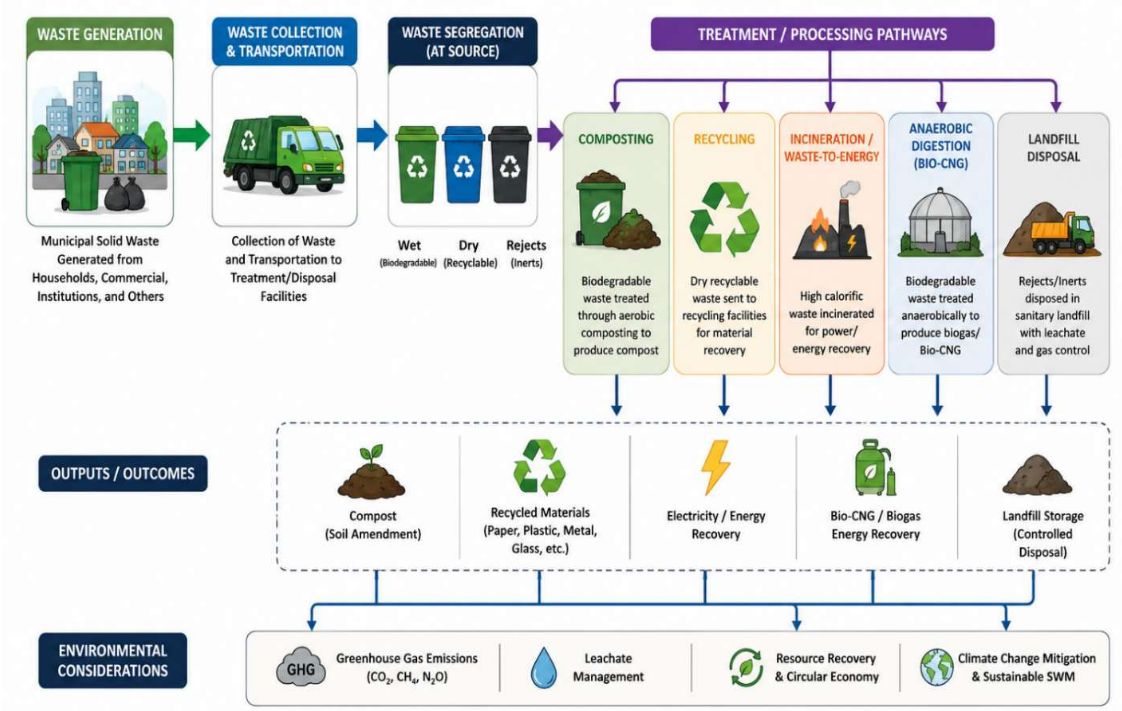


Fig. 1.1 System boundary including the major municipal solid waste treatment pathways

1.2 Objectives

The primary objective of this study is to develop a scientifically robust, user-friendly web-based application (or app) for estimating GHG emissions from municipal solid waste management systems. The specific objectives also include an accurate estimation of GHG emissions associated with the currently practices municipal solid waste treatment pathways (business-as-usual case), and to evaluate multiple user-specified waste management scenarios to assess the effective pathways resulting in minimum GHG emissions.

Other objectives of the project include:

- Incorporation of Material Flow Analysis (MFA) for evaluating waste distribution and treatment efficiency
- Assessment of direct emissions, avoided emissions, and energy recovery benefits associated with different waste treatment technologies

Thus, the app development activity is aimed to support sustainable waste management planning and climate-oriented environmental assessment for Indian cities.

Chapter 2

GHG Calculator App

This chapter presents the structure and key functionalities of the developed web-based GHG Calculator for municipal solid waste management systems. The chapter describes the major components of the system, including the dashboard, user workflow, emission estimation modules, scenario comparison framework, and data management features. These components collectively support data entry, greenhouse gas estimation, visualization of results, and evaluation of alternative waste management strategies.

2.1 Preamble

The developed web-based GHG Calculator, tentatively named **ENVISAGE (Environmental Navigation & Vision for Impact Scenario Analysis and Greenhouse Gas Estimation)**, is designed to estimate GHG and Short-Lived Climate Pollutant (SLCP) emissions associated with municipal solid waste management systems (Fig. 2.1). The application framework is based on the Emission Quantification Tool (EQT) developed by the Institute for Global Environmental Strategies (IGES), Japan.

Fig. 2.1 The homepage of the developed GHG Calculator platform

The platform enables users to rapidly assess emissions associated with different waste management activities and evaluate alternative waste management strategies. Emissions are estimated for waste collection and transportation, composting, anaerobic digestion, recycling, incineration, landfill disposal, open burning, and uncollected waste.

The application adopts a Life Cycle Assessment (LCA) approach by considering emissions generated during transportation, treatment, and disposal processes, together with potential emission reductions resulting from material recovery and energy recovery activities. The estimated results are displayed through interactive tables, charts, and graphical outputs, facilitating comparison between Business-As-Usual (BAU) and alternative scenarios and supporting the identification of climate-friendly waste management options.

2.2 Dashboard

The dashboard serves as the primary interface of the GHG Calculator platform for presenting greenhouse gas estimation results and key waste management indicators. It provides an integrated environment for visualizing waste-related information, emission estimates, and resource recovery performance through interactive charts, tables, and graphical summaries. In addition, city-specific information, including population, area, and waste generation, is displayed to provide an overview of the selected municipal solid waste management system. The typical dashboard display of the key city statistics is given in Fig. 2.2, 2,3 and 2.4.

The dashboard comprises the following major components:

- City profile and waste generation summary.
    - Waste collection and diversion statistics.
    - Waste composition and wet, dry, and mixed waste distribution.
    - Greenhouse gas emission summaries and treatment-wise emission distribution.
    - Material recovery indicators.
    - Material Flow Analysis (MFA) diagrams representing waste movement among treatment pathways.

The integrated visualization framework enables users to identify major emission sources, evaluate system performance, assess resource recovery potential, and interpret greenhouse gas estimation results effectively. The graphical representation of output facilitates easier interpretation for both technical and non-technical users.

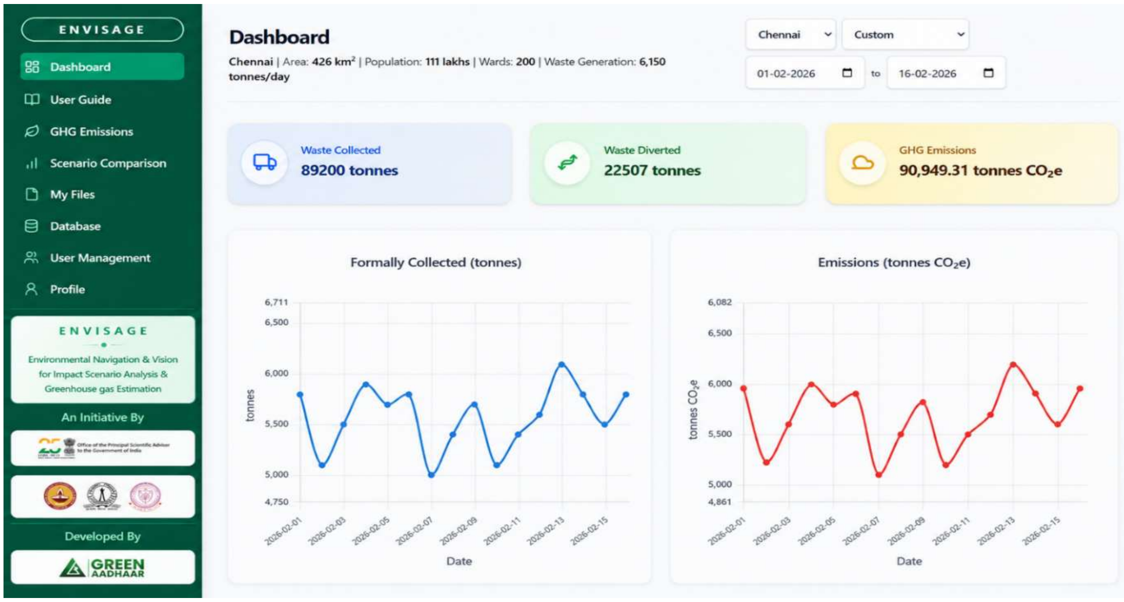


Fig. 2.2 Dashboard interface showing city waste management and GHG emissions

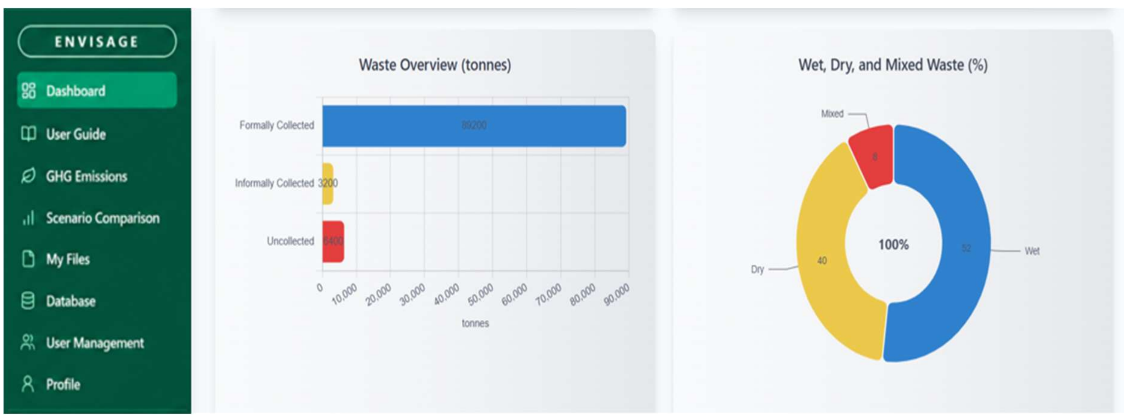


Fig. 2.3 Dashboard interface showing waste collection statistics and waste distribution

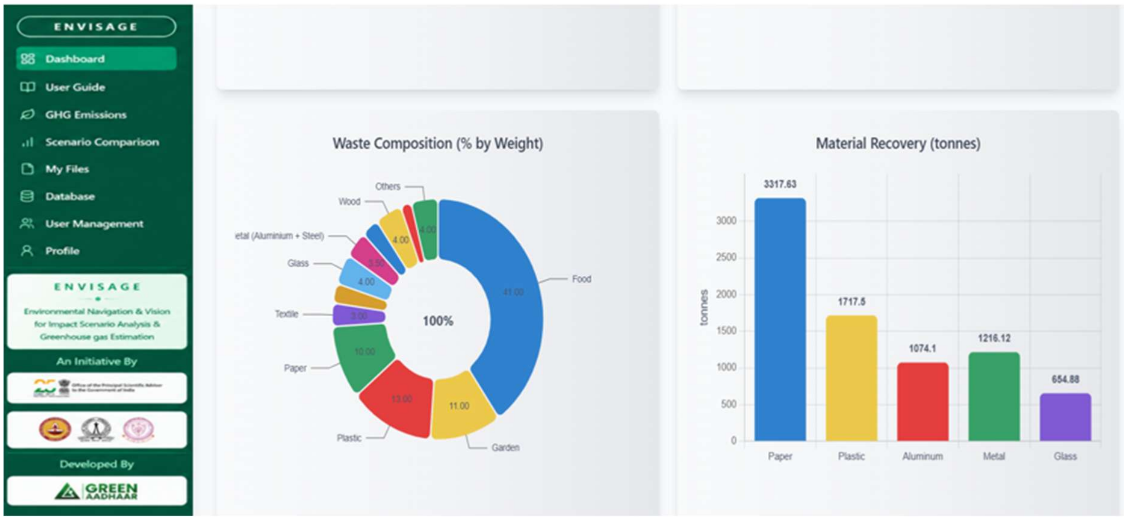


Fig. 2.4 Dashboard interface showing waste composition and material recovery indicators

2.3 User Guide

The User Guide module provides a structured workflow to assist users in performing greenhouse gas assessments for municipal solid waste management systems. The module offers step-by-step guidance to facilitate data entry, emission estimation, and interpretation of results. A typical user guide prepared by us is appended towards the end of this report as Annexure A.

The major steps involved in using the application are as follows:

Step 1: Create or Select a City File

Users initiate the assessment by creating a new city file or selecting an existing file for more data entry / further analysis. Basic information related to the study area, assessment year, and scenario details is recorded in this step.

Step 2: Enter Key Data

Users provide essential city-level information, including population, waste generation, collection efficiency, waste composition, and other relevant parameters required for the assessment.

Step 3: Enter Technology-Specific Data

Information related to different waste treatment technologies, such as transportation, composting, anaerobic digestion, recycling, incineration, and landfill disposal, is entered in the respective modules. Activity data, including waste allocation, fuel consumption, electricity usage, and operational parameters, are specified in this stage.

Step 4: Estimate Emissions and View Results

Based on the input data, the application automatically estimates greenhouse gas emissions, avoided emissions, and net emissions associated with different waste management processes. The estimated results are presented through tables, charts, and graphical outputs.

Step 5: Compare Alternative Scenarios

Users can compare BAU with upto 4 alternative waste management scenarios to evaluate the environmental implications of different strategies and identify those scenarios with lower GHG emissions. The basic workflow of the GHG calculator is depicted in Fig. 2.5.

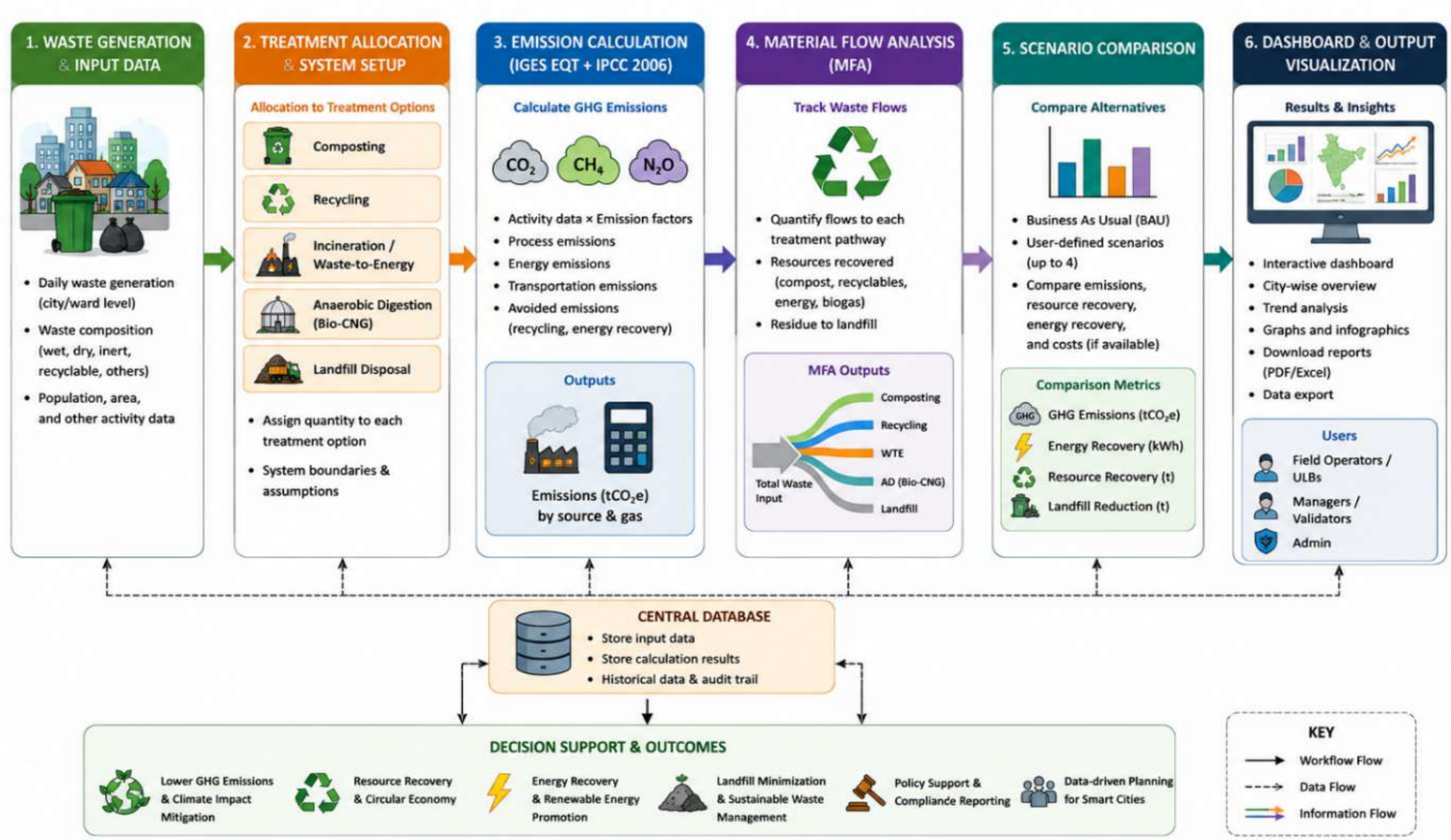


Fig. 2.5 Workflow of the GHG Calculator

2.4 GHG Emissions Calculation

The GHG Calculator quantifies emissions associated with different municipal solid waste management activities through dedicated technology-specific modules. Emissions are estimated separately for each treatment pathway using user-defined activity data and operational parameters. Table 2.1 describes the major emission categories considered in the app.

The platform comprises individual modules for transportation, composting, anaerobic digestion, recycling, incineration and landfill disposal. Each module requires process-specific information related to waste allocation, energy consumption, fuel usage, and operational characteristics of the selected treatment technology.

Estimated emissions are calculated for individual treatment processes and subsequently integrated to evaluate the overall greenhouse gas emissions associated with the municipal solid waste management in a ULB or corporation or city.

Table 2.1 Major emission categories considered for waste treatment pathways

Category	Description
Transportation	Fuel-based emissions generated during waste collection and transportation for all type of vehicles including petrol, diesel, Compressed Natural Gas (CNG), and Electric Vehicle (EV).
Composting	Emissions generated during aerobic treatment of biodegradable waste; Fossil energy (grid electricity and diesel) for various operational activities at the facility
Anaerobic Digestion	Emissions and energy recovery associated with anaerobic digestion processes; Fossil energy (grid electricity and diesel) for various operational activities at the facility
Recycling	Recycling emissions and avoided emission assessment
Incineration	Waste combustion and energy recovery emissions
Landfilling	Methane emissions generated from anaerobic decomposition of waste in landfill disposal facilities.

2.4.1 Composting

Composting is an aerobic biological treatment process used for stabilizing biodegradable municipal solid waste and producing compost as a useful soil amendment. The composting module quantifies GHG emissions arising from the treatment of organic waste under aerobic conditions. The module requires information related to the quantity of waste allocated for composting, transportation of input and output materials, energy consumption, and operational activities at the composting facility. Users provide details on vehicle types, fuel consumption, electricity use, compost production, and the proportion of compost utilized for agricultural and gardening purposes.

Based on the input data, methane (CH_4) and nitrous oxide (N_2O) emissions generated during the composting process are estimated. In addition to direct process emissions, the module also accounts for emissions resulting from transportation and facility operations. Potential emission reductions associated with compost utilization are considered to determine the net greenhouse gas impact of composting activities. Backend calculations employed in the app for determining the net GHG emissions associated to composting process are as follows:

(i) GHG emissions from operational activities of composting:

$$Emissions_{GHG\ (i)-Operation} = \frac{Fuel\ \left(\frac{unit}{day}\right) \times NCV\ \left(\frac{MJ}{unit}\right) \times EF\left(\frac{kg}{MJ}\right) + EC \times EF_{El}}{AOW(tonnes/day)}$$

$Emissions_{GHG(i)\text{-}operation}$ – Emissions ith GHG (different type of GHG e.g. CO_2, CH_4, N_2O);
Fuel (unit) – Total amount of fossil fuel units (kg or L) consumption per day;
NCV – Net calorific value of fossil fuel consumed;
EF – CO_2, CH_4, N_2O emission factor of fuel (e.g. diesel: 0.074 kg CO_2/MJ) EC- Electricity consumption for operation activities (kWh/day);
EF_{el} – Emission factor of grid electricity production (kg CO_2-eq/kWh);
AOW – Amount of Waste used for composting (tons/day);
(ii) Black carbon (BC) emissions from operational activities:

$$Emissions_{BC-Operatio} = \frac{Fuel\ \left(\frac{unit}{day}\right) \times NCV\ \left(\frac{MJ}{unit}\right) \times EF\left(\frac{kg}{MJ}\right)}{AOW(tonnes/day)}$$

EF – EF of black carbon has given in g/MJ.

(iii) GHG Emissions from waste degradation:

$$Emissions_{GHG(i)-degradati} = EF\ (kg/tonne)$$

EF – Emissions of CH_4 and N_2O from organic waste degradation (kg/ton of organic waste).

(iv) Total ith GHGs emissions from composting process:

$$Total\ GHG\ Emissions_i = Emissions_{Operation} + Emission_{Degradation}$$

(v) Avoided GHG emissions by replacing chemical fertilizers:

$$Avoided\ GHG_{(i)} = AC \times PC_{Agriculture} \times A_{GHG}$$

$AvoidedGHG_{(i)}$– Avoided i[th]GHG from composting due to avoidance of chemical fertilizer production (kg/ton);

AC – Amount of compost produced (ton of compost/ton of waste);

$PC_{Agriculture}$ – Percentage of compost use for agricultural and gardening purpose (%);

$AGHG_{(i)}$ – i^{th} GHG Avoidance potential from chemical fertilizer production which is equivalent to one ton of compost (kg/ton of compost).

(vi) Net i^{th} GHG emissions and net BC emissions:

$$Net\ (GHG)_{(i)} = Total\ (GHG)_{(i)} - Avoided\ (GHG)_{(i)}$$

(vii) Net climate impact from all GHGs estimated as kgCO_2-eq/ton:

$$Net\ GHG_{(CO2\ \ /tonne)} = CO_{2(net)} \times 1 + CH_4(biogenic)_{net} \times 28 + CH_4(fossil)_{(net)} \times 30 + N_2O_{(net)} \times 265$$

The estimated results are presented as individual GHG emissions and net emissions, enabling evaluation of the environmental performance of composting as a waste management option.

2.4.2 Anaerobic Digestion

Anaerobic digestion is a biological treatment process in which biodegradable waste is decomposed in the absence of oxygen to produce biogas and digestate. The anaerobic digestion module quantifies GHG emissions associated with the treatment of organic waste through controlled anaerobic process.

The module incorporates information on waste allocation, transportation of input and output materials, operational energy requirements, and fuel consumption. Users are also required to specify the type of energy recovered from the digestion process, such as heat, electricity, combined heat and power, or direct utilization of biogas. In addition, information related to digestate recovery and the proportion of recovered compost is included.

Based on the input data, the module estimates emissions generated during anaerobic treatment operations while accounting for biogas recovery and utilization. The substitution of conventional energy sources through recovered energy is considered to estimate potential emission reductions. This facilitates assessment of the role of anaerobic digestion in reducing GHG emissions and promoting sustainable waste management. Calculations used in the app for the determination of net GHG emissions from AD are as follows:

(i) GHG emissions from operational activities of AD:

$$Emissions_{GHG(i)-Operation} = \frac{Fuel\ \left(\frac{unit}{day}\right) \times NCV\ \left(\frac{MJ}{unit}\right) \times EF\left(\frac{kg}{MJ}\right) + EC \times EF_{El}}{AOW(tons/day)}$$

$Emissions_{GHG(i)\text{-}operation}$ – Emissions i[th] GHG (different type of GHG e.g. CO_2, CH_4, N_2O);
Fuel (unit) – Total amount of fossil fuel units (kg or L) consumption per day;
NCV – Net calorific value of fossil fuel consumed;
EF – CO_2, CH_4, N_2O emission factor of fuel (e.g. diesel: 0.074 kg CO_2/MJ);
EC – Electricity consumption for operation activities (kWh/day);
EF_{el} –Emission factor of grid electricity production (kg CO_2-eq/kWh);
AOW- Amount of waste used for AD (tons/day).

(ii) Black carbon (BC) emissions from operational activities of AD:

$$Emissions_{BC-Operation} = \frac{Fuel\ \left(\frac{unit}{day}\right) \times NCV\ \left(\frac{MJ}{unit}\right) \times EF\left(\frac{kg}{MJ}\right)}{AOW(tons/day)}$$

EF – EF of black carbon has given in kg/MJ.

(iii) GHG emissions from AD process:

$$Emissions_{GHG(i)-Leakage} = EF\ (kg/tonne)$$

EF – Emissions of CH_4 due to unavoidable leakages (kg/ton of organic waste).

(iv) Total i[th] GHGs emissions from AD process:

$$Total\ GHG\ Emissions_i = Emissions_{Operation} + Emission_{Leakage}$$

(v) Avoided GHG emissions by recovering electricity:

$$Avoided\ GHG_{(i)} = A_{Biogas} \times P_{CH4} \times E_{CH4} \times \frac{1}{CF_{Energy}} \times E_{Powerplant} \times EF_{el}$$

Avoided $GHG_{(i)}$– Avoided i^{th} GHG from composting due to avoidance of chemical fertilizer production (kg/ton);

A_{Biogas} –Amount of biogas produced (m^3/ton);
P_{CH4} – Percentage of CH_4 in biogas (%);
E_{CH4} – Energy content of CH_4 (MJ/m^3);
CF_{Energy} – Conversion factor of energy (3.6 MJ/kWh);
$E_{Powerplant}$ – Efficiency of the power plant (%);
EF_{el} - Emission factor of country grid electricity production (kg CO_2-eq/kWh);

(vi) Avoided GHG emissions by biogas replacing fossil energy:

$$Avoided\ GHG_{(i)} = C_{Biogas} \times P_{CH4} \times E_{CH4} \times EF_{(i)}$$

Avoidance GHG_i–i^{th} GHG avoidance due to thermal energy production (kg /ton);
C_{Biogas} – Collected amount of biogas (m^3/ton);
P_{CH4} –Percentage of CH_4 in biogas (%);
E_{CH4} –Energy content of CH_4 (MJ/m^3);
$EF_{(i)}$- Emission factor of i^{th} GHG by avoided fossil fuel combustion (kg/MJ).

(vii) Avoided GHG emissions by utilizing digestate as compost and thereby replacement of chemical fertilizer:

$$Avoided\ GHG_{(i)} = AC \times PC_{Agriculture} \times A_{GHG}$$

Avoided $GHG_{(i)}$– Avoided i^{th} GHG from AD due to avoidance of chemical fertilizer production (kg/ton);
AC – Amount of digestate/compost produced (ton of compost/ton of waste);
$PC_{Agriculture}$ – Percentage of digestate used for agricultural and gardening purpose (%);
$A_{GHG(i)}$ – ith GHG Avoidance potential from chemical fertilizer production which is equivalent to one ton of compost (kg/ton of compost).

(viii) Net i^{th} GHG emissions and net BC emissions:

$$Net\ (GHG)_{(i)} = Total\ (GHG)_{(i)} - Avoided\ (GHG)_{(i)}$$

(ix) Net climate impact from all GHGs estimated as kgCO_2-eq/ton:

$$Net\ GHG_{(CO2-e\ \ /ton)} = CO_{2(net)} \times 1 + CH_4(biogenic)_{net} \times 28 + CH_4(fossil)_{(net)} \times 30 + N_2O_{(net)} \times 265$$

The estimated results are presented as individual GHG emissions and net emissions, enabling evaluation of the environmental performance of AD as a waste management option.

2.4.3 Recycling

Recycling involves the recovery, processing, and reintroduction of recyclable materials into the production cycle, thereby reducing the demand for virgin raw materials. The recycling module quantifies GHG emissions and emission reductions associated with material recovery activities.

The module incorporates information related to waste allocation, transportation requirements, and the composition of recyclable materials recovered through both formal and informal sectors. Users provide data on the recovery of paper and cardboard, plastics, aluminium, steel, and glass, together with material-specific processing requirements.

For each recyclable material, the module considers electricity consumption, fuel usage, and recyclability rates during processing activities. Emissions arising from collection, transportation, and processing operations are estimated, while the environmental benefits associated with substituting virgin materials with recycled products are also considered. The calculations involved to determine the GHG emissions from recycling operations are as follows:

(i) GHG emissions from operational activities of one type of recyclables:

$$Emissions_{GHG(i)-Operati} = \frac{Fuel\left(\frac{unit}{day}\right) \times NCV\left(\frac{MJ}{unit}\right) \times EF\left(\frac{kg}{MJ}\right) + EC \times EF_{El}}{AOR(tons/day)}$$

$Emissions_{GHG(i)-operation}$ – Emissions i^{th} GHG (different type of GHG e.g. CO_2, CH_4, N_2O);
Fuel (unit) – Total amount of fossil fuel units (kg or L) consumption per day;
NCV – Net calorific value of fossil fuel consumed;
EF – CO_2, CH_4, N_2O emission factor of fuel (e.g. diesel: 0.074 kg CO_2/MJ);
EC – Electricity consumption for operation activities (kWh/day);
EF_{el} –Emission factor of grid electricity production (kg CO_2-eq/kWh);
AOR- Amount of recyclables managed (tons/day);

(ii) GHG emissions from recyclable mix:

$$Emissions_{GHG(i)} = Total_{Recyclables} \times PC_{Paper} \times E_{Paper(i)} + Total_{Recyclables} \times PC_{Plastic} \times E_{Plastic(i)} + Total_{Recyclables} \times PC_{Aluminium} \times E_{Aluminium(i)} + Total_{Recyclables} \times PC_{Metal} \times E_{Metal(i)} + Total_{Recyclables} \times PC_{Glass} \times E_{Glass(i)}$$

Avoided $_{GHG(i)}$– Avoided i^{th} GHG emissions from recovery of material (kg/ton);

Total recyclables– Total amount of recyclables collected (tons/day);

PC– Percentage of different types in the composition (e.g. paper, plastic, aluminium);

$E_{(i)}$– Amount of i^{th} Emissions per ton material recycling. (kg/ton).

(iii) Avoided GHG emissions from recyclable mix through material recovery:

$$Avoided_{GHG(i)} = Total_{Recyclables} \times PC_{Paper} \times RE_{Paper} \times EV_{Paper(i)} + Total_{Recyclables} \times PC_{Plastic} \times RE_{Plastic} \times EV_{Plastic(i)} + Total_{Recyclables} \times PC_{Aluminium} \times RE_{Aluminium} \times EV_{Aluminium(i)} + Total_{Recyclables} \times PC_{Metal} \times RE_{Metal} \times EV_{Metal(i)} + Total_{Recyclables} \times PC_{Glass} \times RE_{Glass} \times EV_{Glass(i)}$$

Avoided $_{GHG(i)}$– Avoided i^{th} GHG emissions from recovery of material (kg/ton);

Total recyclables– Total amount of recyclables collected (tons/day);

PC– Percentage of different types in the composition (e.g. paper, plastic, aluminium);

RE– Recyclability of materials (actual amount of materials recovery per ton of waste (%);

$EV_{(i)}$– Amount of i^{th} Emissions per ton Virgin material production. (kg/ton).

(iv) Net i^{th} GHG emissions:

$$Net\ (GHG)_{(i)} = Total\ (GHG)_{(i)} - Avoided\ (GHG)_{(i)}$$

(v) Net climate impact from all GHGs estimated as kg CO_2 eq/ton

$$Net\ GHG_{(CO2-e\ \ /ton)} = CO_{2(net)} \times 1 + CH_4(biogenic)_{net} \times 28 + CH_4(fossil)_{(net)} \times 30 + N_2O_{(net)} \times 265$$

The module facilitates assessment of the contribution of recycling towards resource conservation and GHG mitigation within the municipal solid waste management system.

2.4.4 Incineration

Incineration is a thermal treatment process in which municipal solid waste is combusted under controlled conditions to reduce waste volume and recover useful energy. The incineration module quantifies GHG emissions associated with the thermal processing of mixed waste.

The module incorporates waste allocation, transportation requirements, and information related to the characteristics of waste subjected to incineration. Users provide data on the composition of mixed waste, calorific value, and the type of incineration technology employed. Operational information related to electricity consumption, fuel usage, and transportation activities is also considered.

The module estimates emissions arising from waste combustion and evaluates energy recovery options, including heat generation, electricity production, or combined heat and power systems. Information on energy recovery efficiencies, onsite energy utilization, and the substitution of conventional fossil fuels by recovered energy is incorporated to estimate potential emission reductions. The calculation steps employed in the app in determining net climate impact associated to incineration operations are listed below:

(i) GHG emissions from operational activities at incineration facility:

$$Emissions_{GHG(i)-Operati} = \frac{Fuel\left(\frac{unit}{day}\right) \times NCV\left(\frac{MJ}{unit}\right) \times EF\left(\frac{kg}{MJ}\right) + EC \times EF_{El}}{AOW\,(tons/day)}$$

$Emissions_{GHG(i)\text{-}operation}$ – Emissions i[th] GHG (different type of GHG e.g. CO_2, CH_4, N_2O);
Fuel (unit) – Total amount of fossil fuel units (kg or L) consumption per day;
NCV – Net calorific value of fossil fuel consumed;
EF – CO_2, CH_4, N_2O emission factor of fuel (e.g. diesel: 0.074 kg CO_2/MJ);
EC – Electricity consumption for operation activities (kWh/day);
EF_{el} –Emission factor of grid electricity production (kg CO_2-eq/kWh);
AOW- Amount of waste used for AD (tons/day).

(ii) BC emissions from operational activities at incineration facility:

$$Emissions_{BC-Operation} = \frac{Fuel\left(\frac{unit}{day}\right) \times NCV\left(\frac{MJ}{unit}\right) \times EF\left(\frac{kg}{MJ}\right)}{AOW\,(tons/day)}$$

EF – EF of black carbon has given in kg/MJ.

(iii) Quantify the GHG emissions from combustion of waste:

$$CE = \sum(SW_i \times dm_i \times CF_i \times FCF_i \times OF_i)\frac{44}{12}$$

i – type of fossil fuel-based waste incinerated such as textiles, rubber and leather, plastics;

CE – Combustion Emissions (kg CO_2/ton);

SW_i – total amount of i[th] type of waste (wet weight) incinerated (kg/tonne of waste);

dm_i – dry matter content in the waste (partially wet weight) incinerated;

CF_i –fraction of carbon in the dry matter (total carbon content);

FCF_i – fraction of fossil carbon in the total carbon;

OF_i – oxidation factor,

44/12 – conversion factor from C to CO_2

(iv) Total i[th] emissions from incineration:

$$Total\ GHG_{(i)} = Emission_{Degradation} + Emission_{Combustion}$$

(v) Avoided GHG emissions via heat recovery:

$$Avoided\ GHG_{(i)} = LHV_{Waste} \times E_{HR} \times OC \times EF_i$$

(vi) Avoided GHG emissions via electricity recovery:

$$Avoided\ GHG_{(i)} = LHV_{Waste} \times \frac{E_{HR}}{CF} \times OC \times EF_{el(i)}$$

Avoided $GHG_{(i)}$– Avoided i[th] GHG from heat recovery from incineration (MJ /ton);

LHV_{waste} – Low Heating Value of mixed waste (MJ/ton);

EHR–Efficiency of Heat Recovery (%); OC– Percentage of onsite Consumption (%);

EF_i–Emission Factor of i[th] GHGs from avoided fossil fuel combustion (kg/MJ) to provide equivalent amount of energy; EER– Efficiency of Electricity Recovery (%);

CF– Conversion Factor (3.6 MJ/kWh)

EFel –Emission factor i[th] GHGs from grid electricity production (kg CO_2-eq/kWh)

(vii) Net i[th] GHG emissions:

$$Net\ (GHG)_{(i)} = Total\ (GHG)_{(i)} - Avoided\ (GHG)_{(i)}$$

(viii) Net climate impact from all GHGs estimated as kg CO_2 eq/ton:

$$Net\ GHG_{(CO2-e\ \ /ton)} = CO_{2(net)} \times 1 + CH_4(biogenic)_{net} \times 28 + CH_4(fossil)_{(net)} \times 30 + N_2O_{(net)} \times 265$$

The estimated results facilitate assessment of the environmental implications of thermal waste treatment and the contribution of energy recovery towards GHG mitigation.

2.4.5 Landfilling

Landfilling is the final disposal stage of municipal solid waste management, in which waste is deposited in engineered landfill facilities or open dumping sites. The landfill module quantifies greenhouse gas emissions associated with waste disposal, with particular emphasis on methane (CH_4) generation arising from the in situ anaerobic degradation of organic waste. The module incorporates information related to waste allocation and energy requirements associated with landfill operations. Users provide information on landfill characteristics, including the type of disposal facility, annual waste disposal growth, disposal period, and the proportion of waste subjected to open burning at the site.

Methane emissions from disposal facilities are estimated using the IPCC First Order Decay (FOD) approach integrated within the IGES EQT framework. The module further incorporates landfill gas recovery practices, treatment options, recovery efficiency, and the utilization of recovered gas for energy generation or fuel substitution. The calculations involved in determining net climate impact associated to landfill operations are listed below:

(i) GHG emissions from operational activities at landfill:

$$Emissions_{GHG(i)-Operati} = \frac{Fuel\left(\frac{unit}{day}\right) \times NCV\left(\frac{MJ}{unit}\right) \times EF\left(\frac{kg}{MJ}\right) + EC \times EF_{El}}{AOW(tons/day)}$$

$Emissions_{GHG(i)-operation}$ – Emissions ith GHG (different type of GHG e.g. CO_2, CH_4, N_2O);
Fuel (unit) – Total amount of fossil fuel units (kg or L) consumption per day;
NCV – Net calorific value of fossil fuel consumed;
EF – CO_2, CH_4, N_2O emission factor of fuel (e.g. diesel: 0.074 kg CO_2/MJ);
EC – Electricity consumption for operation activities (kWh/day);
EF_{el} –Emission factor of grid electricity production (kg CO_2-eq/kWh);
AOW- Amount of waste used for AD (tons/day).
(ii) BC emissions from operational activities at landfill:

$$Emissions_{BC-Operation} = \frac{Fuel\left(\frac{unit}{day}\right) \times NCV\left(\frac{MJ}{unit}\right) \times EF\left(\frac{kg}{MJ}\right)}{AOW(tons/day)}$$

EF – EF of black carbon has given in kg/MJ.

(iii)CH4 emissions from waste degradation in the landfill (IPCC 2006 waste model)

The basic equation for the first order decay model is:

$DDOC_m = DDOC_{m(0)} \times e^{-kt}$

$DDOC_{m(0)}$ – mass of decomposable degradable organic carbon (DDOC) at the start of the reaction, k – reaction constant; t – time in years. DDOCm – mass of DDOC at any time.

Mass of decomposable DOC (DDOCm) amount of waste material; $DDOC_{md(T)} = W_{(T)} \times DOC \times DOC_f \times MCF$

$DDOC_{md(T)}$ – mass of DDOC deposited year T; $W_{(T)}$ – amount deposited in year T; MCF – Methane Correction Factor; DOC – Degradable organic carbon; DOC_f – Fraction of DOC decomposing under anaerobic conditions.

The amount of deposited $DDOC_m$ remaining at the end of deposition year T:

$DDOC_{mrem(T)} = DDOC_{md(T)} \times e(-k \bullet ((13\text{-}M)/12)$

$DDOC_{mrem(T)}$ – mass of DDOC deposited in year T, remaining at the end of year; M – Month of reaction start.

The amount of deposited DDOCm decomposed during deposition year T: DDOCmdec(T) = $DDO_{Cmd(T)} \times (1 - e\ (-k \bullet ((13\text{-}M)/12)))$

$DDOC_{mdec(T)}$ – mass of DDOC deposited decomposed during the year T.

The amount of $DDOC_m$ accumulated in the disposal site at the end of year T $DDOC_{ma(T)} = DDOC_{mrem(T)} + (\ DDOC_{ma(T\text{-}1)} \times e\text{-}k)$

$DDOC_{ma(T)}$ – total mass of DDOC left (not decomposed) at end of year T. $DDOC_{ma(T\text{-}1)}$ – total mass of DDOC left not decomposed at end of year T-1.

The total amount of $DDOC_m$ decomposed in year T:

$DDOC_{mdecomp(T)} = DDOC_{mdec(T)} + (DDOC_{ma(T\text{-}1)} \times (1 - e^{-k}))$

$DDOC_{mdecomp(T)}$ – total mass of DDOC decomposed in year T.

The amount of CH_4 generated from DOC decomposed:

$CH_4\ generated_{(T)} = DDOC_{mdecomp(T)} \times F \times 16/12.$

$CH_4\ generated_{(T)}$ – CH_4 generated in year T; F – Fraction of CH_4 by volume in generated landfill gas (0.0 – 1.0); 16/ Molecular weight ratio CH_4/C.

The amount of CH_4 emitted from disposal site:

CH_4 emitted in year T = (ΣCH_4 generated $_{(T)}$ – $R_{(T)}$) × (1- $OX_{(T)}$)

$R_{(T)}$ – Recovered CH_4 in year T; $OX_{(T)}$ – Oxidation factor in year T (fraction)

$$CH_4(kg/ton) = \frac{\sum_0^t CH_4}{\sum_0^t AOW}$$

0-t– total emission during year 0 to t

AOW – Amount of waste dispose during year 0 to t

(iv) Total i^{th} emissions from landfill:

$$Total\ GHG_{(i)} = Emission_{Degradation}$$

(v) Avoided GHG emissions via heat recovery:

$$Avoided\ GHG_{(i)} = LFG_{Collected} \times P_{CH4} \times HV_{CH4} \times EF_i$$

Avoided $GHG_{(i)}$– Avoided i^{th} GHG/SLCP from electricity production from LFG (kg of CO_2-eq/ton); $LFG_{Collected}$ – Collected LFG (m^3/ton)

PCH4 –Percentage (%) of CH_4 in LFG (%); $HVCH_4$ – Heating value of CH4 (MJ/m^3)

EF_i-Emission Factor of i^{th} GHG from avoided fossil fuel combustion (kg/MJ) to provide equivalent amount of energy

(vi) Net i^{th} GHG emissions:

$$Net\ (GHG)_{(i)} = Total\ (GHG)_{(i)} - Avoided\ (GHG)_{(i)}$$

(vii) Net climate impact from all GHGs estimated as kg CO_2 eq/ton:

$$Net\ GHG_{(CO2-eq/ton)} = CO_{2(net)} \times 1 + CH_4(biogenic)_{net} \times 28 + CH_4(fossil)_{(net)} \times 30 + N_2O_{(net)} \times 265$$

The estimated results provide information on methane emissions, landfill gas recovery potential, and the climate implications associated with waste disposal activities. Fig. 2.6 presents a summary of the technology options incorporated in the web app, and the typical emission output.

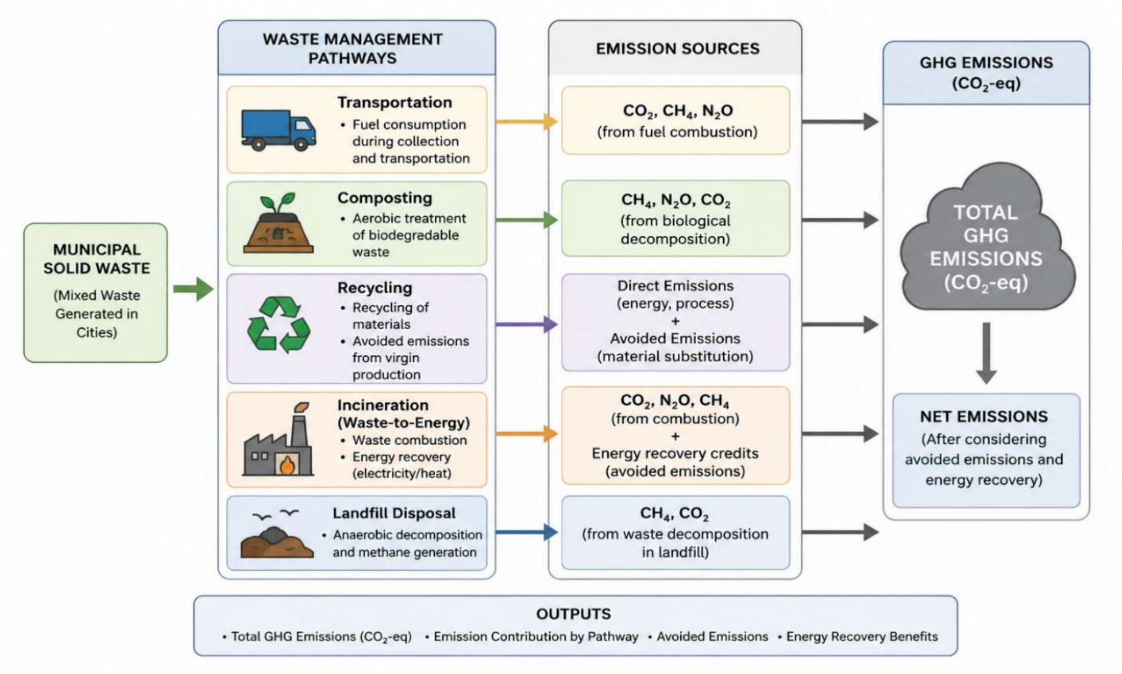


Fig. 2.6 Emission estimation pathways considered in the GHG Calculator

2.5 Scenario Comparison

The Scenario Comparison module enables users to evaluate the environmental implications of different municipal solid waste management strategies. The module supports comparison between a previously saved Business-As-Usual (BAU) scenario and alternative waste management scenarios.

Users can select a saved BAU scenario file and specify the number of scenarios (upto 4) to be analysed. Alternative scenarios are developed by modifying waste allocation among different treatment technologies, including composting, anaerobic digestion, recycling, incineration, and landfill disposal. For each scenario, the total quantity of waste allocated among the treatment options should remain consistent with the total waste considered in the assessment.

The module facilitates comparison across various components, including waste generation and allocation, transportation activities, treatment processes, and overall system performance. Estimated emissions are presented in graphical and tabular formats, enabling users to compare emission patterns and identify waste management strategies with lower environmental impacts. Fig. 2.7 presents a scenario comparison framework implemented in the app, and the associated emissions and indicators for an effective comparative assessment.

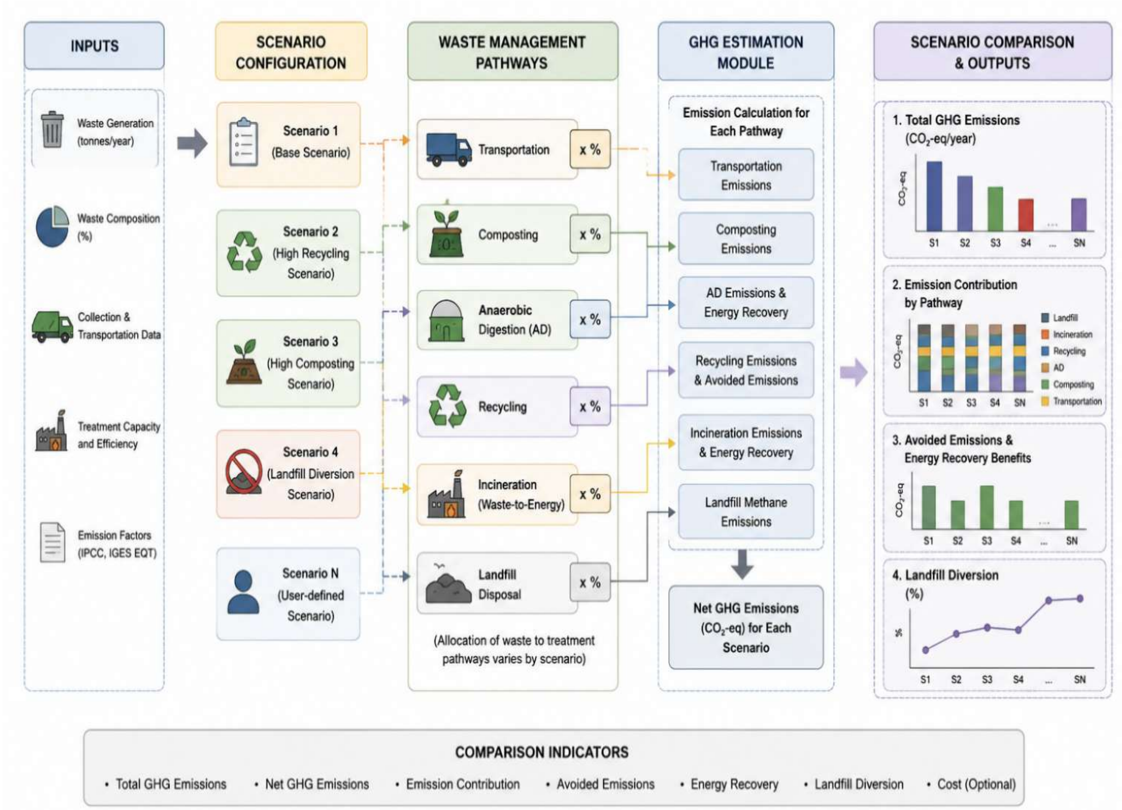


Fig. 2.7 Scenario comparison framework for alternative waste management pathways

2.6 My Files

The My Files module enables users to manage previously saved assessment files within the application (Fig. 2.8). The module serves as a centralized repository for storing city assessment files and scenario comparison results generated during the analysis process.

Users can browse and search the saved files using the file search option. The module also allows users to view, download, and delete previously stored files as required. In addition, saved files can be retrieved for further analysis, modification of input data, and re-evaluation of GHG emissions under different waste management scenarios.

The file management system facilitates efficient storage, retrieval, and maintenance of assessment records, thereby supporting continuous monitoring and analysis of municipal solid waste management practices.

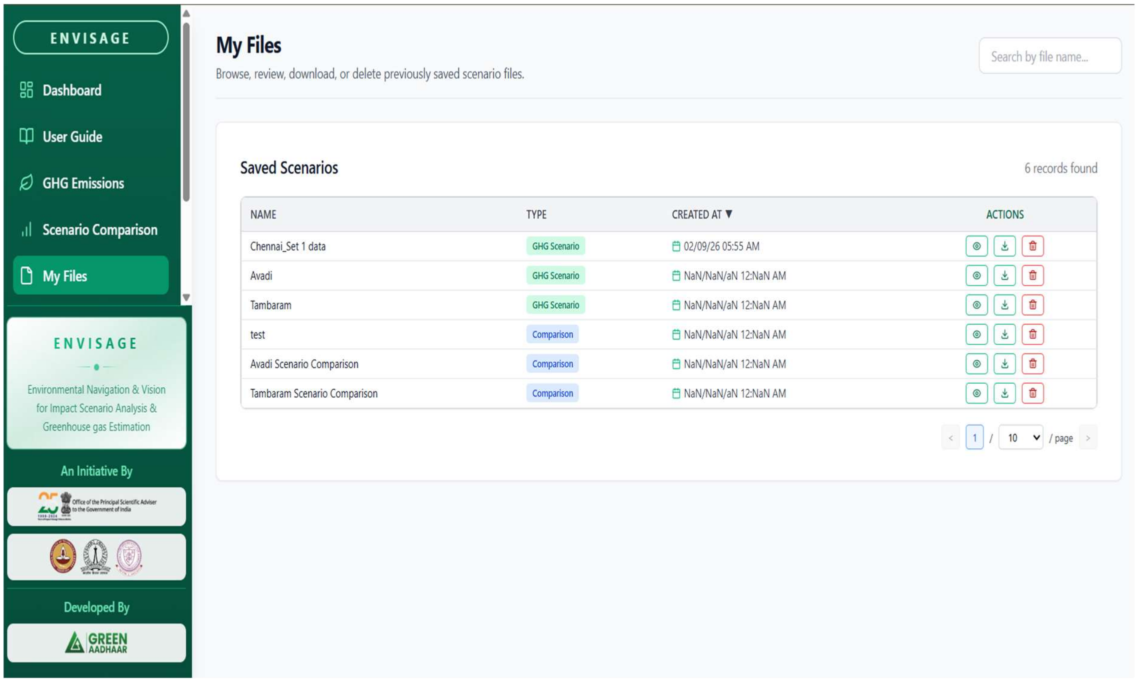


Fig. 2.8 My Files interface for managing saved GHG assessment files

2.7 User Management

The User Management module facilitates the administration and control of user access within the GHG Calculator application. The module enables authorized administrators to create, modify, and manage user accounts to ensure secure access to the platform.

Users can register and log in to the application using valid credentials. Depending on the assigned roles and permissions, users may access specific functionalities related to data entry, scenario development, database management, and result interpretation. The user hierarchy can be configured from ground-level personnel, such as the ULB data entry manager, through successive levels of Engineers in the SWM department, Chief Engineer, and Admin, allowing each level to control the activities permitted within its scope.

The module supports activities such as user registration, authentication, password management, and profile updates. Administrative users can monitor user activities and manage access privileges whenever necessary.

The User Management module ensures secure operation of the platform by maintaining controlled access to system functionalities and safeguarding assessment data from unauthorized modifications. Fig. 2.9 presents a snapshot of the user directory in the app linked to various cities and roles.

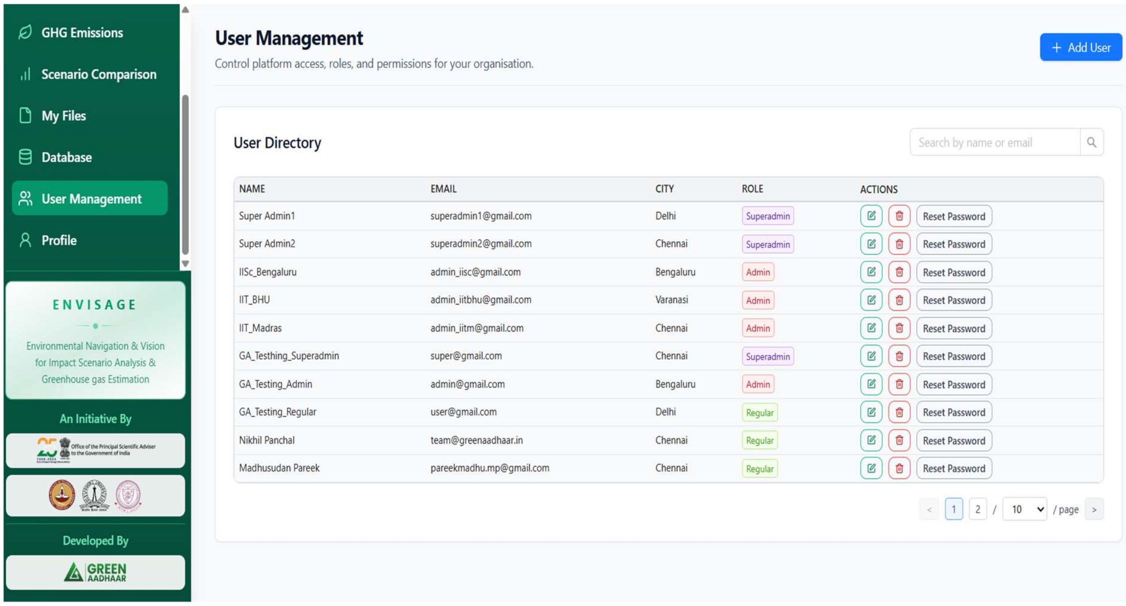


Fig. II.9 User Management interface for managing user accounts and access privileges

2.8 Database

The Database module provides a centralized platform for maintaining the reference values used within the GHG Calculator application. It stores emission factors, conversion factors, and other input parameters required for different waste management processes.

Records are organized according to coverage level, city, process type, parameter category, and units to facilitate efficient data management. Users can filter records based on process type and access detailed information related to individual parameters.

The module supports the addition of new records as well as the updating and removal of existing entries through dedicated management options. Parameter values can be revised whenever updated information becomes available, thereby ensuring that the application utilizes the most recent reference data. To preserve the integrity of the backend calculation structure, such database modifications are restricted to users with super-admin privileges. This functionality is supported by a three-tier login architecture comprising, from highest to lowest authority, super-admin, admin, and operator levels.

In addition, the database maintains information related to the latest updates and user modifications, ensuring traceability and transparency of parameter changes within the application (Fig. 2.10).

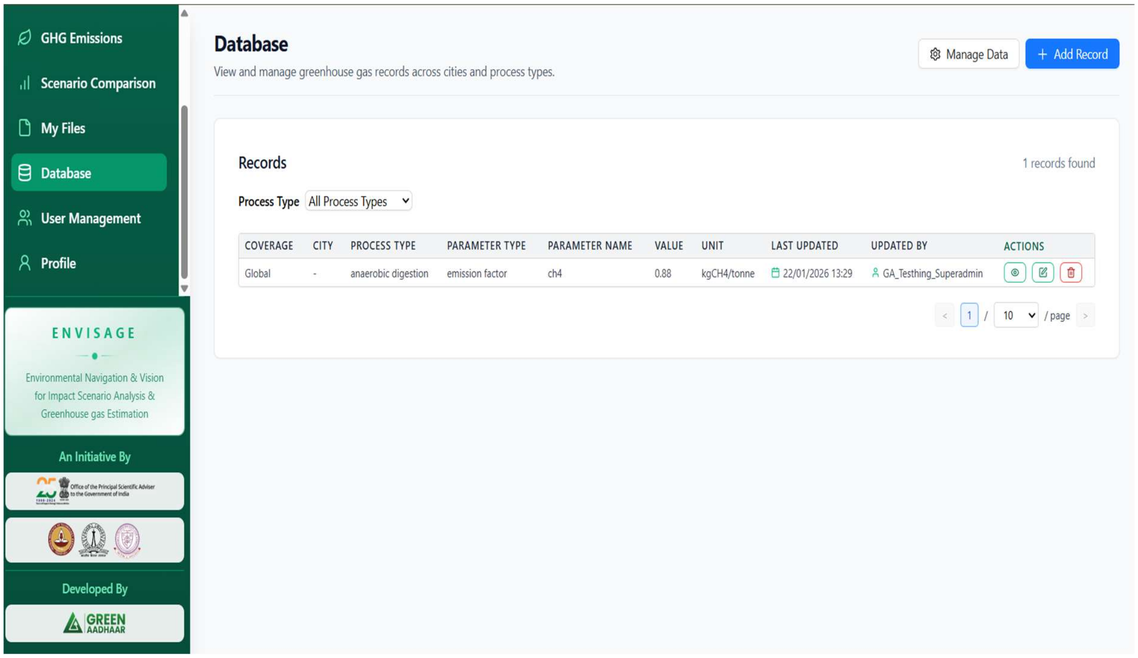


Fig. II.10 Database management interface of the GHG Calculator

2.9 Profile

The Profile module serves as the primary data entry interface of the GHG Calculator application. The module enables users to enter and maintain baseline information related to municipal solid waste management systems for a selected city.

Users are required to provide city-level information such as population, geographical area, number of wards, waste generation rate, and waste treatment methods adopted. In addition, the module captures detailed information on waste composition, including the percentage distribution of different waste fractions such as food waste, plastics, paper, glass, metals, textiles, and other components (Fig. 2.11).

The module also incorporates transportation-related information, including vehicle types, fuel consumption patterns, and transfer station activities associated with waste collection and transportation operations. Furthermore, process-specific input parameters related to composting, anaerobic digestion, recycling, incineration, and landfill disposal are recorded in accordance with the IGES EQT framework.

The information entered through the profile module forms the basis for GHG estimation, scenario evaluation, and environmental assessment within the application.

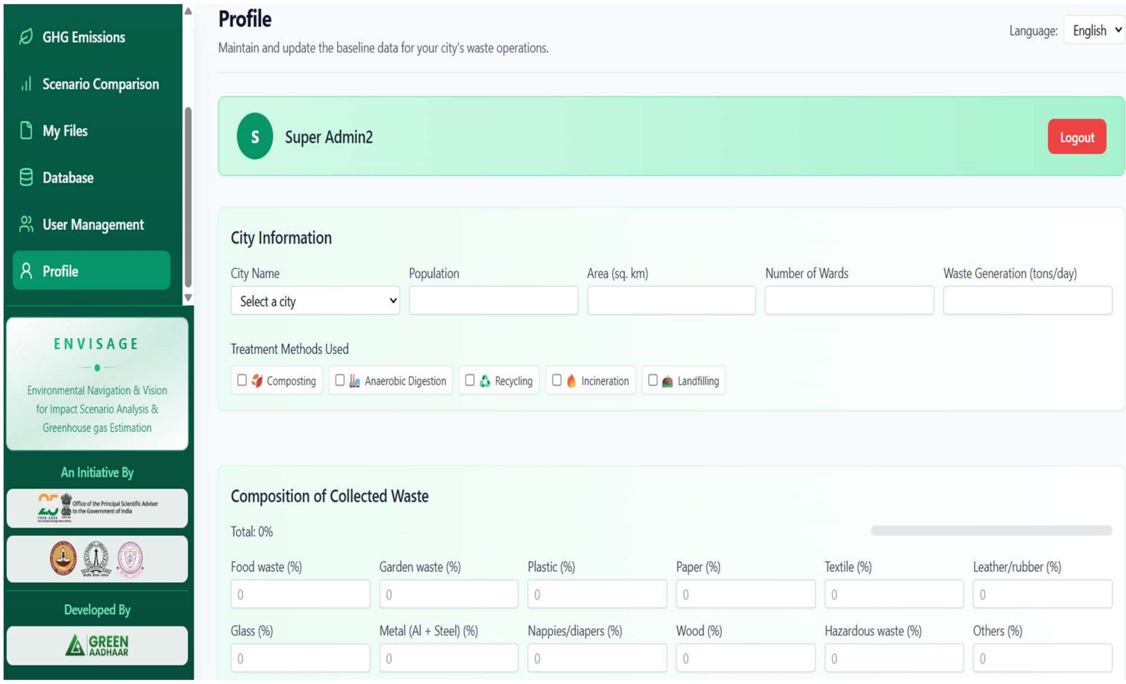


Fig. 2.9 Profile interface for entering city-level and process-specific input data

Chapter 3
Case Study

3.1 Preamble

This chapter describes the data input framework developed for the GHG Calculator application and presents the baseline information required to support scenario-based emission estimation. It introduces the source and structure of the operational data used for each module, including waste management, transportation, composting, anaerobic digestion, recycling, incineration, and landfilling, thereby establishing the foundation for subsequent calculations and comparisons.

3.2 Baseline Waste Management Data for Avadi and Tambaram

The baseline waste management data for Avadi and Tambaram are presented in Table 3.1. These data serve as the primary inputs for the development and evaluation of the GHG calculator scenarios.

Table 3.1 Waste generation and composition data for Avadi and Tambaram

Field	Parameter	Value	
City Waste Data			
1	City name	**Avadi**	**Tambaram**
2	Population	10,02,798	15,28,400
3	Total waste generation (TPD)	382	607
4	Formally collected waste (TPD)	286.5	455.25
5	Informally collected waste (TPD)	19.1	30.35
6	Uncollected waste (TPD)	76.4	121.4
7	Wet waste (%)	54.00	51.00
8	Dry waste (%)	34.00	36.00
9	Mixed waste (%)	12.00	13.00
Composition of Collected Waste (%)			
1	Food waste (%)	54.00	51.00

2	Garden waste (%)	0.00	0.00
3	Plastic (%)	16.00	17.00
4	Paper (%)	5.00	6.00
5	Textile (%)	3.00	4.00
6	Leather/Rubber (%)	1.00	3.00
7	Glass (%)	2.00	1.00
8	Metal (%)	1.00	2.00
9	Nappies/Diappers (%)	0.00	0.00
10	Wood (%)	6.00	3.00
11	Hazardous waste (%)	0.00	0.00
12	Others (%)	12.00	13.00
13	Total (%)	100.00	100.00
Waste Allocation			
1	Composting (TPD)	78	95
2	Anaerobic Digestion (TPD)	5	5
3	Recycling (TPD)	7	45
4	Incineration (TPD)	0	0
5	Landfill (TPD)	196.5	310.25

3.3 Transportation Module Input Data

The transportation module is based on fuel and energy consumption data for solid waste collection and transportation. Table 3.2 summarizes the baseline transportation input data for Avadi and Tambaram.

Table 3.2 Transportation fuel and energy consumption data for Avadi and Tambaram

Field	Parameter	Value	
		Avadi	**Tambaram**
Fuel Consumption for Solid Waste Collection & Transportation			
1	Vehicle type		
	-Older trucks	-	-

	-Modern trucks	-	-
	-Both older & modern trucks	YES	YES
2	Fuel type & amount		
	-Petrol (L/day)	-	-
	-Diesel (L/day)	3600	4560
	-CNG (L/day)	-	-
	-Ev (kWh/day)	1228	188
Energy Consumption at Transfer Station			
1	Waste handled (TPD)	-	
2	Electricity used (kWh/day)	-	75
3	Fuel type & amount	-	-
	-Petrol (L/day)	-	-
	-Diesel (L/day)	-	70
	-CNG (L/day)	-	-
	-Ev (L/day)	-	-

3.4 Composting Module Input Data

Composting related operational data, including waste allocation, energy consumption, and process parameters were collected to estimate emissions from composting activities, The input parameters used in the composting module are presented in Table 3.3.

Table 3.3 Baseline and scenario-wise composting input parameters for Avadi and Tambaram

Field	Parameter	Value									
		Avadi	**S1**	**S2**	**S3**	**S4**	**Tambaram**	**S1**	**S2**	**S3**	**S4**
1	Waste Allocation (TPD)	78	100	15	40	70	95	140	20	95	110
Energy Consumption for Composting Operations											
1	Electricity used (kWh/day)	100	128	19	51	90	150	220.5	31.5	150	174
2	Fuel type & amount -Petrol -Diesel -CNG	-	-	-	-	-	-	-	-	-	-
Compost Production & Usage											
1	Compost production (kg/ton)	100	100	100	100	100	100	100	100	100	100

2	% of produced compost used for agriculture & gardening	90	90	90	90	90	90	90	90	90	90

3.5 Anaerobic Digestion Module Input Data

Anaerobic digestion related operational data, including waste allocation, energy consumption, and process parameters were collected to estimate emissions from anaerobic digestion activities. The input parameters used in the AD module are presented in Table 3.4.

Table 3.4 Baseline and scenario-wise anaerobic digestion input parameters for Avadi and Tambaram

Field	**Parameter**	**Value**									
		Avadi	**S1**	**S2**	**S3**	**S4**	**Tambaram**	**S1**	**S2**	**S3**	**S4**
1	Waste allocation (TPD)	5	30	120	50	70	5	50	200	50	110
Energy Consumption for AD Operations											
1	Electricity used (kWh/day)	50	300	1200	500	700	50	500	2000	500	1100
2	Fuel type & amount -Petrol -Diesel -CNG	-	-	-	-	-	-	-	-	-	-

Energy Production & Compost Recovery											
1	The product of energy from AD										
	-Heat	-	-	-	-	-	-	-	-	-	-
	-Electricity	-	-	-	-	-	-	-	-	-	-
	-Combined Heat & Electricity	-	-	-	-	-	-	-	-	-	-
	-Bio-gas as direct energy source	YES	YES	YES	YES	YES	YES	YES	YES	YES	YES
2	Recovery of anaerobic compost										
	-Yes	YES	YES	YES	YES	YES	YES	YES	YES	YES	YES
	-No	-	-	-	-	-	-	-	-	-	-
3	% of recovered anaerobic compost	20	20	20	20	20	20	20	20	20	20

3.6 Recycling Module Input Data

Recycling related operational data, including waste allocation, material composition, and recovery parameters were collected to estimate emissions from recycling activities. The input parameters used in the recycling module are presented in Table 3.5.

Table 3.5. Baseline and scenario-wise recycling input parameters for Avadi and Tambaram

Field	Parameter	Value									
		Avadi	**S1**	**S2**	**S3**	**S4**	**Tambaram**	**S1**	**S2**	**S3**	**S4**
1	Waste allocation (TPD)	7	15	40	20	65	45	50	45	60	100
Recycling Composition Formal Sector (Authorized Companies)											
1	Paper & cardboard (%)	25	25	25	25	25	20	20	20	20	20
2	Plastic (%)	45	45	45	45	45	55	55	55	55	55
3	Aluminium (%)	5	5	5	5	5	5	5	5	5	5
4	Metal/Steel (%)	10	10	10	10	10	10	10	10	10	10
5	Glass (%)	15	15	15	15	15	15	15	15	15	15
Informal Sector (Waste Pickers)											
1	Paper & cardboard (%)	20	20	20	20	20	30	30	30	30	30
2	Plastic (%)	60	60	60	60	60	40	40	40	40	40
3	Aluminium (%)	5	5	5	5	5	10	10	10	10	10
4	Metal/Steel (%)	10	10	10	10	10	15	15	15	15	15

5	Glass (%)	5	5	5	5	5	5	5	5	5	5
Recycling Processing Activities											
Paper & cardboard											
1	Electricity used (kWh/ton)	2	2	2	2	2	2	2	2	2	2
2	Fuel type & amount -Petrol -Diesel -CNG -Coal	-	-	-	-	-	-	-	-	-	-
3	Recyclability (%)	90	90	90	90	90	85	85	85	85	85
Plastic											
1	Electricity used (kWh/ton)	4	4	4	4	4	4	4	4	4	4
2	Fuel type & amount -Petrol -Diesel -CNG -Coal	-	-	-	-	-	-	-	-	-	-
3	Recyclability (%)	75	75	75	75	75	75	75	75	75	75

Aluminium											
1	Electricity used (kWh/ton)	1	1	1	1	1	1	1	1	1	1
2	Fuel type & amount -Petrol -Diesel -CNG -Coal	-	-	-	-	-	-	-	-	-	-
3	Recyclability (%)	95	95	95	95	95	95	95	95	95	95
Metal/Steel											
1	Electricity used (kWh/ton)	2	2	2	2	2	2	2	2	2	2
2	Fuel type & amount -Petrol -Diesel -CNG -Coal	-	-	-	-	-	-	-	-	-	-
3	Recyclability (%)	95	95	95	95	95	92	90	90	90	90
Glass											
1	Electricity used (kWh/ton)	1	1	1	1	1	1	1	1	1	1

2	Fuel type & amount -Petrol -Diesel -CNG -Coal	-	-	-	-	-	-	-	-	-	-
3	Recyclability (%)	90	90	90	90	90	90	90	90	90	90

3.7 Incineration Module Input Data

Incineration related operational data, including waste allocation, calorific value, and incinerator characteristics were collected to estimate emissions from incineration activities. The input parameters used in the incineration module are presented in Table 3.6.

Table 3.6 Baseline and scenario-wise incineration input parameters for Avadi and Tambaram

Field	Parameter	Value									
		Avadi	**S1**	**S2**	**S3**	**S4**	**Tambaram**	**S1**	**S2**	**S3**	**S4**
1	Waste allocation (TPD)	0	20	10	100	65	0	30	40	150	100
Incinerator info											
1	Calorific Value (LHV) of Waste	7.5	7.5	7.5	7.5	7.5	8	8	8	8	8
2	Incineration Type										
	-Continuous stoker	YES	YES	YES	YES	YES	YES	YES	YES	YES	YES

	-Continuous fluidized bed	-	-	-	-	-	-	-	-	-	-
	-Semi continuious stoker	-	-	-	-	-	-	-	-	-	-
	-Semi continuous fluidized stoker	-	-	-	-	-	-	-	-	-	-
Composition of Mixed Waste for Incineration (%)											
1	Food waste (%)	5	5	5	5	5	4	4	4	4	4
2	Garden waste (%)	5	5	5	5	5	4	4	4	4	4
3	Plastic (%)	35	35	35	35	35	38	38	38	38	38
4	Paper (%)	20	20	20	20	20	21	21	21	21	21
5	Textile (%)	10	10	10	10	10	10	10	10	10	10
6	Leather/Rubber (%)	5	5	5	5	5	6	6	6	6	6
7	Glass (%)	2	2	2	2	2	2	2	2	2	2
8	Metal (%)	1	1	1	1	1	1	1	1	1	1
9	Nappies/Diappers (%)	5	5	5	5	5	5	5	5	5	5
10	Wood (%)	8	8	8	8	8	6	6	6	6	6

11	Hazardous waste (%)	0	0	0	0	0	0	0	0	0	0
12	Others (%)	4	4	4	4	4	3	3	3	3	3
13	Total (%)	100	100	100	100	100	100	100	100	100	100
Energy Consumption for Incineration Operations											
1	Electricity used (kWh/day)	0	100	50	500	325	0	150	200	750	500
2	Fuel type & amount										
	-Petrol (L/day)	-	-	-	-	-	-	-	-	-	-
	-Diesel (L/day)	0	5	2.5	25	16.25	0	7.5	10	37.5	25
	-CNG (L/day)	-	-	-	-	-	-	-	-	-	-
Energy recovery from Incineration											
1	Energy recovered										
	-No energy recovered	YES	-	-	-	-	YES	-	-	-	-
	-Heat	-	-	-	-	-	-	-	-	-	-
	-Electricity	-	YES	YES	YES	YES	-	YES	YES	YES	YES
	-Heat & Electricity	-	-	-	-	-	-	-	-	-	-

2	Efficiency of electricity recovery (%)	0	20	20	20	20	0	20	20	20	20
3	Percentage of electricity used onsite (%)	0	10	10	10	10	0	10	10	10	10
4	Efficiency of heat recovery (%)	0	0	0	0	0	0	0	0	0	0
5	Percentage of recovered heat (%)	0	0	0	0	0	0	0	0	0	0
6	Fossil fuel replaced by recovered energy -Petrol -Diesel -CNG	-	-	-	-	-	-	-	-	-	-

3.8 Landfilling Module Input Data

Landfilling related operational data, including waste allocation, energy consumption, and landfill characteristics were collected to estimate emissions from landfill activities. The input parameters used in the landfilling module are presented in Table 3.7.

Table 3.7 Baseline and scenario-wise landfilling input parameters for Avadi and Tambaram

Field	Parameter	Value									
		Avadi	**S1**	**S2**	**S3**	**S4**	**Tambaram**	**S1**	**S2**	**S3**	**S4**
1	Waste allocation (TPD)	196.5	121.5	101.5	76.5	16.5	310.25	185.25	150.25	100.25	35.25

Energy Consumption for Landfill Operations											
1	Electricity used (kWh/day)	5	3.1	2.6	1.95	0.4	10	6	4.8	3.2	1.1
2	Fuel type & amount										
	-Petrol (L/day)										
	-Diesel (L/day)	5	3.1	2.6	1.95	0.4	15	9	7.2	4.8	1.65
	-CNG (L/ton)										
Landfill Operations											
1	Type of landfill										
	-Sanitary landfill with gas recovery	-	-	-	-	-	-	-	-	-	-
	-Sanitary landfill without gas recovery	-	-	-	-	-	-	-	-	-	-
	-Managed semi aerobic	-	-	-	-	-	-	-	-	-	-

	-Open dumping weed (>5m waste)	YES	YES	YES	YES	YES	YES	YES	YES	YES	YES
	-Open dumpimg shallow (<5m waste)	-	-	-	-	-	-	-	-	-	-
	-Uncategorized	-	-	-	-	-	-	-	-	-	-
2	% of disposed waste ultimately fired/open-burned in site	1	1	1	1	1	1	1	1	1	1
3	Estimated growth of annual disposal (%)	1.5	1.5	1.5	1.5	1.5	2	2	2	2	2
4	Starting year of waste disposal	2006	2006	2006	2006	2006	2005	2005	2005	2005	2005
5	End year of waste disposal	2045	2045	2045	2045	2045	2045	2045	2045	2045	2045
6	Current year of disposal	2026	2026	2026	2026	2026	2026	2026	2026	2026	2026

Chapter 4
Results GHG Calculator

4.1 Preamble

This chapter presents the data input, application and outputs of the developed web-based GHG Calculator for the selected case study corporations in Chennai, namely Avadi and Tambaram Municipal Corporations. The results include city-specific waste management profiles, GHG emission estimates, and scenario-based analyses.

Emissions associated with different waste management processes are evaluated to assess the environmental performance of existing municipal solid waste management practices and alternative waste management strategies. The findings provide insights into major emission sources and identify potential opportunities for reducing GHG emissions through improved waste management approaches.

4.2 City-wise Waste Management Profile

The developed GHG Calculator was applied to two selected case study areas, namely Avadi Municipal Corporation and Tambaram City Municipal Corporation, representing the western and southern regions of the Chennai Metropolitan Area, respectively. The existing municipal solid waste management conditions in these places were analysed to establish baseline conditions for GHG estimation.

The city profiles presented in the following sections summarize the key characteristics of Avadi and Tambaram, including waste generation, collection status, treatment practices, and disposal patterns. These baseline conditions provide the necessary context for interpreting GHG emission estimates and evaluating the results of subsequent scenario analyses.

4.2.1 Avadi Waste Management Profile

Avadi Municipal Corporation, located in the western part of the Chennai Metropolitan Area, covers a total area of 188 km^2 and comprises 48 administrative wards. It has a total population of approximately 1.0 million, including both the core municipal area and the extended region. The average per capita waste generation is estimated at 0.38 kg/person/day. The municipality generates about 220 TPD of waste within the ULB area and an additional 162 TPD from the extended area, resulting in a total municipal solid waste generation of 382 TPD.

The municipal solid waste stream in Avadi is predominantly organic, with food and vegetable waste accounting for 54% of the total waste generated. Plastics constitute 16% of the waste stream, followed by inert materials (11%), wood (6%), paper (5%), and other recyclable and recoverable fractions such as cloth, glass, metals, and leather/rubber. Formal collection systems handle approximately 286.5 TPD of waste, while an additional 19.1 TPD is recovered through informal recycling activities. Source segregation levels range between 50% and 60%, and door-to-door collection coverage is reported to be between 70% and 80%. Waste collection and transportation activities are supported by a fleet comprising 307 battery-operated vehicles (BOVs), 135 light commercial vehicles (LCVs), and 45 heavy commercial vehicles (HCVs).

Decentralized treatment infrastructure includes 30 functional Micro Composting Centres (MCCs) with a combined treatment capacity of 114.5 TPD. Approximately 78 TPD of biodegradable waste is processed through aerobic composting, resulting in a compost production of about 7.8 TPD. In addition, a biomethanation facility with a treatment capacity of 5 TPD has been established for organic waste processing. Dry waste management is facilitated through a Resource Recovery Centre (RRC) with a processing capacity of 10 TPD, where materials such as plastics, paper, metals, cloth, and rubber are recovered.

Residual waste remaining after processing is currently disposed at the Sekkadu dumpsite through open dumping practices. Although scientific landfill facilities are not presently available, biomining activities have been successfully completed at the legacy waste site, resulting in complete remediation of the accumulated legacy waste.

4.2.2 Tambaram Waste Management Profile

Tambaram City Municipal Corporation, situated in the southern region of the Chennai Metropolitan Area, encompasses a total area of 175.38 km² and consists of 70 wards. The corporation serves a population of approximately 1.53 million distributed across the municipal and extended areas. The average per capita waste generation is estimated at 0.40 kg/person/day. It generates nearly 607 TPD of municipal solid waste, of which 450 TPD originates from the ULB area and 157 TPD from the extended area.

The municipal solid waste stream is characterized by a high proportion of biodegradable materials, with food and vegetable residues contributing 51% of the total waste generated. Recyclable fractions such as plastics (17%) and paper (6%) constitute a significant share, while inert materials account for 11%. The formal collection system manages approximately 455.25 TPD of waste, supplemented by informal recovery activities handling around 30.35 TPD.

Source segregation levels vary between 40% and 50%, whereas door-to-door collection services cover nearly 70–80% of households.

Waste collection and transportation activities are supported by a fleet comprising 136 battery-operated vehicles, 378 light commercial vehicles, and 78 heavy commercial vehicles. Organic waste management is primarily undertaken through decentralized treatment facilities, including 29 operational Micro Composting Centres (MCCs) with a combined treatment capacity of 135 TPD. Approximately 95 TPD of biodegradable waste is processed through aerobic composting, yielding about 9.5 TPD of compost. A biomethanation plant with a capacity of 5 TPD further supplements the treatment of organic waste.

Resource recovery activities are carried out through five functional Resource Recovery Centres, which collectively process around 45 TPD of dry waste. Materials recovered from these facilities include plastics, paper, metals, cloth, and rubber. The remaining residual waste is transported to the Appur disposal site, where open dumping remains the predominant disposal practice. In addition, biomining operations are being undertaken at the Vengadamangalam legacy waste site, with approximately 83.6% of the accumulated legacy waste already remediated.

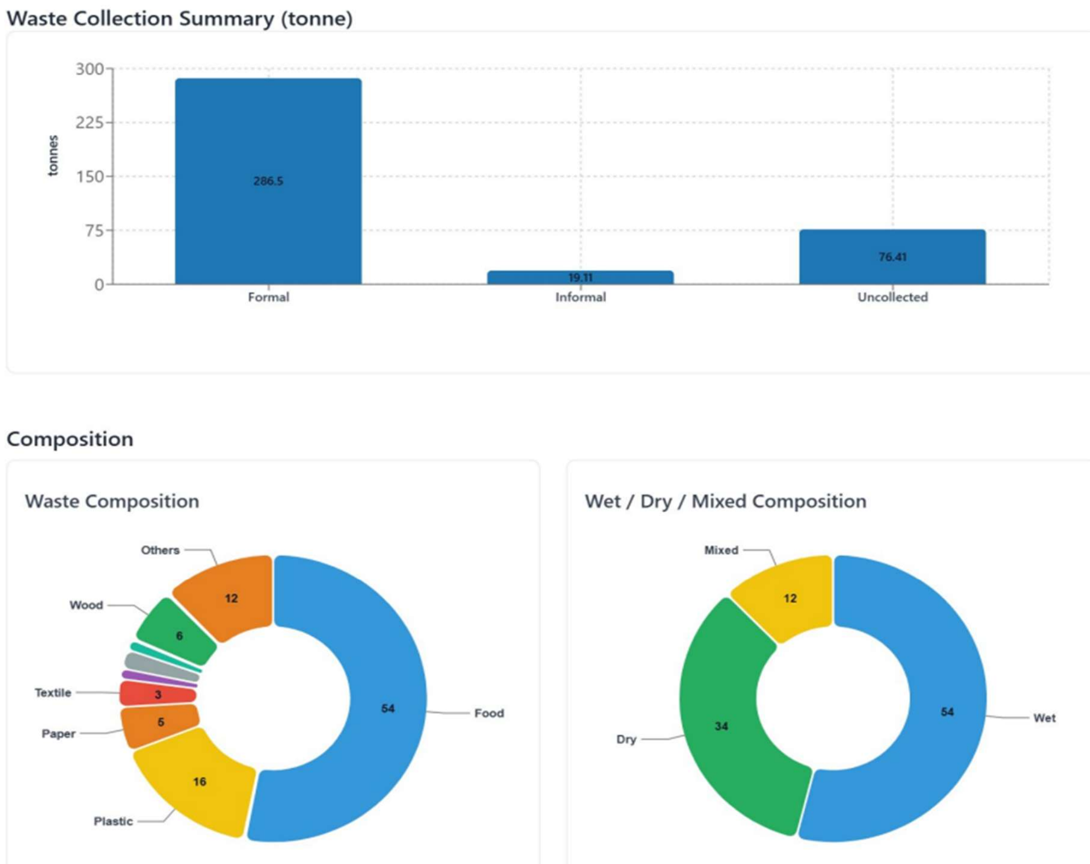
Table 3.1-3.7 depicts the typical data needed to be filled-up in various fields of the web app for predicting the GHG emissions from Tambaram and Avadi corporations.

4.3 GHG Emission Results

This section presents the GHG emission estimates obtained for the selected study areas under existing waste management practices. The results generated using the developed GHG Calculator quantify emissions associated with the prevailing waste management practices in Avadi and Tambaram. The analysis includes gross emissions, avoided emissions, and net emissions for individual waste management activities. The city-specific results are further examined to identify major emission sources and establish baseline emission levels for subsequent scenario evaluation.

4.3.1 Avadi GHG Emission Results

The GHG assessment for Avadi was carried out under the BAU scenario to establish the baseline climate impacts associated with the existing waste management system. The assessment considered emissions arising from transportation, composting, anaerobic digestion, recycling, and landfill disposal activities. In the present study, the recycling module represents material recovery activities undertaken through Resource Recovery Centres (RRCs), which constitute the primary facilities for segregation and recovery of recyclable materials in Avadi. Fig. 4.1 presents the waste collection, composition, allocation and GHG profiles in the Avadi corporation in a BAU case. The emission results are presented in Table 4.1.



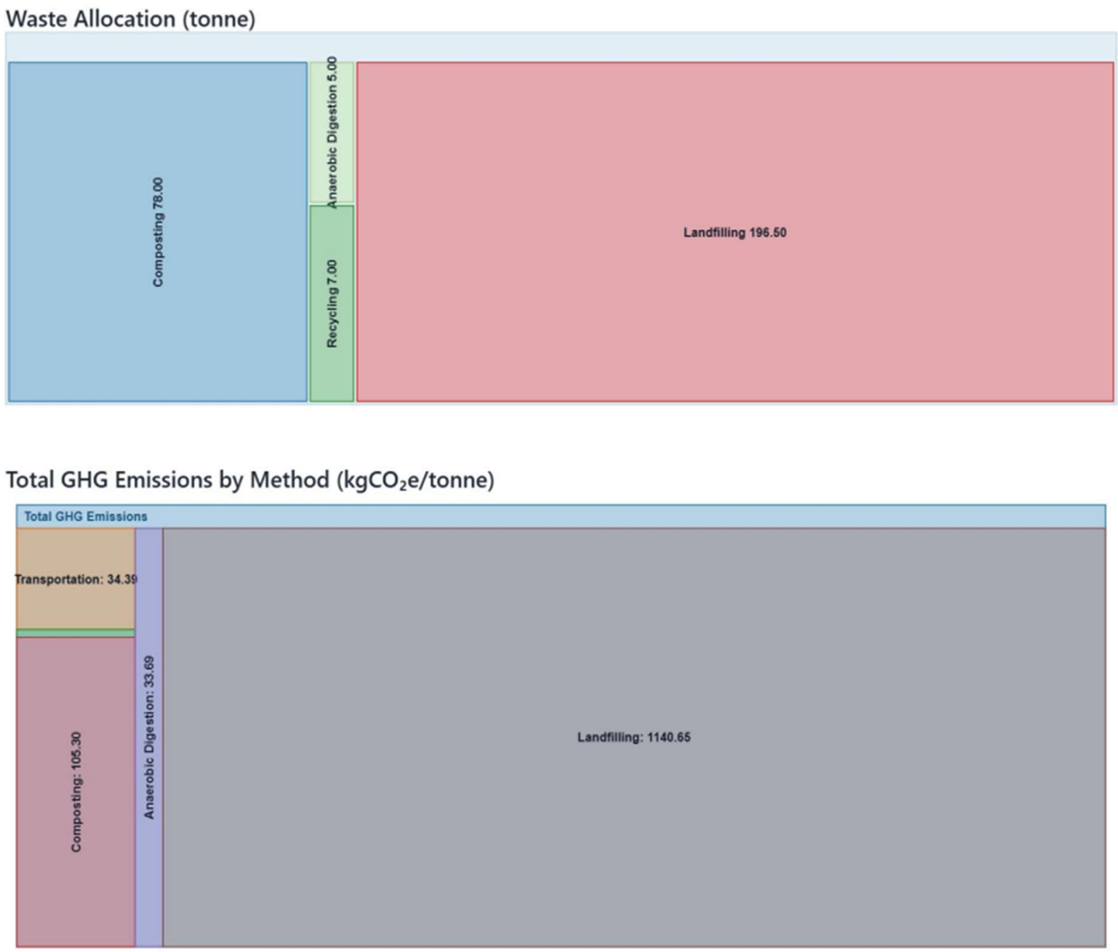


Fig. 4.1 GHG calculator interface showing the waste management profile of Avadi

Table 4.1 GHG emission results for Avadi under the BAU scenario

Category	Metric	Transportation	Composting	Anaerobic Digestion	Recycling	Landfilling	Total
Emissions kgCO_2e/ton	CO_2	33.87	1.16	9.05	2.71	0.02	32.44
	CH_4	0.05	24.64	24.64	0.00	1140.62	740.14
	N_2O	0.47	79.50	0.00	0.00	0.00	20.73
	BC	0.02	0.00	0.00	0.00	0.00	0.01
	Total	**34.39**	**105.30**	**33.69**	**2.71**	**1140.65**	**793.31**

Avoided Emissions kgCO₂e/ ton	CO_2	0.00	1.92	172.18	1767.58	0.00	154.32
	CH_4	0.00	0.01	0.03	0.40	0.00	0.04
	N_2O	0.00	1.63	0.81	0.75	0.00	0.49
	BC	0.00	0.00	0.00	0.01	0.00	0.00
	Total	**0.00**	**3.56**	**173.02**	**1768.73**	**0.00**	**154.85**
Net Emissions kgCO₂e/ ton	CO_2	33.87	-0.76	-163.13	-1764.88	0.02	-121.88
	CH_4	0.05	24.63	24.61	-0.40	1140.62	740.10
	N_2O	0.47	77.87	-0.81	-0.75	0.00	20.24
	BC	0.02	0.00	0.00	0.01	0.00	0.01
	Total	**34.39**	**101.74**	**-139.33**	**-1766.03**	**1140.65**	**638.46**

The analysis indicates that the overall gross GHG emission from the existing waste management system to be 793.31 kgCO_2e/ton of waste managed. This value represents the weighted average emission of the entire system based on the quantity of waste allocated to different treatment and disposal pathways. Among the individual processes, landfill disposal exhibited the highest emission intensity, contributing 1140.65 kgCO_2e/ton. The substantial contribution from landfilling is primarily attributed to methane (CH_4) generated during the anaerobic decomposition of organic waste at the disposal site. Composting accounted for 105.30 kgCO_2e/ton, while transportation and anaerobic digestion contributed 34.39 kgCO_2e/ton and 33.69 kgCO_2e/ton, respectively. Material recovery activities carried out through RRCs generated only 2.71 kgCO_2e/ton, indicating comparatively lower direct emissions.

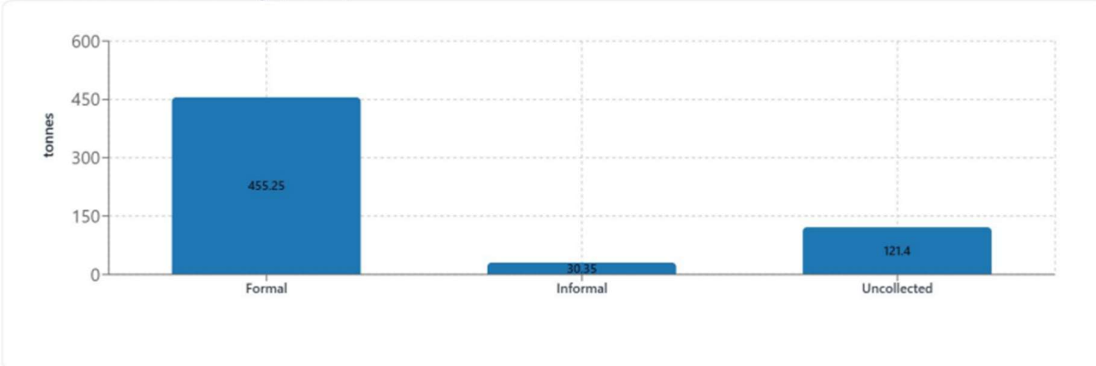
Methane constituted the largest share of total emissions, particularly from landfill disposal and biological treatment processes. Carbon dioxide emissions are mainly associated with fuel and electricity consumption during transportation and treatment operations, whereas nitrous oxide emissions are predominantly linked to composting activities.

The assessment further quantified emission reductions achieved through resource recovery and energy utilization. Material recovery through RRCs exhibited the highest mitigation potential, resulting in avoided emissions of 1768.73 kgCO_2e/ton. Anaerobic digestion and compost utilization provided additional avoided emissions of 173.02 kgCO_2e/ton and 3.56 kgCO_2e/ton, respectively. After accounting for these reductions, the net GHG emission for Avadi is estimated to be 638.46 kgCO_2e/ton. The findings indicate that reducing dependence on landfill disposal, while enhancing material recovery and resource utilization can substantially lower the climate impacts associated with waste management in Avadi.

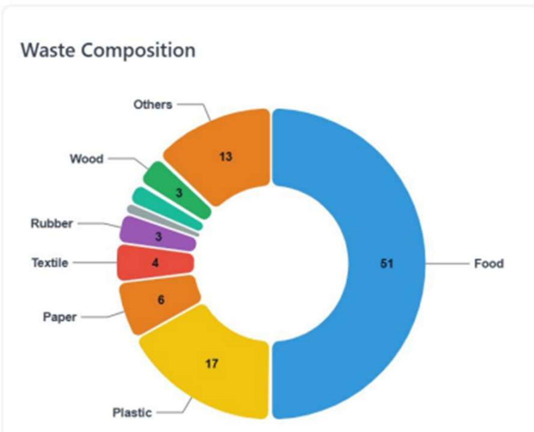
4.3.2 Tambaram GHG Emission Results

The GHG inventory developed for Tambaram under the BAU scenario provides an overview of the climate impacts associated with the existing solid waste management practices. Emissions arising from transportation, composting, anaerobic digestion, recycling, and disposal activities were considered in the assessment. In the present study, the recycling module represents material recovery activities undertaken through RRCs, which serve as the primary facilities for segregation and recovery of recyclable materials in Tambaram. Fig. 4.2 presents the waste collection, composition, allocation and GHG profiles in the Tambaram corporation in a BAU case. The emission results are presented in Table 4.2.

Waste Collection Summary (tonne)



Composition



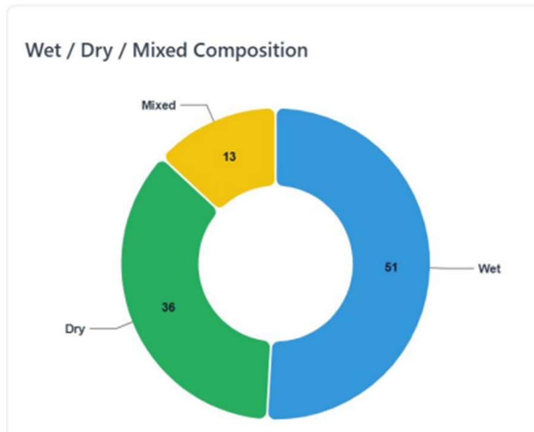


Fig. 4.2 GHG calculator interface showing the waste management profile of Tambaram

Table 4.2 GHG emission results for Tambaram under the BAU scenario

Category	Metric	Transportation	Composting	Anaerobic Digestion	Recycling	Landfilling	Total
Emissions $kgCO_2e$/ ton	CO_2	27.56	1.43	9.05	2.56	0.03	26.63
	CH_4	0.04	24.64	24.64	0.00	1140.62	733.86
	N_2O	0.38	79.50	0.00	0.00	0.00	15.91
	BC	0.01	0.00	0.00	0.00	0.00	0.01
	Total	**27.99**	**105.57**	**33.69**	**2.56**	**1140.65**	**776.40**
	CO_2	0.00	1.92	172.18	1991.74	0.00	311.20

Avoided Emissions $kgCO_2e$/ ton	CH_4	0.00	0.01	0.03	0.45	0.00	0.07
	N_2O	0.00	1.63	0.81	0.81	0.00	0.45
	BC	0.00	0.00	0.00	0.01	0.00	0.00
	Total	**0.00**	**3.56**	**173.02**	**1993.00**	**0.00**	**311.73**
Net Emissions $kgCO_2e$/ ton	CO_2	27.356	-0.49	-163.13	-1989.18	0.03	-284.58
	CH_4	0.04	24.63	24.61	-0.45	1140.62	733.79
	N_2O	0.38	77.87	-0.81	-0.81	0.00	15.46
	BC	0.01	0.00	0.00	-0.01	0.00	0.01
	Total	**27.99**	**102.01**	**-139.33**	**-1990.44**	**1140.65**	**464.67**

The results indicate that the present waste management system generates an overall gross emission of 776.40 $kgCO_2e$/ton of waste managed. This value represents the weighted average emission of the entire system based on the quantity of waste directed to different treatment and disposal pathways. Disposal activities contribute to the highest emission intensity, with landfill operations accounting for 1140.65 $kgCO_2e$/ton. The elevated emission levels are mainly associated with methane released during the degradation of biodegradable waste under anaerobic conditions at the disposal site. Composting and anaerobic digestion contributed 105.57 $kgCO_2e$/ton and 33.69 $kgCO_2e$/ton, respectively, whereas emissions from transportation amounted to 27.99 $kgCO_2e$/ton. In contrast, material recovery activities carried out through RRCs produced only 2.56 $kgCO_2e$/ton, highlighting the comparatively lower environmental burden associated with resource recovery operations.

Analysis of the emission profile revealed that methane is the principal GHG influencing the overall results, primarily due to disposal and biological treatment processes. Carbon dioxide emissions were predominantly linked to fuel combustion and electricity consumption, while nitrous oxide emissions originated mainly from composting operations, very similar to the Avadi BAU case.

Considerable emission savings can be achieved through resource recovery initiatives implemented in the city. Material recovery through RRCs provided the greatest environmental benefit, yielding avoided emissions of 1993.00 $kgCO_2e/ton$. Additional reductions of 173.02 $kgCO_2e/ton$ and 3.56 $kgCO_2e/ton$ are obtained through anaerobic digestion and compost utilization, respectively. After incorporating these offsets, the net emission from the existing waste management system was estimated to be 464.67 $kgCO_2e/ton$. The results demonstrate that expanding material recovery activities and increasing the treatment of biodegradable waste prior to disposal can significantly improve the environmental performance of the city's waste management system.

4.4 Scenario Comparison

This section presents a comparative evaluation of alternative scenarios developed for Avadi and Tambaram to examine the influence of different waste allocation strategies on overall greenhouse gas emissions.

The results obtained for each scenario are analysed to determine environmentally preferable options and quantify the potential emission reductions achievable through enhanced resource recovery and treatment practices. The assessment provides valuable insights into the effectiveness of various intervention measures and supports the identification of sustainable solid waste management pathways for the selected study areas.

4.4.1 Avadi Scenario Comparison

Four alternative management strategies were developed for Avadi and evaluated against the BAU case. The alternatives comprised a composting-intensive strategy (S1), an anaerobic digestion-intensive strategy (S2), a waste-to-energy intensive strategy (S3), and an integrated approach with minimum landfill disposal (S4). The total quantity of waste considered under all scenarios was maintained at 286.5 TPD to ensure consistency in comparison. Fig. 4.3 depicts the user interface of scenario comparison module.

Fig. 4.4, 4.5, 4.6, 4.7 and Table 4.3 show the results of the GHG calculator depicting the overall GHG emission for all the scenarios, individual emissions and process-specific emissions.

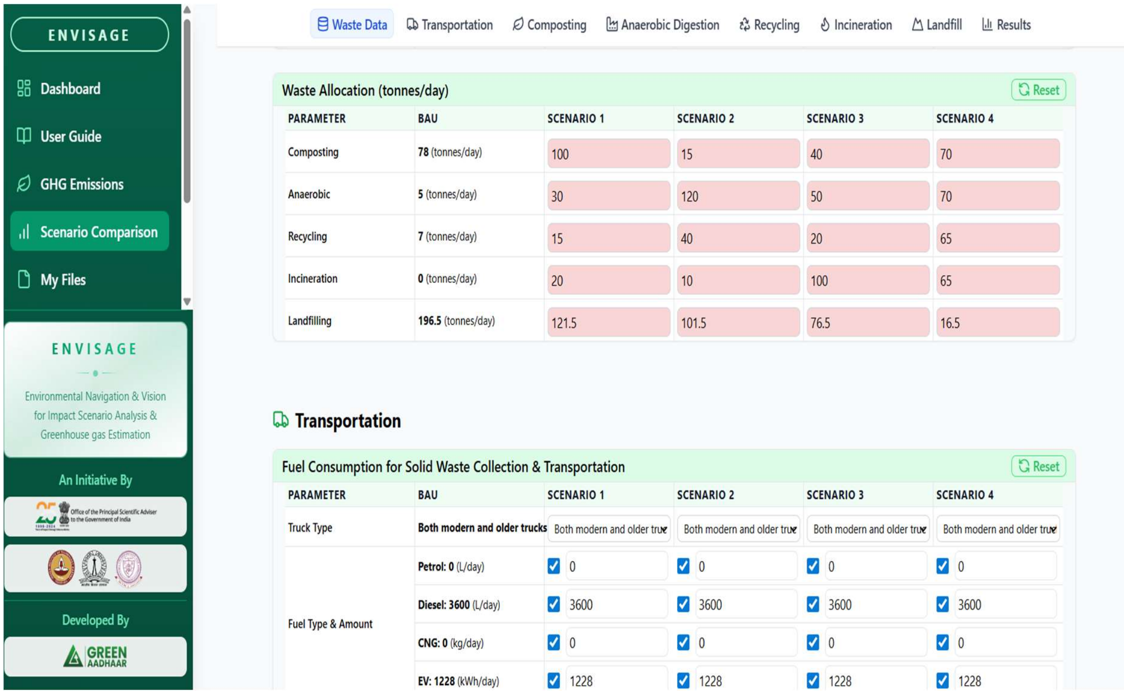


Fig. 4.3 Scenario comparison module showing waste allocation for Avadi

Fig. 4.4 Waste collection and waste composition metrics considered for BAU and all other scenarios of Avadi

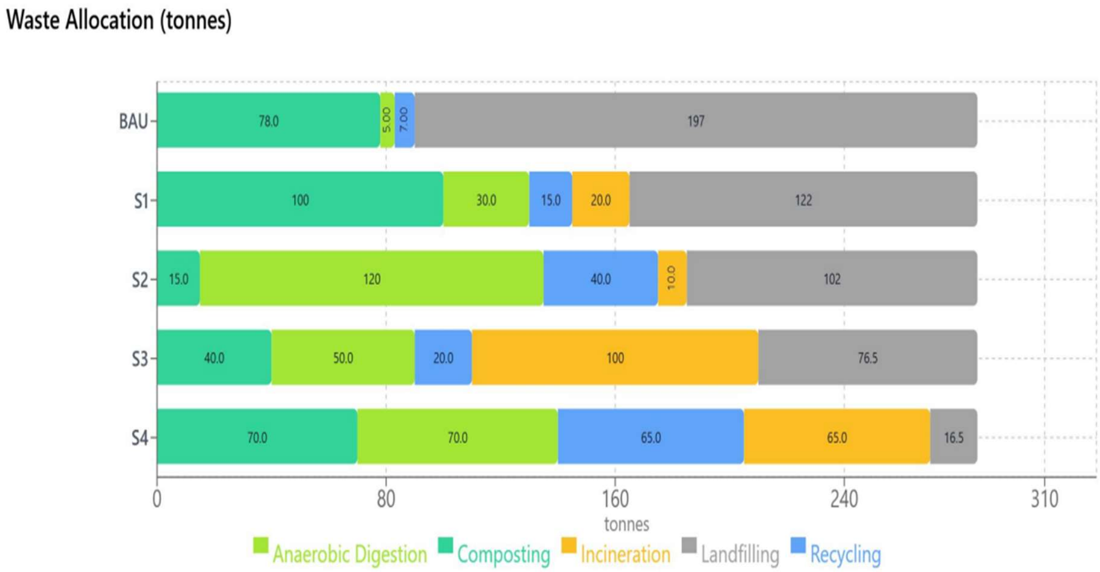


Fig. 4.5 Scenario-wise waste allocation in Avadi

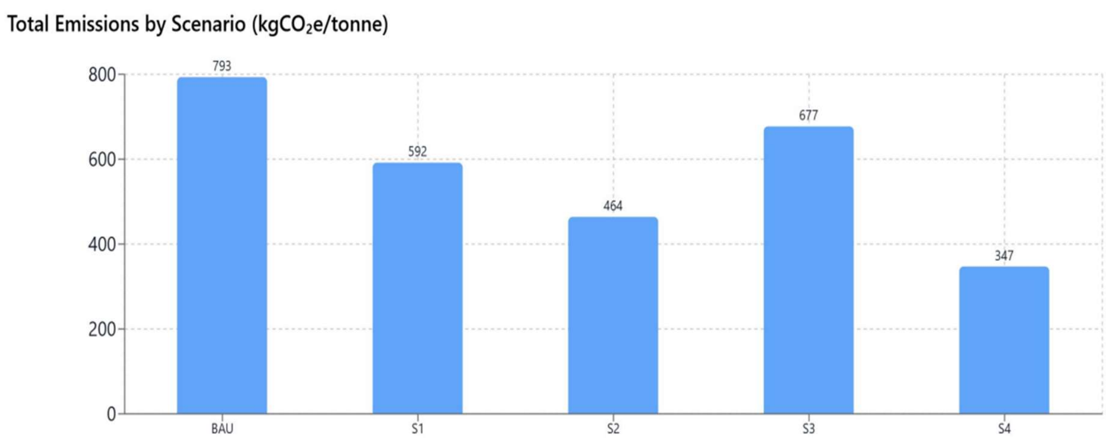


Fig. 4.6 Greenhouse gas emissions under alternative scenarios in Avadi

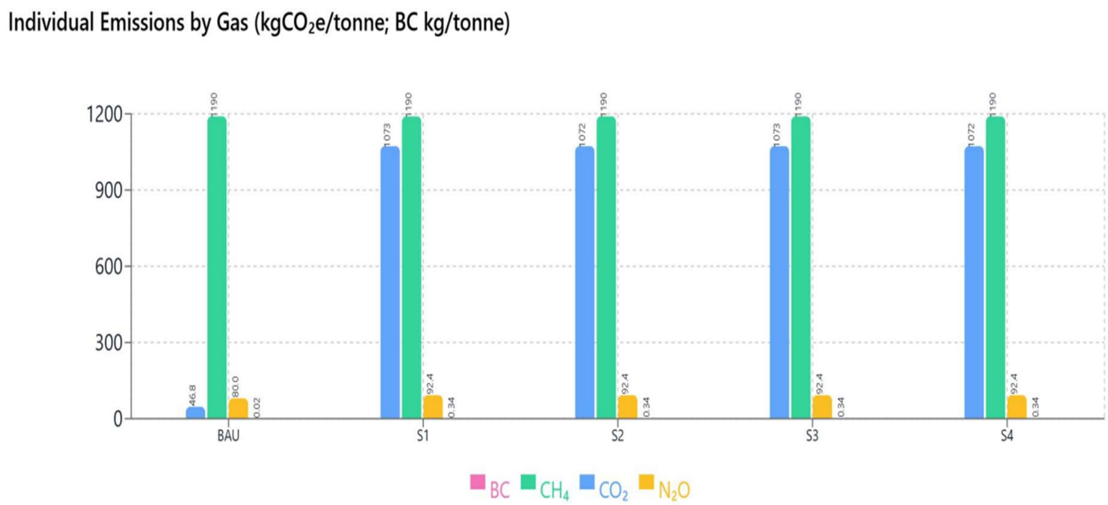


Fig. 4.7 Gas-wise emission comparison for Avadi scenarios

Table 4.3 Process-wise GHG emissions under alternative scenarios for Avadi

Scenario	Method	CO_2 kgCO_2e/ ton	CH_4 kgCO_2e/ ton	N_2O kgCO_2e/ ton	BC kgCO_2e/ ton	Total kgCO_2e/ ton
	Transportation	33.87	0.05	0.47	0.02	34.39
	Composting	1.16	24.64	79.50	0.00	105.30
	Anaerobic Digestion	9.05	24.64	0.00	0.00	33.69
BAU	Recycling	2.71	0.00	0.00	0.00	2.71
	Incineration	0.00	0.00	0.00	0.00	0.00
	Landfilling	0.02	1140.62	0.00	0.00	1140.65
	Grand Total	**32.44**	**740.14**	**20.73**	**0.01**	**793.31**
	Transportation	33.87	0.05	0.47	0.02	34.39
	Composting	1.16	24.64	79.50	0.00	105.30
	Anaerobic Digestion	9.05	24.64	0.00	0.00	33.69
S1	Recycling	2.65	0.00	0.00	0.00	2.65
	Incineration	1025.84	0.01	12.46	0.32	1038.30
	Landfilling	0.02	1140.62	0.00	0.00	1140.65
	Grand Total	**100.46**	**464.02**	**27.27**	**0.04**	**591.75**
	Transportation	33.87	0.05	0.47	0.02	34.39
	Composting	1.15	24.64	79.50	0.00	105.29
	Anaerobic Digestion	9.05	24.64	0.00	0.00	33.69

S2	Recycling	2.56	0.00	0.00	0.00	2.56
	Incineration	1025.84	0.01	12.46	0.32	1038.30
	Landfilling	0.02	1140.62	0.00	0.00	1140.65
	Grand Total	**69.43**	**389.77**	**4.75**	**0.02**	**463.96**
S3	Transportation	33.87	0.05	0.47	0.02	34.39
	Composting	1.15	24.64	79.50	0.00	105.29
	Anaerobic Digestion	9.05	24.64	0.00	0.00	33.69
	Recycling	2.62	0.00	0.00	0.00	2.62
	Incineration	1025.84	0.01	12.46	0.32	1038.30
	Landfilling	0.02	1140.62	0.00	0.00	1140.65
	Grand Total	**369.40**	**292.84**	**14.92**	**0.12**	**677.16**
S4	Transportation	33.87	0.05	0.47	0.02	34.39
	Composting	1.16	24.64	79.50	0.00	105.30
	Anaerobic Digestion	9.05	24.64	0.00	0.00	33.69
	Recycling	2.53	0.00	0.00	0.00	2.53
	Incineration	1025.84	0.01	12.46	0.32	1038.30
	Landfilling	0.02	1140.62	0.00	0.00	1140.65
	Grand Total	**252.98**	**72.92**	**21.30**	**0.08**	**347.20**

Under the BAU condition, the overall GHG emission is estimated at 793.31 kgCO_2e/ton, with landfill disposal representing the principal source of emissions owing to methane generation during waste decomposition. Increasing composting capacity to 100 TPD while reducing landfill disposal to 121.5 TPD in S1 lowered emissions to 591.75 kgCO_2e/ton, corresponding to a reduction of 25.4% relative to BAU. The reduction is primarily achieved through the diversion of biodegradable waste from disposal sites to aerobic treatment facilities.

In S2, 120 TPD of waste is directed to anaerobic digestion and landfill disposal is reduced to 101.5 TPD. This strategy recorded emissions of 463.96 kgCO_2e/ton, representing a decrease of 41.5% compared with the existing system. The improved performance is mainly associated with enhanced biogas recovery and lower methane generation from disposal facilities.

The waste-to-energy-intensive option (S3) allocated 100 TPD of waste for incineration with a reduced landfill disposal of 76.5 TPD. Although a substantial quantity of waste was diverted from landfill, emissions are still estimated to be 677.16 kgCO_2e/ton, only 14.6% lower than BAU, indicating comparatively higher direct emissions from thermal treatment.

The integrated strategy (S4) with composting (70 TPD), anaerobic digestion (70 TPD), resource recovery (65 TPD), and incineration (65 TPD), while restricting landfill disposal to only 16.5 TPD produced the lowest emission value of 347.20 $kgCO_2e/ton$, achieving a 56.2% reduction relative to BAU. The substantial decrease is primarily attributed to increased resource recovery, energy recovery, and minimal reliance on landfill disposal. Table 4.4 presents the summary of total emissions and the percent reduction in emissions of all the scenarios considered.

Table 4.4 Comparative assessment of alternative waste management scenarios for Avadi

	Emissions	**Reduction**	**Ranking**
BAU	793.31 $kgCO_2e/ton$	-	Rank 5
S1- Composting ↑	591.75 $kgCO_2e/ton$	25.4 %	Rank 3
S2 – AD ↑	463.96 $kgCO_2e/ton$	41.5 %	Rank 2
S3 - WtE ↑	677.16 $kgCO_2e/ton$	14.6 %	Rank 4
S4 - (Integrated) Landfill ↓	347.20 $kgCO_2e/ton$	56.2 %	**Rank 1-BEST**

Overall, the integrated strategy (S4) emerged as the most environmentally preferable option for Avadi, achieving the highest reduction in GHG emission among all the alternatives considered. Based on emission reduction performance, the scenarios are ranked in the order: **S4 (56.2%) > S2 (41.5%) > S1 (25.4%) > S3 (14.6%) > BAU**. The superior performance of S4 can be attributed to the balanced integration of multiple treatment technologies, enhanced resource recovery, increased energy recovery, and extensive diversion of waste away from landfill. In contrast, the waste-to-energy intensive strategy (S3) exhibited the least improvement among the alternative scenarios owing to comparatively higher emissions associated with thermal treatment.

4.4.2 Tambaram Scenario Comparison

Four alternative management approaches were developed for Tambaram, similar to Avadi, and assessed in relation to the existing waste management system to examine their potential for reducing GHG emissions. The alternatives include a composting-oriented strategy (S1), an anaerobic digestion-oriented strategy (S2), a waste-to-energy-based strategy (S3), and an integrated resource recovery strategy with minimum landfill disposal (S4). The quantity of waste considered under each alternative was maintained at 455.25 TPD to ensure uniformity in assessment. Fig. 4.8 depict the user interface for scenario comparison module and how to do the waste allocation for different scenarios.

Fig. 4.9, 4.10, 4.11, 4.12, and Table 4.5 show the results of the GHG calculator depicting the overall GHG emission for all the scenarios, individual emissions and process-specific emissions, respectively.

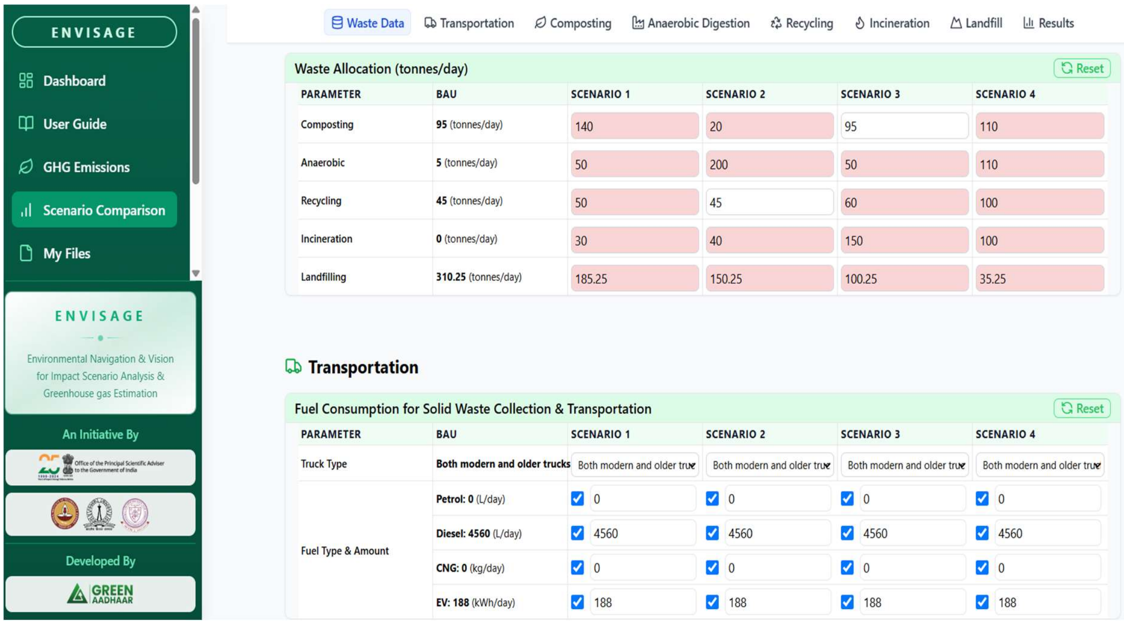


Fig. 4.8 Scenario waste allocation interface for Tambaram

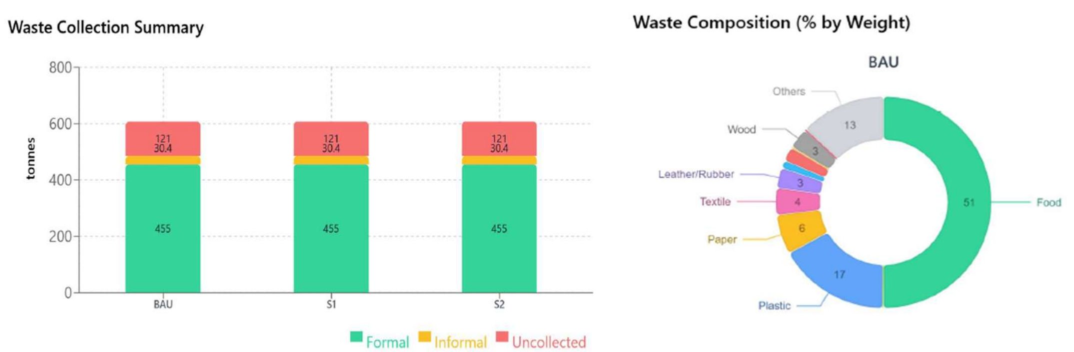


Fig. 4.9 Waste collection and waste composition metrics under different scenarios for Tambaram

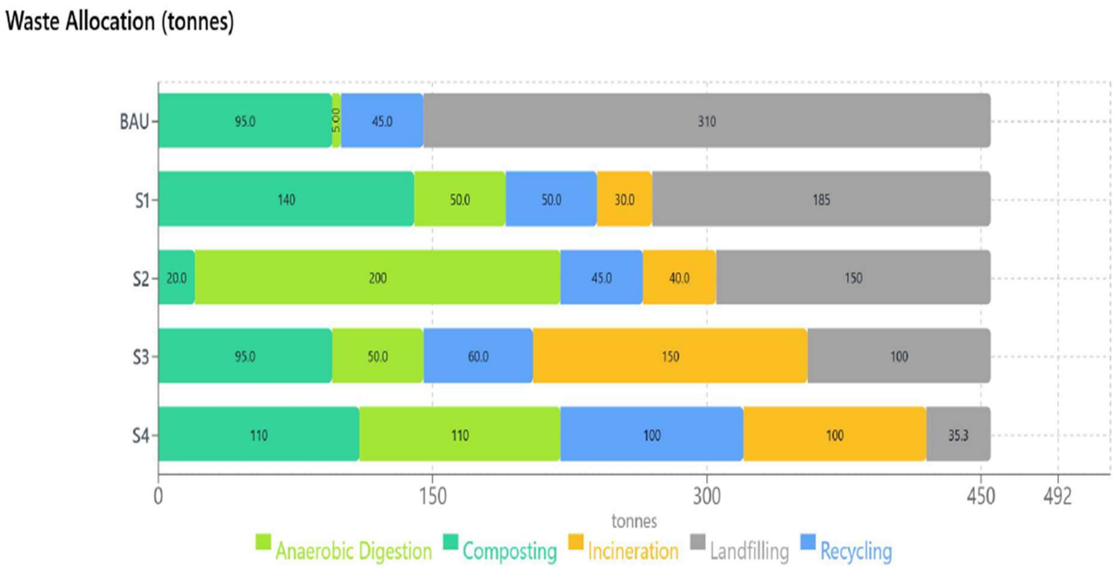


Fig. 4.10 Scenario-wise waste allocation in Tambaram

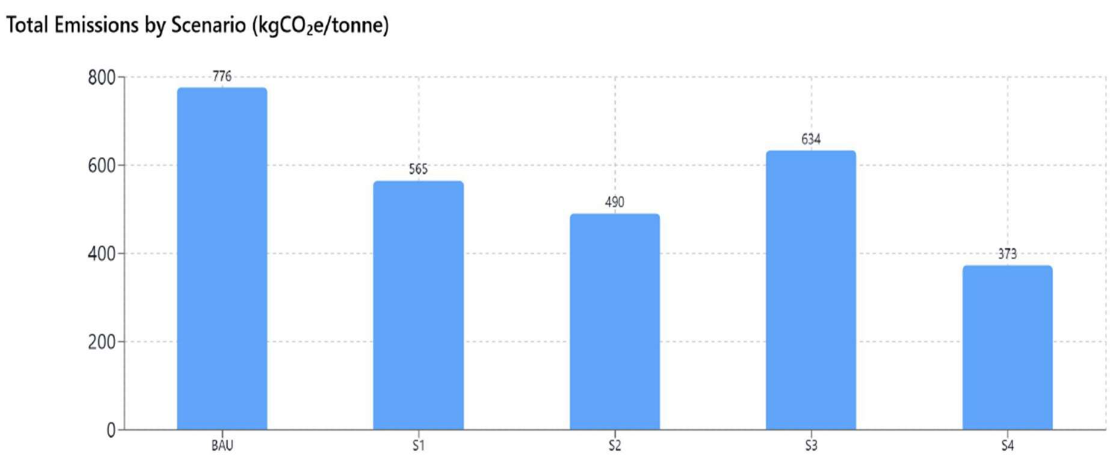


Fig. 4.11 Greenhouse gas emissions under alternative scenarios in Tambaram

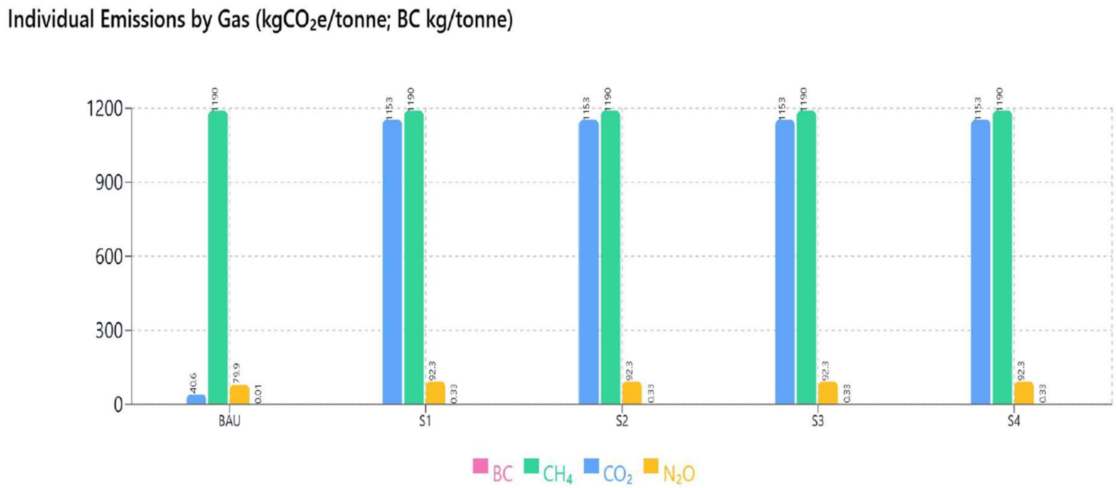


Fig. 4.12 Gas-wise emission comparison for Tambaram scenarios

Table 4.5 Process-wise GHG emissions under alternative scenarios for Tambaram

Scenario	**Method**	**CO_2 $kgCO_2e$/ ton**	**CH_4 $kgCO_2e$/ ton**	**N_2O $kgCO_2e$/ ton**	**BC $kgCO_2e$/ ton**	**Total $kgCO_2e$/ ton**
BAU	Transportation	27.56	0.04	0.38	0.01	27.99
	Composting	1.43	24.64	79.50	0.00	105.57
	Anaerobic Digestion	9.05	24.64	0.00	0.00	33.69
	Recycling	2.56	0.00	0.00	0.00	2.56
	Incineration	0.00	0.00	0.00	0.00	0.00
	Landfilling	0.03	1140.62	0.00	0.00	1140.65
	Grand Total	**26.63**	**733.86**	**15.91**	**0.01**	**776.40**
S1	Transportation	27.56	0.04	0.38	0.01	27.99
	Composting	1.42	24.64	79.50	0.00	105.56
	Anaerobic Digestion	9.05	24.64	0.00	0.00	33.69
	Recycling	2.57	0.00	0.00	0.00	2.57
	Incineration	1112.62	0.01	12.46	0.32	1125.08
	Landfilling	0.03	1140.62	0.00	0.00	1140.65
	Grand Total	**96.35**	**444.81**	**24.05**	**0.03**	**565.21**
	Transportation	27.56	0.04	0.38	0.01	27.99
	Composting	1.42	24.64	79.50	0.00	105.56

S2	Anaerobic Digestion	9.05	24.64	0.00	0.00	33.69
	Recycling	2.56	0.00	0.00	0.00	2.56
	Incineration	1112.62	0.01	12.46	0.32	1125.08
	Landfilling	0.03	1140.62	0.00	0.00	1140.65
	Grand Total	**121.68**	**364.13**	**4.66**	**0.04**	**490.46**
S3	Transportation	27.56	0.04	0.38	0.01	27.99
	Composting	1.43	24.64	79.50	0.00	105.57
	Anaerobic Digestion	9.05	24.64	0.00	0.00	33.69
	Recycling	2.58	0.00	0.00	0.00	2.58
	Incineration	1112.62	0.01	12.46	0.32	1125.08
	Landfilling	0.03	1140.62	0.00	0.00	1140.65
	Grand Total	**371.22**	**242.88**	**19.76**	**0.11**	**633.85**
S4	Transportation	27.56	0.04	0.38	0.01	27.99
	Composting	1.43	24.64	79.50	0.00	105.57
	Anaerobic Digestion	9.05	24.64	0.00	0.00	33.69
	Recycling	2.61	0.00	0.00	0.00	2.61
	Incineration	1112.62	0.01	12.46	0.32	1125.08
	Landfilling	0.03	1140.62	0.00	0.00	1140.65
	Grand Total	**258.03**	**94**	**20.93**	**0.08**	**372.97**

Under the existing condition (BAU), the overall GHG emission is estimated at 776.40 kgCO_2e/ton. The high emission level is primarily associated with the substantial quantity of waste disposed at landfill sites, resulting in significant methane generation. In S1, the quantity of waste processed through composting is increased to 140 TPD, with a concomitant reduction of landfill disposal to 185.25 TPD. This arrangement reduced the overall emission to 565.21 kgCO_2e/ton, representing a 27.2% decrease compared with the existing system. The improvement is mainly attributed to the increased stabilization of biodegradable waste through aerobic treatment.

S2 is focused on biomethanation by allocating 200 TPD of waste to anaerobic digestion and reducing landfill disposal to 150.25 TPD. This option generated 490.46 kgCO_2e/ton, corresponding to a 36.8% reduction relative to BAU. The lower emissions are largely due to enhanced biogas generation and reduced methane release from disposal facilities. Under S3, 150 TPD of waste is diverted to waste-to-energy facilities, by restricting landfill disposal to 100.25 TPD. The resulting emission is estimated at 633.85 kgCO_2e/ton, equivalent to 18.4% reduction compared with the BAU. Although diversion from landfill contributes to emission savings, the comparatively higher emissions associated with thermal processing limits the overall reduction potential.

The integrated strategy (S4) is aimed to distribute the waste among composting (110 TPD), anaerobic digestion (110 TPD), resource recovery (100 TPD), and waste-to-energy (100 TPD) processes, while restricting landfill disposal to only 35.25 TPD. This diversified configuration recorded the lowest emission estimate of 372.97 kgCO_2e/ton, achieving a 51.9% reduction relative to BAU. The substantial improvement is primarily associated with extensive waste diversion, enhanced material recovery, and minimal dependence on landfill disposal. Table 4.6 presents the summary of total emissions and the percent reduction in emissions of all the scenarios considered.

Table 4.6 Comparative assessment of alternative waste management scenarios for Tambaram

Scenario	Emissions	Reduction	Ranking
BAU	776.40 kgCO_2e/ton	-	Rank 5
S1- Composting ↑	565.21 kgCO_2e/ton	27.2 %	Rank 3
S2 – AD ↑	490.46 kgCO_2e/ton	36.8 %	Rank 2
S3 – WtE ↑	633.85 kgCO_2e/ton	18.4 %	Rank 4
S4 - (Integrated)			
Landfill ↓	372.97 kgCO_2e/ton	51.9 %	**Rank 1-BEST**

Overall, the integrated strategy (S4) emerged as the most sustainable option for Tambaram, very similar to Avadi case, achieving the maximum reduction in GHG emissions, among all the alternatives evaluated. Based on emission reduction performance, the scenarios can be ranked as follows: **S4 (51.9%) > S2 (36.8%) > S1 (27.2%) > S3 (18.4%) > BAU**. The superior performance of S4 can be attributed to the combined benefits of resource recovery, biological treatment, energy recovery, and significant reduction in landfill disposal. Conversely, the waste-to-energy intensive strategy (S3) demonstrated the least improvement among the alternative options due to the relatively higher direct emissions associated with thermal treatment.

Chapter 5
Stakeholder Workshop

5.1 Stakeholder Workshop on Sustainable Solid Waste Management through Life Cycle Assessment (LCA)

The Stakeholder Workshop on Sustainable Solid Waste Management through Life Cycle Assessment (LCA) was successfully conducted on 16 February 2026 at ICSR building, IIT Madras as part of the ongoing project. Conceived as a platform for dialogue, demonstration, and collaborative learning, the event brought together key actors from across the solid waste management (SWM) ecosystem.

The primary objective of the workshop was to present the GHG Calculator App developed under the project and to obtain structured feedback from experts representing diverse sectors engaged in waste management and sustainability. The gathering witnessed enthusiastic participation from academia, industry professionals, non-governmental organizations working in SWM, technocrats, and representatives of community-based waste initiatives. Their thoughtful observations, technical critiques, and practical suggestions provided invaluable inputs for refining and strengthening the functionality, usability, and policy relevance of the application.

The programme commenced with a warm welcome address by Prof. R. Vinu, who set the context for the deliberations and invited Prof. Balaji Narasimhan to deliver the inaugural address. Prof. Balaji Narasimhan, Professor in the Department of Civil Engineering, offered an overview of the department's advanced research initiatives and collaborative engagements, highlighting the critical role of academic institutions in advancing sustainable development through interdisciplinary innovation.

This was followed by an address from Dr. Hafsa Ahmad of the Office of the Principal Scientific Advisor (PSA), Government of India. She provided a comprehensive overview of the project: its conceptual foundations, guiding vision, key objectives, and current progress. Her address effectively framed the workshop's purpose, situating the GHG Calculator within the broader national agenda of evidence-based climate action and sustainable waste governance.

The keynote address was delivered by Prof. Ajay Kalamdhad, Professor in the Department of Civil Engineering at Indian Institute of Technology Guwahati and a member of the Project

Review Committee. Speaking on the theme *"Sustainable Waste Valorization: Bridging Technical Performance with Life Cycle Thinking,"* he shared deep insights drawn from his extensive research and field experience in SWM. His reflections underscored the importance of integrating technical efficiency with life cycle perspectives to achieve truly sustainable waste valorization systems. The address was both intellectually stimulating and deeply inspiring, setting a high academic tone for the sessions that followed.

The technical session continued with an illuminating presentation by Prof. G. L. Sivakumar Babu, Distinguished Professor in the Department of Civil Engineering at the Indian Institute of Science. He delivered a comprehensive exposition of the project titled *"Developing Life Cycle Framework for Solid Waste Management Technologies in India,"* presenting its key outcomes with clarity and academic rigor.

Drawing upon detailed case studies from Bengaluru, he demonstrated the application of the framework across major solid waste management technologies, including composting, anaerobic digestion, waste-to-energy, recycling, and landfilling. His presentation systematically articulated the conceptual underpinnings of the framework—defining system boundaries, functional units, impact assessment methodologies, and data considerations adopted in the study.

Prof. Sivakumar Babu further shared the analytical results and distilled key insights emerging from the comparative LCA of different treatment pathways. Importantly, he outlined the principal policy and technical recommendations formulated under the project, which have been formally submitted to the Office of PSA, Government of India.

Following the first tea break, Dr. Yogesh Kumar, Postdoctoral Research Associate from Indian Institute of Technology (BHU) Varanasi, presented a concise yet insightful update on the research outcomes emerging from studies conducted in the Delhi and Varanasi regions. His presentation highlighted region-specific waste management practices, data-driven assessments, and comparative life cycle insights, thereby strengthening the pan-Indian relevance of the project.

The session was followed by the most anticipated segment of the workshop: the live demonstration of the GHG Calculator App, curated and presented by Prof. R. Vinu and Dr. Arun Sathyan, Postdoctoral Research Associate in the Department of Chemical Engineering at Indian Institute of Technology Madras.

Participants were provided with temporary login credentials to access the web-based application, along with a user manual booklet detailing step-by-step operational guidance. The demonstration featured a live walkthrough of the app's key functionalities, using a case study based on Chennai's municipal solid waste management system. The presenters systematically illustrated data input structures, emission calculation pathways, scenario comparison capabilities, and interpretation of outputs, thereby showcasing the tool's practical utility for planning and decision-making.

The session witnessed active participation, with probing questions and constructive discussions reflecting both the technical depth and practical significance of the GHG estimation tool. Structured feedback was also collected through a Google Form, enabling participants to share detailed observations on usability, interface design, data requirements, and analytical outputs. These inputs proved immensely valuable in guiding further refinement and enhancement of the application.

The second session of the workshop featured two panel discussions, beginning with a focused dialogue on the industrial dimensions of the SWM ecosystem. This session brought together leading practitioners representing diverse segments of the waste management and recycling industry.

The panel comprised Mr. Nagesh Prabhu Chinivartha, CEO of Zigma Global Environ Pvt. Ltd.; Ms. Sriranjani Srinivasan, Associate Vice President – Technical Development at Global Network for Zero; Mr. Natarajan P, Founder of Namma Ooru Foundation; Ms. Archana Tripathi, CEO of Saahas; and Mr. Nikhil Panchal, Founder and CEO of Green Aadhaar. The panel represented expertise spanning municipal solid waste management, e-waste processing, recycling systems, sustainability consulting, and grassroots implementation.

The discussion was structured around three thematic areas of high contemporary relevance.

The first theme explored operational realities within the municipal waste, e-waste, and recycling industries. Panelists reflected on the most pressing challenges faced at the ground level, including feedstock variability, segregation inefficiencies, financial sustainability, technology adoption barriers, regulatory compliance burdens, and market fluctuations for recovered materials. They emphasized that the performance and output of processing facilities are influenced not only by technological efficiency but also by upstream segregation practices, logistical coordination, institutional capacity, and community participation.

The second theme addressed the persistent challenge of data availability and reliability in urban waste management systems. Participants acknowledged that discrepancies between reported figures and on-ground realities often complicate carbon footprint assessments and GHG accounting exercises. The panel identified key barriers to standardized data reporting, including fragmented data ownership, absence of harmonized monitoring protocols, limited digital infrastructure, and lack of third-party verification mechanisms. The feasibility of real-time data integration from processing plants was discussed in depth, with panelists noting that while technologically achievable, its success depends on regulatory mandates, cost-sharing models, interoperability standards, and capacity building within Urban Local Bodies (ULBs).

The third and most policy-forward theme examined the evolving regulatory landscape, particularly in light of the forthcoming Solid Waste Management Rules, 2026, notified by the Ministry of Environment, Forest and Climate Change (MoEFCC), Government of India. The panel deliberated on the introduction of economic incentive mechanisms encouraging ULBs to generate carbon credits through improved waste management practices.

Panelists offered nuanced perspectives on the potential implications of such mechanisms for the SWM industry. Key questions included whether legally mandated compliance activities could qualify for carbon credits, how additionality would be defined in the Indian regulatory context, and what safeguards would be necessary to ensure environmental integrity. The discussion also highlighted the enabling role of emerging technologies—such as advanced monitoring systems, decentralized processing units, digital tracking platforms, and life cycle-based assessment tools—in strengthening transparency, improving efficiency, and supporting credible carbon accounting frameworks.

Overall, the session was marked by candid industry insights, policy-oriented reflections, and forward-looking dialogue, offering participants a grounded understanding of the practical and regulatory dynamics shaping India's waste management transition.

The second panel discussion was devoted to the academic dimensions of LCA and its application to India's solid waste management systems. Bringing together eminent scholars and research leaders, the session fostered a rigorous and forward-looking dialogue on strengthening methodological foundations and digital integration.

The panel comprised Prof. Indumathi Nambi, Professor of Civil Engineering at Indian Institute of Technology Madras; Prof. Chanakya Hoysall, Chief Research Scientist at the Centre for Sustainable Technologies, Indian Institute of Science; Prof. Kurian Joseph from Chennai River

Transformation Company Ltd.; Dr. Mohanakrishnan Logan, Assistant Professor of Civil Engineering at Indian Institute of Technology Madras; and Prof. S. V. Srinivasan, Senior Principal Scientist, Department of Environmental Engineering, Central Leather Research Institute.

The discussion was anchored around the central theme: *"Designing an India-Specific LCA Framework: What Must Change from Global Models?"* The panelists critically examined the applicability of conventional international LCA models to Indian waste management contexts. They identified methodological gaps in existing studies, particularly in relation to system boundary definitions, treatment of the informal sector, region-specific emission factors, and the limited incorporation of socio-economic variables.

A significant portion of the discussion focused on data quality challenges in Indian SWM LCAs. Panelists highlighted issues such as inconsistent primary data collection, variability in waste composition, limited temporal datasets, and lack of standardized reporting protocols across Urban Local Bodies. The need for harmonized data templates, third-party validation mechanisms, and integration with national digital platforms was strongly emphasized.

The role of the GHG Calculator App in this landscape was also deliberated upon. A key question posed to the panel was whether digital tools should prioritize methodological precision or user accessibility. The consensus underscored the importance of striking a calibrated balance: ensuring scientific robustness without compromising usability for policymakers and practitioners. The potential integration of such tools with India's Smart Cities initiatives and national climate reporting platforms was discussed as a critical pathway for mainstreaming LCA-informed decision-making.

Regional variability emerged as another focal point of discussion. Panelists stressed that an India-specific LCA framework must explicitly account for differences in waste composition, climatic conditions, technological maturity, and the scale of informal sector participation. Such contextualization was deemed essential for generating realistic and policy-relevant outcomes.

The dialogue further explored appropriate system boundary choices for Indian municipal waste systems, debating gate-to-gate versus cradle-to-grave approaches, and the inclusion of circular loop benefits. The treatment of avoided emissions and co-product credits (including compost, refuse-derived fuel, biogas, and recyclables) was examined carefully to prevent risks of double counting or overestimation of environmental benefits.

Finally, the panel advocated for expanding the scope of future tool versions beyond greenhouse gas emissions. Suggested additional indicators included economic cost analysis, energy balance assessments, land footprint, water footprint, and selected social indicators to reflect livelihood impacts and community dimensions.

Overall, the session was intellectually rich and analytically rigorous, offering substantive guidance for refining the India-specific LCA framework and strengthening its scientific, technological, and policy relevance.

5.2 Stakeholder Feedback and Actions Taken

Stakeholder feedback was collected from academia, industry, NGOs, technocrats, and community-based waste management initiatives to identify the practical barriers to implementation and improve the utility of the GHG Calculator application. The consultation highlighted recurring challenges such as poor waste segregation, variable feedstock quality, financial constraints, technology adoption barriers, regulatory burdens, and unstable recycling markets, all of which influence the reliability and applicability of the model outputs.

In response, the application was revised to address both technical and usability-related limitations. Data availability constraints were managed by introducing harmonized data templates across cities and SWM facilities, while data reliability was improved through standardized reporting protocols, digital integration, and third-party validation. To reduce the burden of manual entry, autofill functionality and a multi-level user structure were introduced, and the user interface was strengthened through regional language support, pictorial icons, and help nodes.

These revisions also led to an improved reporting format and a more comprehensive data-entry schema with additional fields and datasets, thereby enhancing usability and analytical clarity. Overall, the stakeholder engagement process not only improved the operational robustness of the application but also aligned the tool more closely with field realities and user requirements.

5.3 Field Visit to Selected Solid Waste Management Facilities in Chennai

On the second day of the programme, 17 February 2026, interested participants undertook a curated field visit to two major solid waste management facilities in Chennai, enabling them to observe large-scale processing systems in operation and to connect theoretical discussions with on-ground practice.

The first visit was to the biomining site at the Kodungaiyur dumpsite, managed by Zigma Global Environ Pvt. Ltd. The session was led by Mr. Sridhar Jagannathan, Vice President of the organization, who provided a detailed overview of the ongoing biomining operations. He guided participants through the sequential processes involved in legacy waste excavation, segregation, stabilization, resource recovery, and residue management. The walkthrough included explanations of key equipment deployed for screening and material recovery, as well as insights into the downstream utilization and marketing of recovered fractions.

In addition to the site tour, Mr. Jagannathan delivered a concise presentation highlighting the company's completed land reclamation projects at various legacy dumpyards, including Karur, Kumbakonam, Karaikudi, Poonamallee, and Pallavaram. The presentation illustrated the environmental and urban transformation potential of scientifically managed biomining initiatives, particularly in reclaiming land and mitigating long-term environmental liabilities.

The second visit was to the biomethanation plant located at Chetpet, Chennai, operated by Srinivaas Waste Management Solutions Pvt. Ltd. The facility visit was facilitated by Mr. Sankaranarayanan Srinivasan, Director of the company, who briefed participants on the plant’s operational framework, feedstock management, anaerobic digestion processes, and biogas upgrading systems.

Participants were guided through the digestion units, gas purification systems, and bottling infrastructure, gaining first-hand exposure to the technical processes involved in producing compressed biogas from organic waste streams. The visit provided valuable insights into decentralized renewable energy generation from municipal organic waste and demonstrated the practical integration of waste management with clean energy production.

Collectively, the field visits enriched the workshop experience by grounding policy discussions and analytical frameworks in real-world implementation, thereby reinforcing the project’s emphasis on bridging science, technology, and practice in sustainable waste management.

Chapter 6
Conclusion

A web-based GHG Calculator "ENVISAGE" was successfully designed, developed, tested, and validated for estimating emissions associated with municipal solid waste management systems under Indian conditions. The framework, adapted from the IGES Emission Quantification Tool, integrates GHG estimation, LCA, MFA, avoided emission assessment, and scenario comparison within a single decision-support platform. The developed tool enables systematic quantification and visualization of emissions associated with transportation, composting, anaerobic digestion, resource recovery, incineration, and landfill disposal.

Implementation of the platform for Avadi and Tambaram, representing the western and southern regions, respectively, of the Chennai Metropolitan Area, demonstrated its capability to characterize existing municipal solid waste management practices and quantify associated greenhouse gas emissions. Under the prevailing management conditions, the overall gross GHG emissions were estimated to be 793.31 kgCO_2e/ton for Avadi and 776.40 kgCO_2e/ton for Tambaram. The assessment indicated that landfill disposal constituted the dominant emission source in both cities owing to methane generation from the decomposition of biodegradable waste, whereas resource recovery and biological treatment processes contributed significantly towards emission reduction through material recovery and energy substitution benefits.

Scenario evaluation highlighted the importance of improved waste diversion strategies in reducing climate impacts. In both cities, the integrated management scenario comprising composting, anaerobic digestion, resource recovery, and waste-to-energy with minimum landfill disposal recorded the lowest emissions, with values of 347.20 kgCO_2e/ton for Avadi and 372.97 kgCO_2e/ton for Tambaram, corresponding to emission reductions of 56.2% and 51.9%, respectively. Based on emission reduction performance, the scenarios followed the order: Integrated scenario > Anaerobic digestion-intensive scenario > Composting-intensive scenario > Waste-to-energy-intensive scenario > Business-as-Usual (BAU). These findings demonstrate that integration of multiple treatment pathways while minimizing landfill dependence represents the most effective approach for mitigating greenhouse gas emissions from municipal solid waste management systems.

The emission estimates generated by the calculator are compared with published literature and established assessment methodologies, and the results showed good agreement with reference values. This confirmed the reliability and applicability of the developed framework for greenhouse gas assessment under Indian municipal solid waste management conditions.

Overall, the validated GHG Calculator was found to be a reliable, scientifically robust, and user-friendly decision-support tool for municipal authorities, planners, and researchers. The platform can support climate-oriented planning, facilitate the selection of environmentally preferable waste management strategies, and contribute towards the transition to sustainable and low-carbon municipal solid waste management systems.

References

Intergovernmental Panel on Climate Change (IPCC). (2006). 2006 IPCC Guidelines for National Greenhouse Gas Inventories. Institute for Global Environmental Strategies (IGES), Hayama, Japan. IPCC 2006 Guidelines for National Greenhouse Gas Inventories

Eggleston, H.S., Buendia, L., Miwa, K., Ngara, T., & Tanabe, K. (Eds.). (2006). 2006 IPCC Guidelines for National Greenhouse Gas Inventories: Overview Volume. IPCC. IPCC 2006 Guidelines Overview Volume

IPCC. (2006). 2006 IPCC Guidelines for National Greenhouse Gas Inventories, Volume 5: Waste. IPCC Volume 5 Waste Sector Guidelines

IPCC Task Force on National Greenhouse Gas Inventories. (2016). Waste Sector Methodology Presentation. IPCC Task Force on National Greenhouse Gas Inventories

United States Environmental Protection Agency (USEPA). Waste Reduction Model (WARM). Washington, DC, USA. USEPA Waste Reduction Model (WARM)

Institute for Global Environmental Strategies (IGES). Emission Quantification Tool (EQT) for Solid Waste Management. IGES Emission Quantification Tool (EQT)

International Organization for Standardization (ISO). (2006). ISO 14040:2006 Environmental Management—Life Cycle Assessment—Principles and Framework. Geneva, Switzerland. ISO 14040:2006 Standard

International Organization for Standardization (ISO). (2006). ISO 14044:2006 Environmental Management-Life Cycle Assessment-Requirements and Guidelines. Geneva, Switzerland. ISO 14044:2006 Standard

Cheela, V. R. S., John, M., Biswas, W. K., & Dubey, B. (2021). Environmental Impact Evaluation of Current Municipal Solid Waste Treatments in India Using Life Cycle Assessment. Energies, 14(11), 3133. Environmental Impact Evaluation of Current Municipal Solid Waste Treatments in India Using LCA

Annexure I

User Manual for the GHG Emission Calculator App

Environmental Navigation & Vision for Impact Scenario Analysis & Greenhouse Gas Estimation

GHG Emissions Calculator

User Manual

An Initiative By

Office of the Principal Scientific Adviser to the Government of India

1999-2024 Years of Impact through Science Advice

Developed By

GREEN AADHAAR

<u>Contents</u>

1 Introduction 343
2 System Requirements and Access 344
3 User Roles and Permissions 344
4 Authentication – Login and Session Management 345
5 Application Navigation 347
6 Module-by-Module Operating Instructions 349
7 Calculation Methodology – Technical Overview 369
8 Recommended End-to-End Workflow 372
9 Data Validation Rules 372
10 Troubleshooting and Frequently Asked Questions 373
11 Session Termination – Logout 374
Appendix A – Waste Composition Categories 376
Appendix B – Treatment Methods Supported 376
Appendix C – Glossary of Terms 377

1. INTRODUCTION

• Purpose of This Document

ENVISAGE is a web-based decision-support application designed to quantify greenhouse gas (GHG) emissions associated with municipal solid waste (MSW) management systems. It enables authorised users to calculate emissions from multiple waste treatment pathways, evaluate alternative management strategies, and generate outputs suitable for regulatory reporting and policy analysis.

This manual provides structured, step-by-step operational instructions for all end-user functions, from initial authentication through to session termination. A technical overview of the underlying calculation methodology is included to support informed interpretation of results.

• Scope of Application

Users of ENVISAGE may perform the following functions within the system:

- Characterise city-level waste generation, collection, and material composition.
- Model GHG emissions from treatment pathways including transportation, composting, anaerobic digestion, recycling, incineration, and landfilling.
- Account for avoided emissions arising from material recovery, energy recovery, and fertiliser displacement.
- Compare alternative waste-management scenarios against a Business-as-Usual (BAU) baseline.
- Archive, retrieve, and export calculation results for reporting and policy analysis.

• Document Conventions

Convention	Meaning
Bold text	User interface labels, buttons, or menu items
Italic text	Field names or data values entered by the user
NOTE/CAUTION callouts	Operational guidance, warnings, or important constraints

2. SYSTEM REQUIREMENTS AND ACCESS

Supported Operating Environment

Component	Requirement
Web Browser	Google Chrome (recommended), Mozilla Firefox, or Microsoft Edge
Network Connectivity	Stable internet connection to reach the application server; offline operation is not supported
User Credentials	Valid email address and password issued by an authorised system administrator
Display Resolution	Minimum 1280 × 720 pixels recommended for optimal layout rendering

Obtaining User Access

User accounts are created exclusively by authorised administrators via the User Management module. Self-registration is not available to end-users. To request a new account or a password reset, contact your organisation's designated system administrator.

NOTE: User credentials must not be shared between individuals. Each user must hold a uniquely assigned account.

3. USER ROLES AND PERMISSIONS

The application implements Role-Based Access Control (RBAC) with three primary user roles. Module visibility and data operations are governed by the assigned role and module permissions.

Role	Description	Typical Module Access
Superadmin	Full system authority	All modules – including User Management, Database Administration, and Reference Data Manager

Admin	Organisational administrator	All modules except User Management; city access may be restricted by assignment
Regular	Standard end-user	Dashboard, User Guide, GHG Emissions, Scenario Comparison, My Files, and Profile. No Database or User Management access.

In addition to roles, users are assigned one or more accessible cities (e.g., Chennai, Bengaluru, Delhi, Varanasi). Data views and stored files are filtered according to these assignments.

NOTE: Navigation menu items are displayed only when a user holds read permission for the corresponding module. Write permissions govern create, edit, and delete operations within specific modules.

4. AUTHENTICATION — LOGIN AND SESSION MANAGEMENT

- ## Accessing the Login Page

1. Open the application URL http://envisage.iitm.ac.in/ in your web browser.
2. If no valid session exists, the system will redirect you automatically to the Login page (/login).
3. The login screen displays the ENVISAGE title, a waste-management process illustration, and the logos of the supporting institutions, as shown in Figure 1.

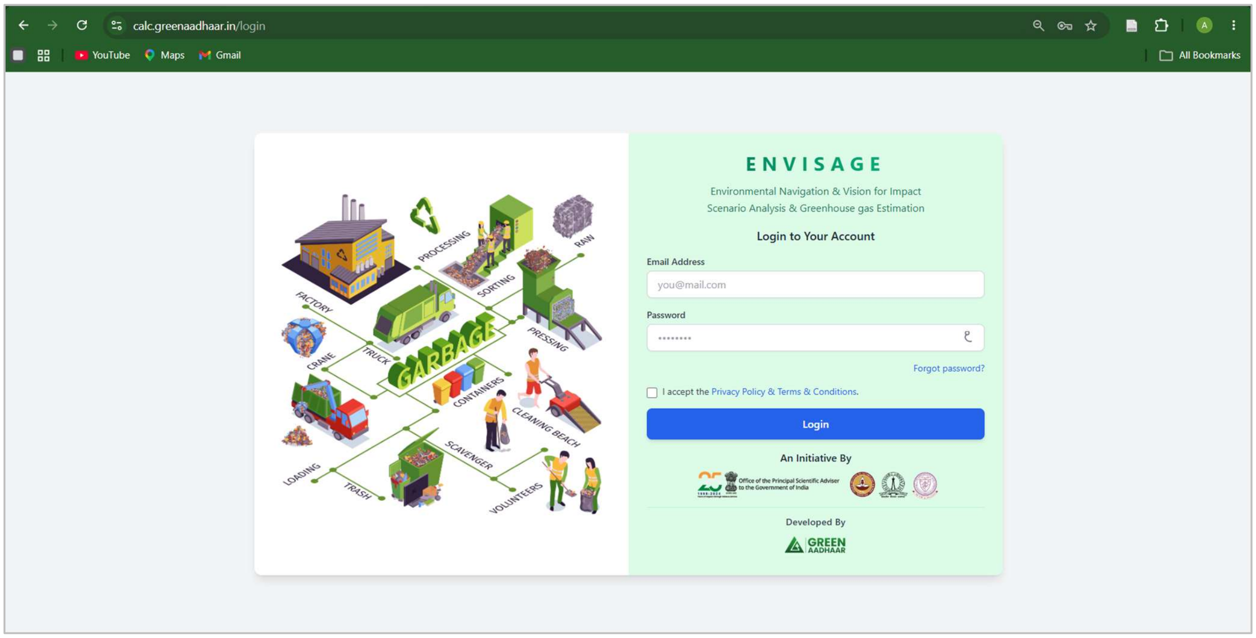


Figure 1. Login screen with username and password fields

- **Login Procedure**

Step	Action	Details
1	Enter Email Address	Type your registered email address in the designated field
2	Enter Password	Enter your password. Use the eye icon to toggle visibility if required.
3	Accept Terms	Review and accept the Privacy Policy and Terms & Conditions by checking the mandatory checkbox. The policy opens in a new browser tab.
4	Submit	Click the Login button to authenticate.

Upon successful authentication, the system performs the following actions:

1. Validates credentials against the backend authentication server.
2. Stores a secure access token in local browser storage.
3. Retrieves user profile data and module permissions.
4. Redirects the user to the Dashboard (/dashboard).

- **Login Error Conditions**

Condition	System Response	Recommended Action

Invalid email or password	Error notification: Invalid email or password.	Verify credentials. Contact administrator if credentials are unknown.
Account lockout (rate limiting)	Error notification including mandatory wait duration	Wait for the specified period before attempting to log in again.
Forgotten password	Information message directing user to administrator	Contact your system administrator to initiate a password reset.
Expired session (during active use)	Automatic redirect to the Login page	Log in again. Unsaved form data may be lost.

• Session Persistence

The application maintains authenticated sessions using JSON Web Tokens (JWT). Sessions persist across browser tabs until one of the following conditions is met:

- The user explicitly logs out.
- The token expires during an idle period (1 hour).
- The server returns an HTTP 401 (Unauthorised) response.

5. APPLICATION NAVIGATION

• Interface Layout

Following successful login, all authenticated pages share a consistent layout structure:

- Left Sidebar – Primary navigation menu, fixed on desktop displays (see Figure 2) and collapsible on mobile screens.
- Main Content Area – Module-specific page content and data entry forms.
- Mobile Menu – A hamburger icon (top-left) opens the sidebar as an overlay on smaller screen sizes.

• Navigation Menu Reference

Menu Item	Route	Function
Dashboard	/dashboard	City-level analytics and visual summaries of waste management indicators

User Guide	/userguide	In-application orientation and quick-start reference for new users
GHG Emissions	/emissions	Single-scenario greenhouse gas emission calculator (multi-step wizard)
Scenario Comparison	/comparison	Multi-scenario comparative analysis against a BAU baseline
My Files	/repository	Repository of saved scenarios and comparison datasets
Database	/database	Emission-factor and reference parameter data records
User Management	/users	User account administration (Superadmin only)
Profile	/profile	City baseline data, language preferences, and session logout

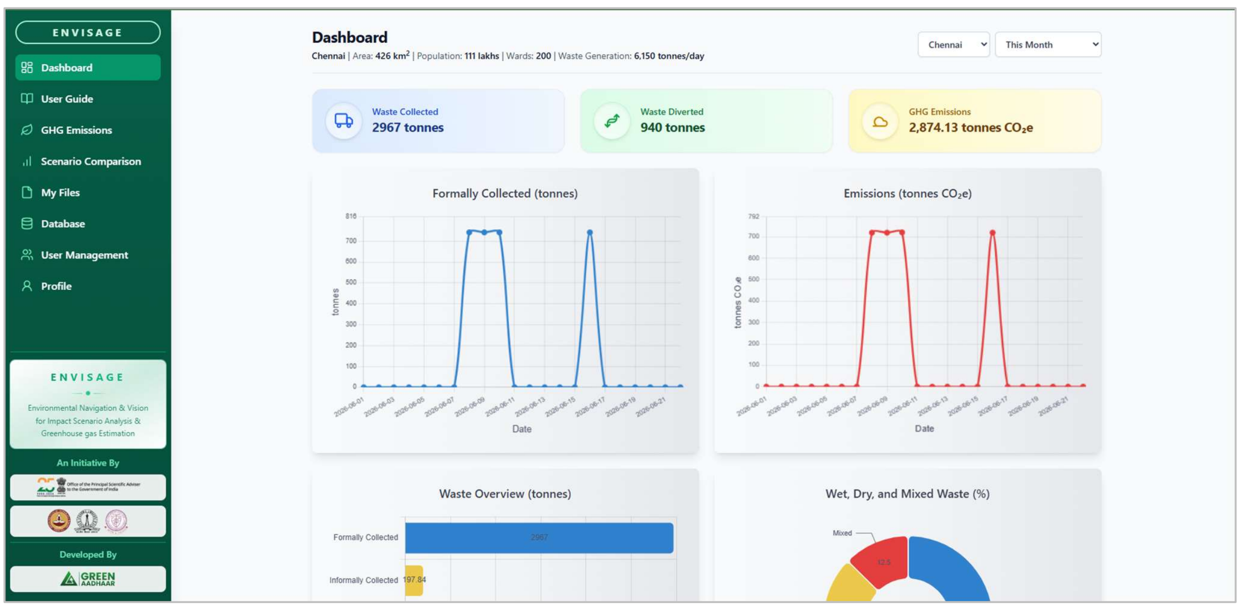


Figure 2. Interface layout

NOTE: Menu items are displayed only for modules to which the user has been granted read permission. Contact your administrator if expected modules are not visible.

6. MODULE-BY-MODULE OPERATING INSTRUCTIONS

- ## Dashboard

Purpose: *To provide a consolidated visual overview of waste-management performance indicators and GHG emission trends for a selected city.*

Operating Procedure

1. Navigate to Dashboard from the sidebar.
2. Select a City from the dropdown (only cities assigned to your account are available).
3. Optionally, adjust the Date Range using preset filters (Today, This Week, This Month, Custom) or specific start and end dates.
4. Review the displayed analytics, which may include:
   - Waste Collected, Waste Diverted, and GHG Emissions summary cards
   - Waste collected and GHG emission trends over time
   - Waste composition charts
   - Material recovery performance indicators
   - Material Flow chart from waste generation to treatment

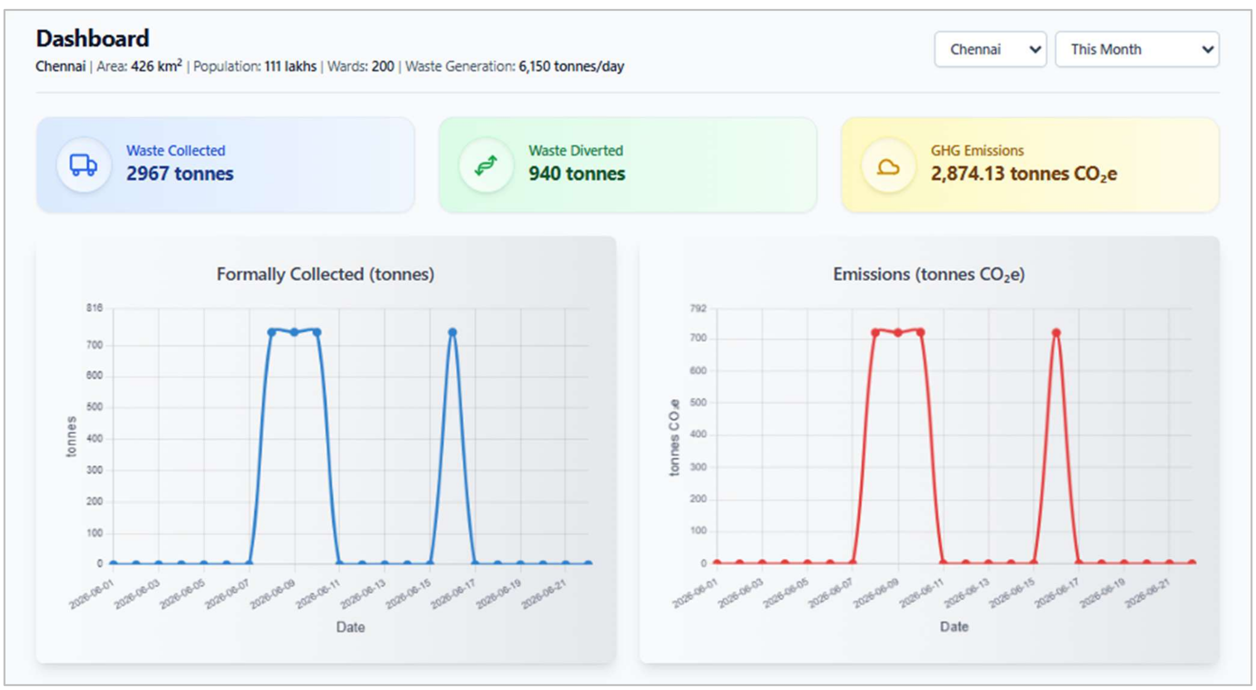


Figure 3. Dashboard

NOTE: The Dashboard presents reference and historical data for monitoring purposes only.

- ## User Guide

Purpose: To provide introductory orientation to the application's functional capabilities and supported waste treatment methods.

Contents

The User Guide page presents the following reference material:

1. Treatment Method Cards – Brief descriptions of Composting, Anaerobic Digestion, Recycling, Incineration, and Landfilling.
2. Quick-Start Guide – Five sequential steps:
    - Step 1: Select Waste Treatment Methods
    - Step 2: Enter Waste Composition Data
    - Step 3: View Emission Results
    - Step 4: Review Avoided Emissions
    - Step 5: Compare Alternative Scenarios

Hover over each step in the left panel to display detailed guidance in the right panel.

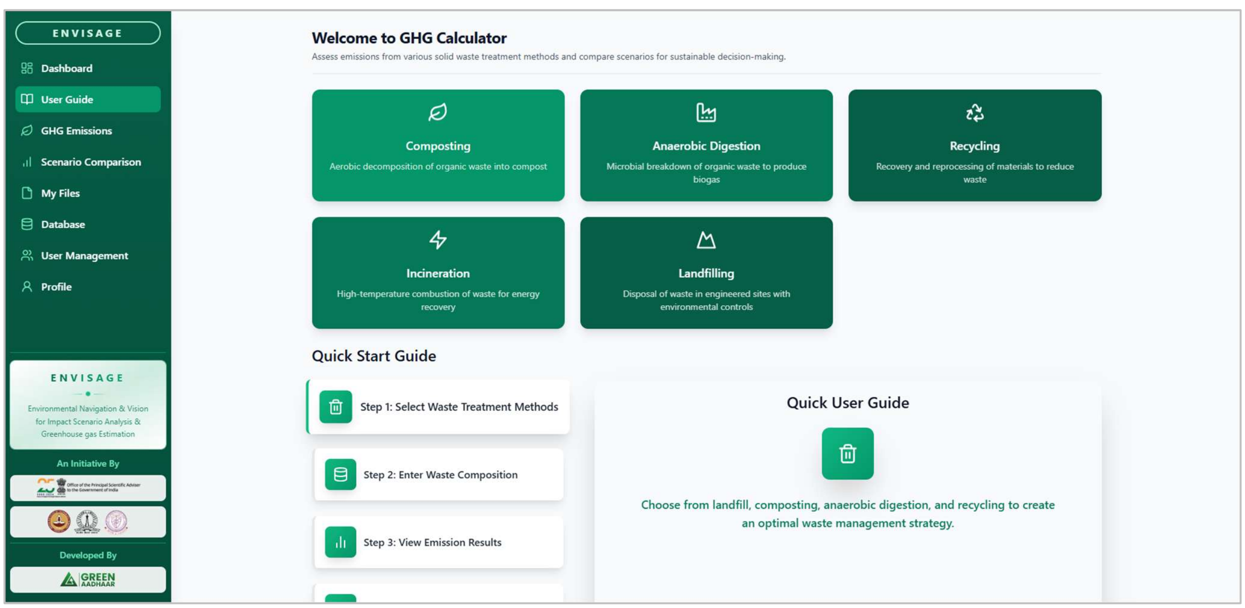


Figure 4. User guide

NOTE: The User Guide module does not accept data input. It serves exclusively as an in-application orientation reference. Consult this module prior to initiating your first calculation.

- ### GHG Emissions Calculator

Purpose: To execute a complete, single-scenario GHG inventory for a city's municipal solid waste management system.

This module operates as a multi-step wizard. Progress through the calculation sequence is indicated by a step navigation bar at the top of the form.

Step 0 — Initial Data Entry

Navigate to GHG Emissions from the sidebar.

A. Select Waste Treatment Methods (Mandatory)

Select one or more treatment methods by clicking the corresponding option buttons:

- Composting
- Anaerobic Digestion
- Recycling
- Incineration
- Landfilling

NOTE: At least one treatment method must be selected. Transportation is always included as the first operational step, regardless of the methods selected.

B. City and Waste Data

Complete the following fields. Informational tooltips (i) are available within the application for each field.

Field	Description	Unit
City Name	Municipality where waste is generated (selection from assigned cities)	Selection
Date	Date of waste data collection (not the data entry date)	Date

Total Waste Generation	Total MSW generated within the city per day	tons/day
Formally Collected	Waste collected by official municipal agencies	tons/day
Informally Collected	Waste collected by informal sector actors (e.g., waste pickers)	tons/day
Uncollected	Waste not collected by any formal or informal system	tons/day
Wet Waste Percentage	Organic/wet fraction of total collected waste	%
Dry Waste Percentage	Recyclable/dry fraction of total collected waste	%
Mixed Waste Percentage	Residual fraction – auto-calculated from the above two values	%

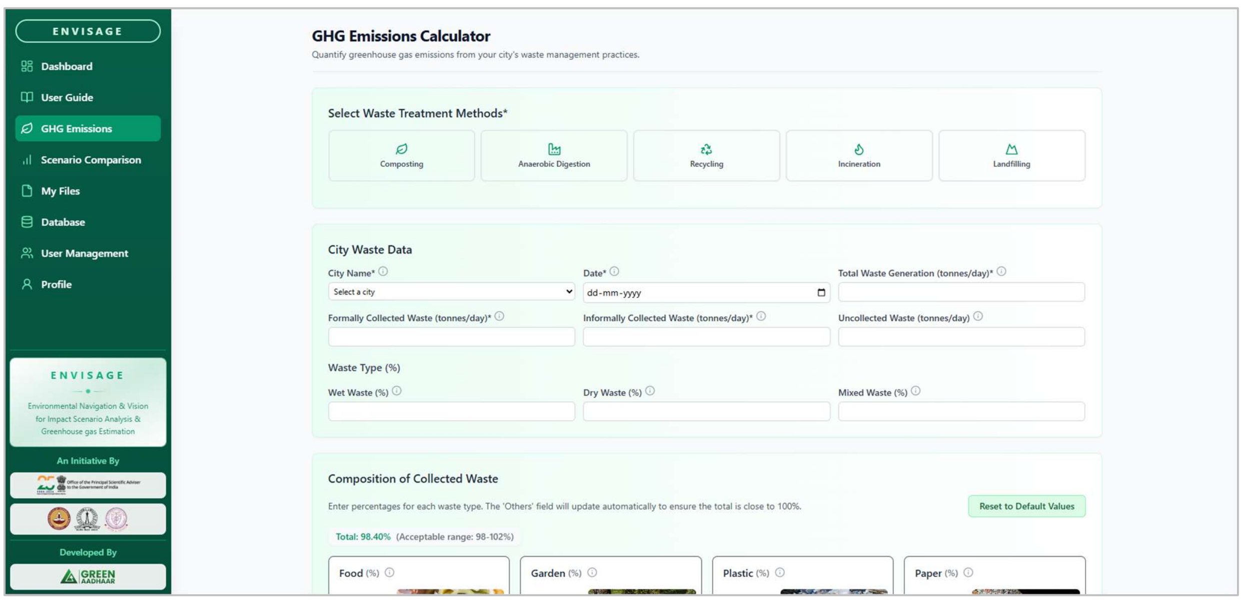


Figure 5. City waste data form

NOTE: The sum of formally collected, informally collected, and uncollected waste must not exceed total waste generation.

C. Waste Composition of Collected Waste

Enter the percentage share of each waste material category. The total must equal exactly 100%.

Default values based on IPCC South-Central Asia regional data are pre-populated. These may be overridden with city-specific audit data where available.

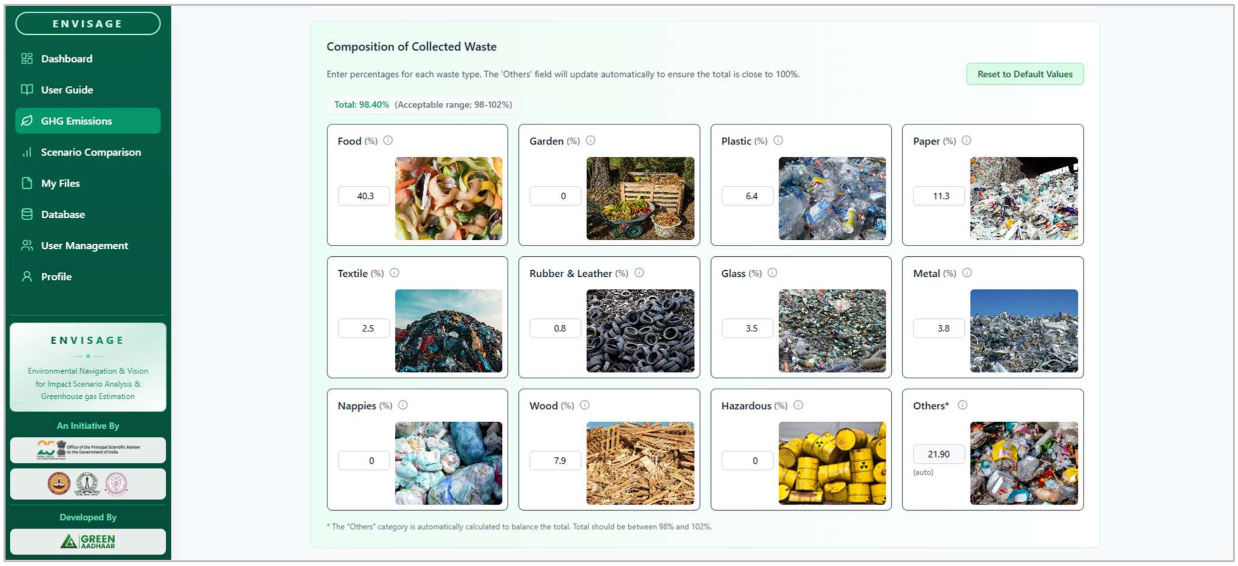


Figure 6. Waste composition data form

D. Waste Allocated to Treatment Methods

Distribute formally collected waste (tons/day) across the selected treatment methods:

- Composting
- Anaerobic Digestion
- Recycling
- Incineration
- Landfilling

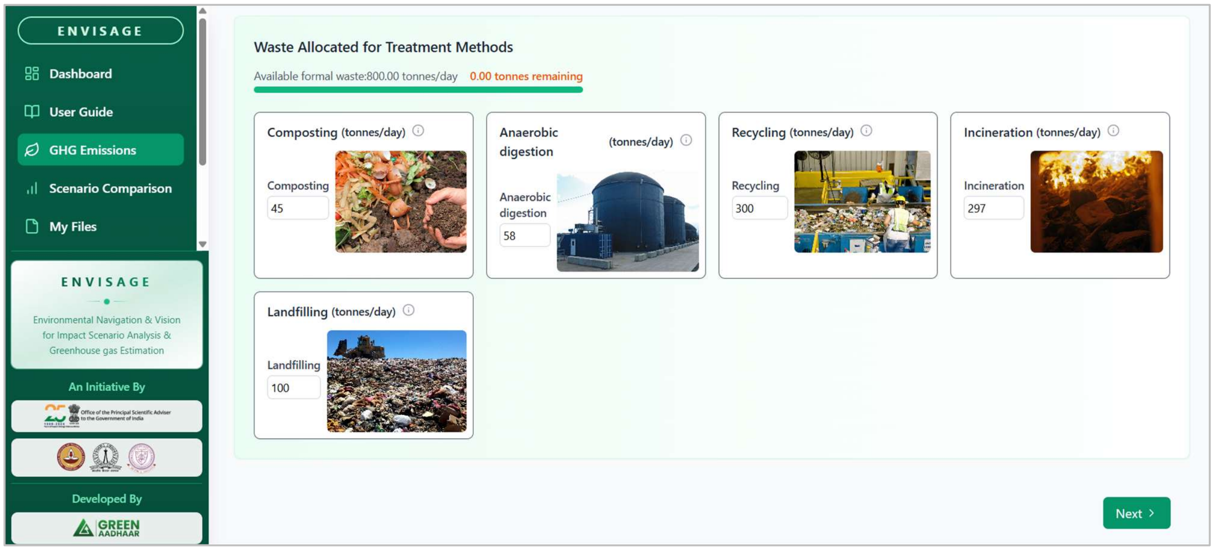


Figure 7. Waste allocation data form

NOTE: Total allocated waste must not exceed formally collected waste. The Next button remains disabled until all validation errors are resolved.

Step 1 — Transportation

Provide data on waste collection and transfer operations:

Section	Key Input Parameters
Waste Collection	Formally collected waste (auto-populated from Step 0); Vehicle type (Older Trucks / Modern Trucks / Both); Fuel types and daily consumption (Petrol, Diesel, CNG, Electric Vehicle)
Transfer Station	Waste handled (tons/day); Grid electricity consumption (kWh/day); Fuel types and consumption quantities

Click Next to advance or Back to return to the initial step.

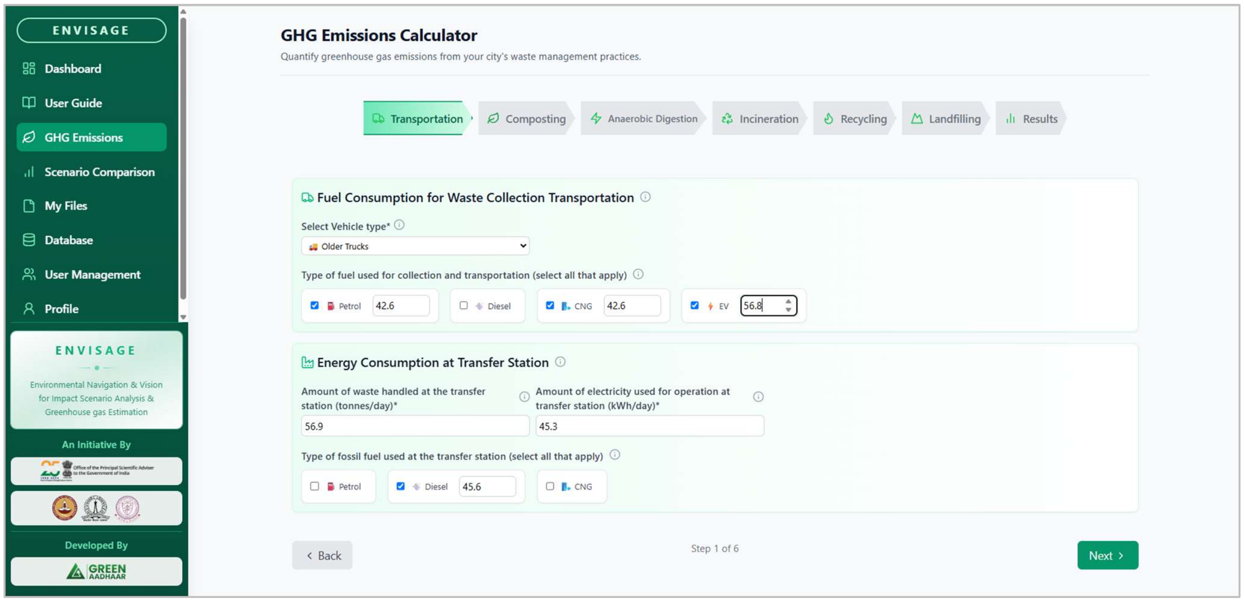


Figure 8. Transportation data form

Steps 2 to N — Treatment Method Forms

For each selected treatment method, complete the corresponding data entry form. Forms appear in the sequence in which methods were selected. Common sections across all treatment forms include:

- Operational fuel consumption and grid electricity use.
- Process-specific parameters (e.g., compost production rate, biogas recovery efficiency, recyclability percentages).
- Optional Input Transportation and Output Transportation sections for upstream and downstream logistics.

Detailed field-level guidance is available via informational tooltips on each form.

Composting — Key Input Parameters

- Waste composted (tons/day – auto-populated from Step 0 allocation)
- Compost production rate (kg per ton of wet waste input)
- Compost utilisation percentage (%)
- Operational fuels and grid electricity consumption

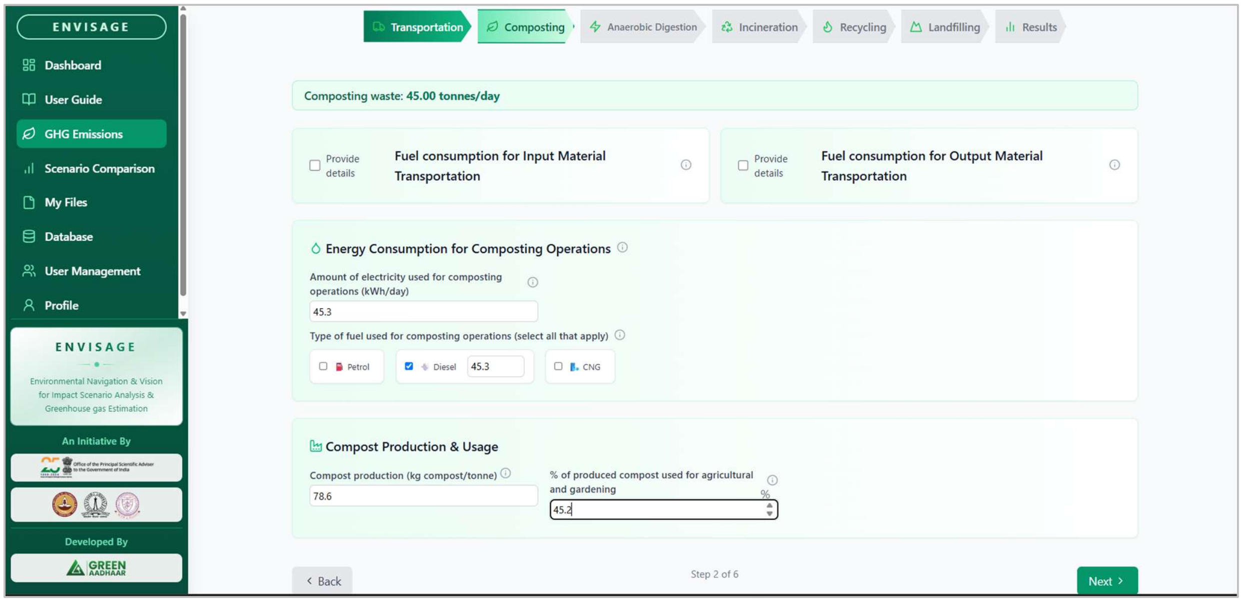


Figure 9. Composting data form

Anaerobic Digestion — Key Input Parameters

- Waste digested (tons/day)
- Energy product type (electricity only; electricity and heat; direct biogas use)
- Fossil fuel displaced by recovered energy (Diesel; CNG; Petrol)
- Digestate or compost recovery rate and utilisation percentage
- Operational fuels and grid electricity consumption

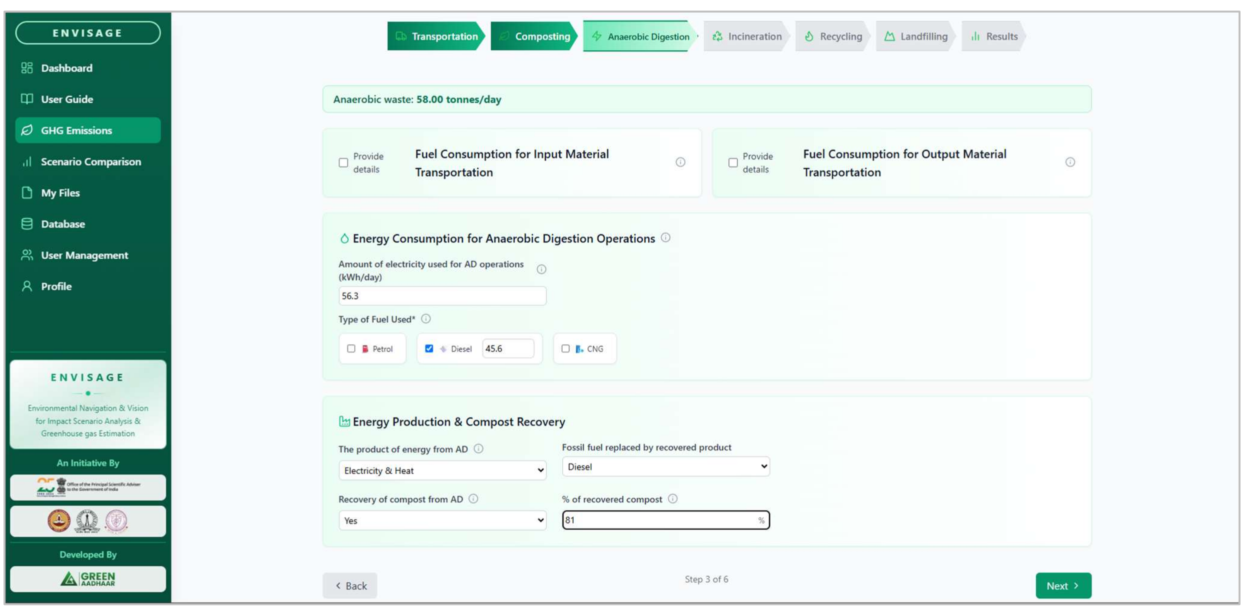


Figure 10. Anaerobic digestion data form

Recycling — Key Input Parameters

- Formal and informal collection stream quantities (tons/day)
- Material composition for each stream (paper, plastic, aluminium, metal, glass – %)
- Energy inputs per material type (grid electricity and fuels)
- Recyclability percentage per material

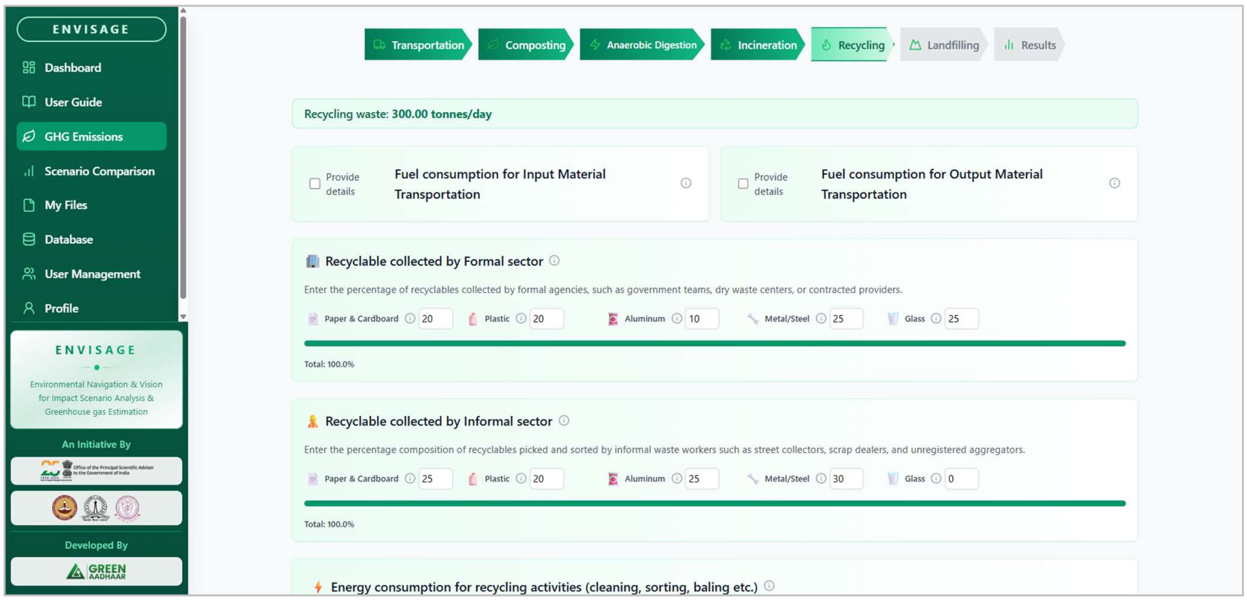


Figure 11. Recycling data form

Incineration — Key Input Parameters

- Waste incinerated (tons/day)
- Incineration technology type and net calorific value
- Mixed waste composition for fossil carbon accounting
- Energy recovery type (heat, electricity, or both) with conversion efficiency and on-site utilisation percentages
- Auxiliary fuel consumption and grid electricity use

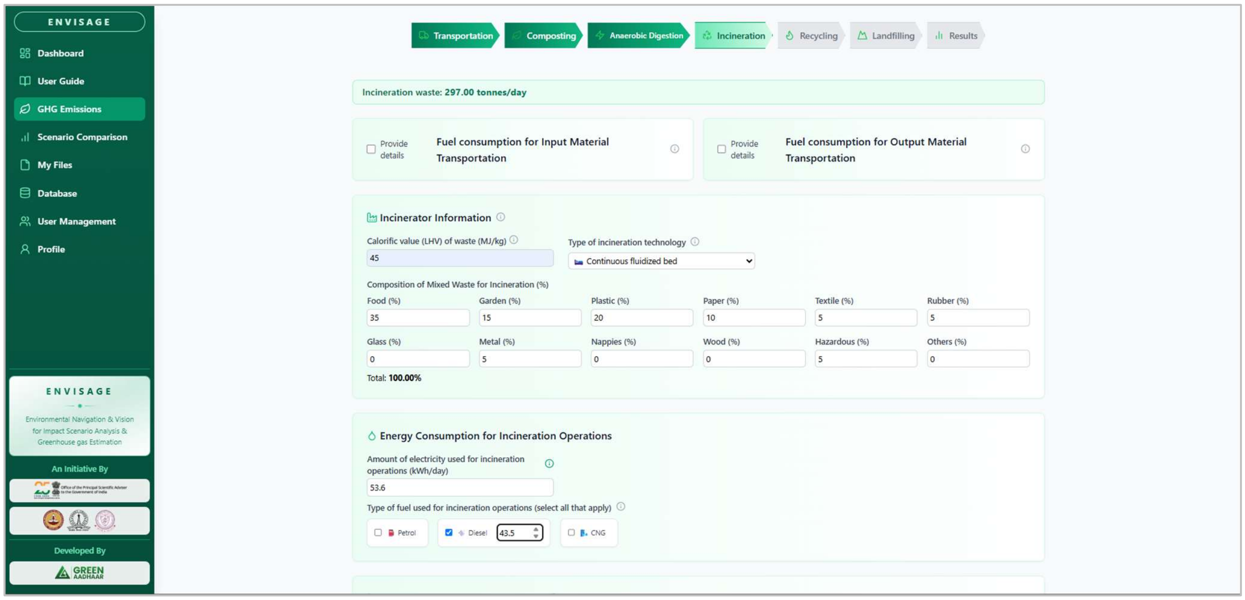


Figure 12. Incineration data form

Landfilling — Key Input Parameters

- Waste disposed (tons/day)
- Landfill type (sanitary with/without gas recovery; semi-aerobic; open dumping)
- Open burning fraction (%)
- Disposal timeline (start year; end year; current year; annual waste growth rate)
- Landfill gas (LFG) collection efficiency; treatment method; and utilisation efficiency
- Fossil fuel displaced by recovered landfill gas energy

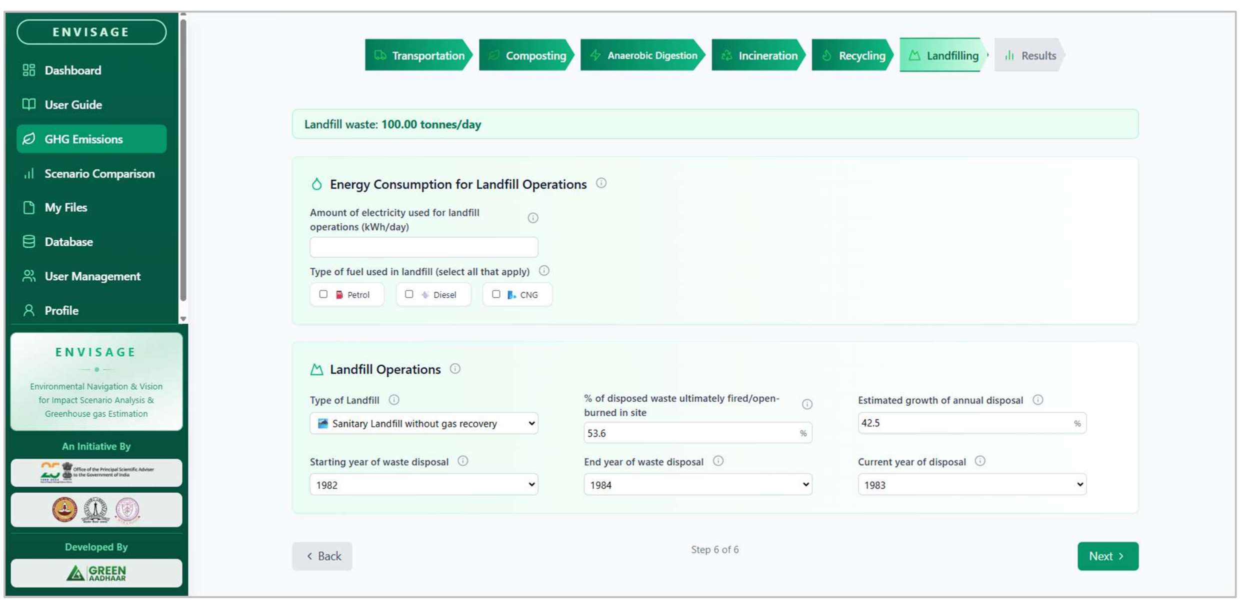


Figure 13. Landfill data form

NOTE: After completing each form, click Next to proceed. On the final treatment form, clicking Next advances to the Results page.

Results

The Results page automatically invokes the backend calculation engine and displays the following outputs:

Output Component	Description
Waste Collection Bar Chart	Comparison of formal, informal, and uncollected waste
Donut Charts	Waste Compositions
Treemap Chart	Visual representation of emission proportions by treatment method
Net Emissions Bar Chart	Comparative net GHG impact across all selected treatment methods
Upstream/Downstream Chart	Transportation emissions associated with material input and output flows
Emissions Breakdown Table	Per-method totals for CH_4, CO_2, N_2O, and Black Carbon – including gross emissions, avoided emissions, and net emissions

Available actions on the Results page:

Action	Procedure
Save Scenario	Click Save Scenario, enter a unique scenario name in the modal dialog, and confirm. The dataset is stored in the database and accessible via My Files.
Download Report	Click the download icon to export a PDF report of the results.
Back	Return to the previous form step to revise input data.

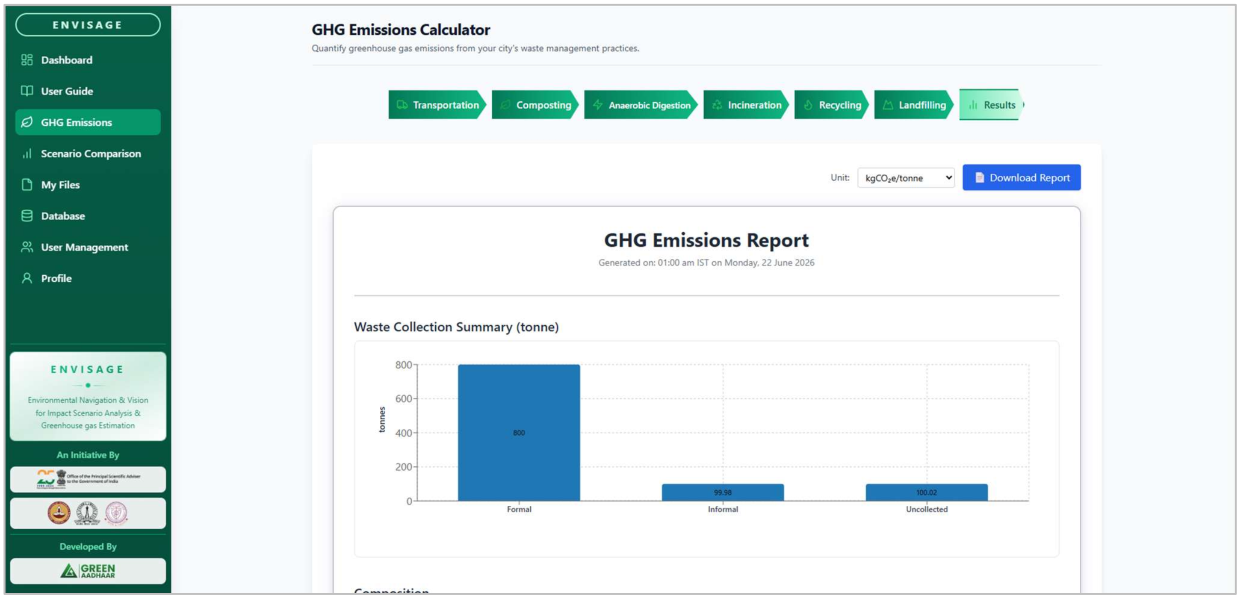


Figure 14. GHG Emission Report(Plots & Chart Results)


Emissions Breakdown by Method

CATEGORY	METRIC	TRANSPORTATION	COMPOSTING	ANAEROBIC DIGESTION	RECYCLING	INCINERATION	LANDFILLING	TOTAL
Emissions	CO_2 kgCO_2e/tonne	0.47	3.62	3.00	73.39	587.38	1.74	227.44
	CH_4 kgCO_2e/tonne	0.01	24.64	24.64	0.00	0.00	1283.21	145.41
	N_2O kgCO_2e/tonne	0.01	79.51	0.00	0.00	17.76	0.00	9.84
	BC kg/tonne	0.00	0.00	0.00	0.00	0.32	0.00	0.11
	Total kgCO_2e/tonne	0.48	107.77	27.64	73.39	605.14	1284.94	382.69
Avoided Emissions	CO_2 kgCO_2e/tonne	0.00	0.76	385.91	2469.51	2828.74	0.00	2055.94
	CH_4 kgCO_2e/tonne	0.00	0.00	0.15	0.50	0.00	0.00	0.23
	N_2O kgCO_2e/tonne	0.00	0.65	3.19	0.83	0.00	0.00	0.61
	BC kg/tonne	0.00	0.00	0.04	0.01	0.00	0.00	0.01
	Total kgCO_2e/tonne	0.00	1.41	389.25	2470.84	2828.74	0.00	2056.78
Net Emissions	CO_2 kgCO_2e/tonne	0.47	2.87	-382.91	-2396.12	-2241.37	1.74	-1828.50
	CH_4 kgCO_2e/tonne	0.01	24.64	24.49	-0.50	0.00	1283.21	145.18
	N_2O kgCO_2e/tonne	0.01	78.86	-3.18	-0.83	17.76	0.00	9.23
	BC kg/tonne	0.00	0.00	-0.04	-0.01	0.32	0.00	0.10
	Total kgCO_2e/tonne	0.48	106.37	-361.61	-2397.45	-2223.61	1284.94	-1674.09

← Back
Save Report

Figure 15. GHG Emission Report (Tabular Results)

- ## Scenario Comparison

Purpose: To compare GHG emissions across multiple waste-management scenarios relative to a Business-as-Usual (BAU) baseline.

Overview

The Scenario Comparison module presents a tabbed interface containing the following sections: Waste Data; Transportation; Composting; Anaerobic Digestion; Recycling; Incineration; Landfill; Results

Each section contains side-by-side input panels for the BAU scenario and up to four alternative scenarios (S1, S2, S3, S4).

Operating Procedure

Step 1 – Load or Define Scenarios

1. Navigate to Scenario Comparison from the sidebar.
2. Optionally, select a previously saved scenario from the dropdown to pre-populate BAU data from My Files.
3. Configure the number of comparison scenarios (1 to 4).
4. Enter or modify waste data, treatment allocations, and method-specific parameters for each scenario column.
5.

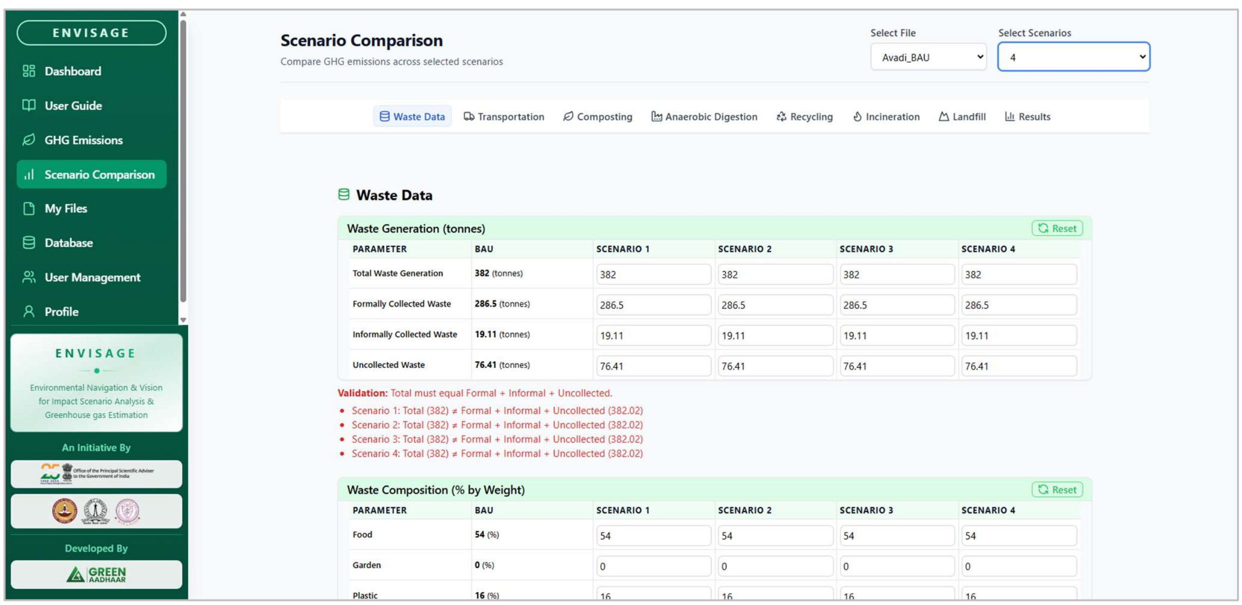


Figure 16. Scenario comparison data form

Step 2 – Complete All Tabs

Progress through each tab systematically, ensuring data consistency across all scenarios:

- Waste Data Tab: City, waste volumes, material composition (must total 100%), and treatment method allocation.
- Transportation through Landfill Tabs: Method-specific parameters, mirroring the fields in the GHG Emissions Calculator.

Use the sticky tab bar to navigate between sections. The application scrolls to the selected section automatically.

Step 3 – View Comparison Results

Navigate to the Results tab. The system performs the following operations:

1. Executes calculation API calls for each scenario in parallel.
2. Adjusts landfill waste composition by subtracting fractions already processed through composting, anaerobic digestion, and recycling.
3. Displays comparative visualisations including side-by-side summary tables, radar charts, treemaps, and method-level emission breakdowns.

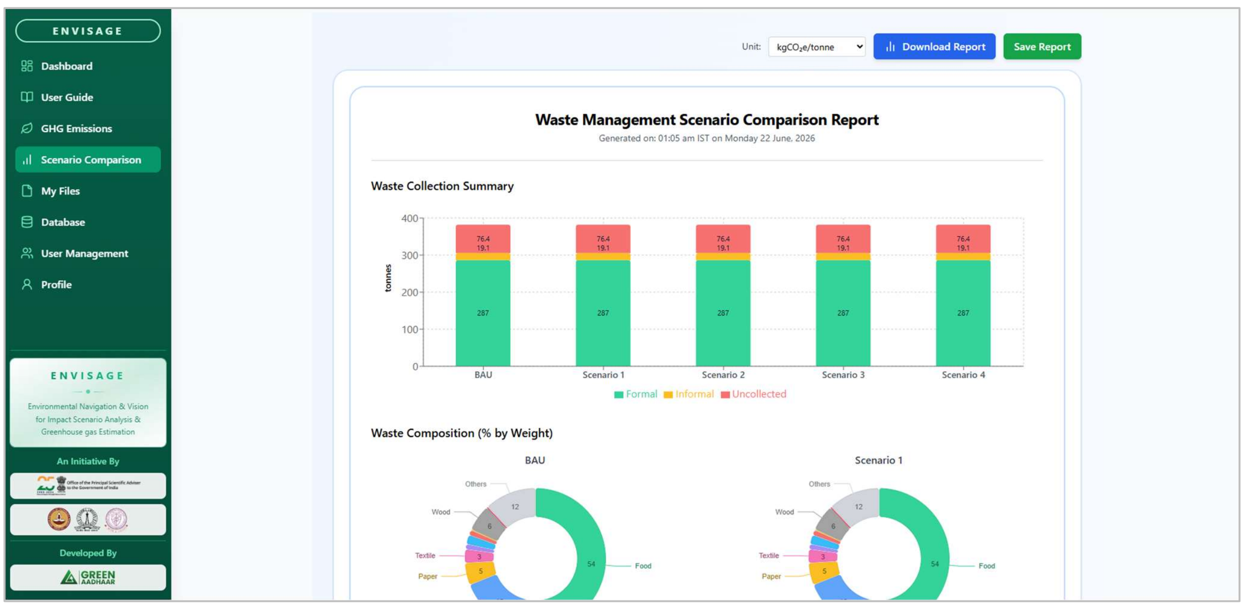


Figure 17. Scenario comparison report

Step 4 – Save Comparison

1. Click Save Comparison.
2. Enter a descriptive name for the comparison data.
3. Confirm to persist the full scenario set and emission results to the database.

NOTE: Saved comparisons are accessible in My Files, identified by the type label Comparison.

My Files (Repository)

Purpose: To manage, retrieve, and export saved scenarios and scenario comparisons.

Viewing Saved Files

1. Navigate to My Files from the sidebar.
2. The table displays all saved entries with columns for name, type (Scenario or Comparison), and creation date.
3. Use the Search field to filter entries by name.
4. Sort entries by name or creation date using the column header controls.
5. Adjust the number of records displayed per page using the page size selector.

Available Actions

Action	Control	Description
Review	View icon	Opens a read-only modal displaying all input parameters for the selected entry
Download	Download icon	Exports scenario data as a JSON file to the local device
Delete	Delete icon	Permanently removes the entry from the database (confirmation required)
Load in Comparison	Context-dependent button	Loads the saved scenario as the BAU baseline in the Scenario Comparison module

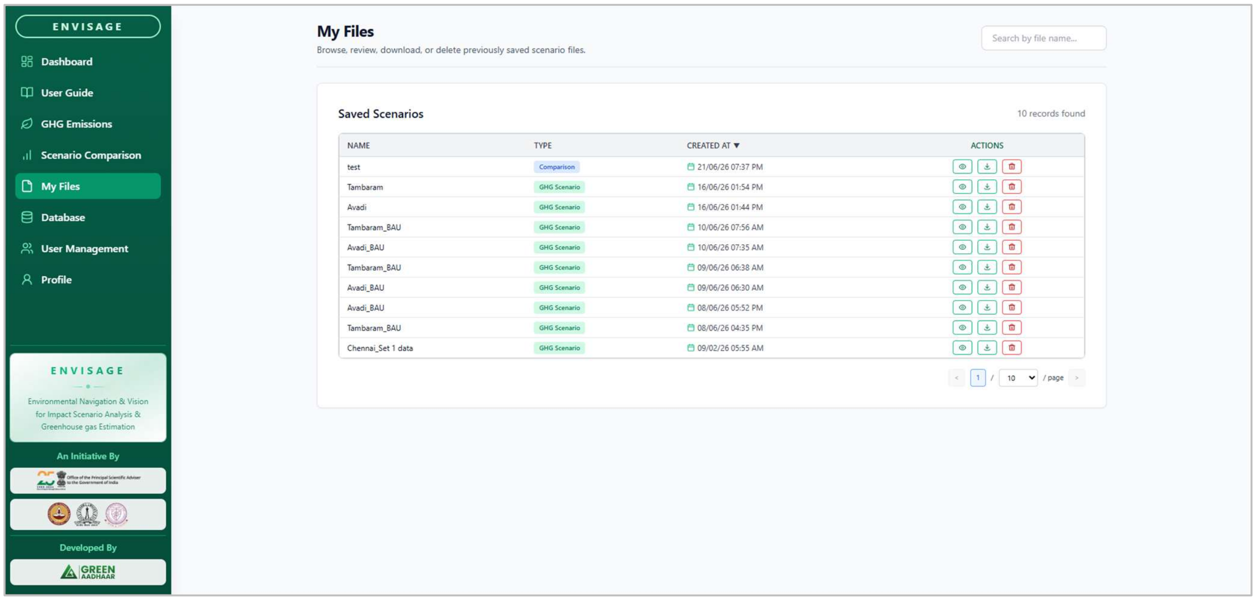


Figure 18. My files (Repository)

NOTE: Regular and Admin users can only view files associated with their assigned accessible cities.

CAUTION: Deletion is permanent and irreversible. Maintain local JSON backups using the Download function for all critical datasets.

- ## Database

Purpose: To maintain the emission-factor and reference parameter records used by the calculation engines.

Access to this module requires the database module read permission. Write permission is required to create, edit, or delete records.

Viewing Records

1. Navigate to Database from the sidebar.
2. Use the Filter Bar to filter records by process type.
3. Browse the paginated table, which displays the parameter name, value, unit, source, and associated metadata.

Managing Records

Action	Permission Required	Procedure

Add Record	Write permission	Click Add, complete the modal form with the required fields, and save.
Edit Record	Write permission	Click the edit icon on the target row, modify the relevant fields, and save.
Delete Record	Write permission	Click the delete icon and confirm the deletion.

Record fields include: Coverage Level, City, Process Type, Parameter Type, Parameter Name, Value, Unit, Activity Basis, Source URL, Data Quality Score, Uncertainty Range, and Description.

Reference Data Manager (Superadmin Only)

Superadmin users may access the Reference Data Manager to configure master data categories, including:

- Process Types
- Parameter Types
- Units
- Activity Bases
- Cities

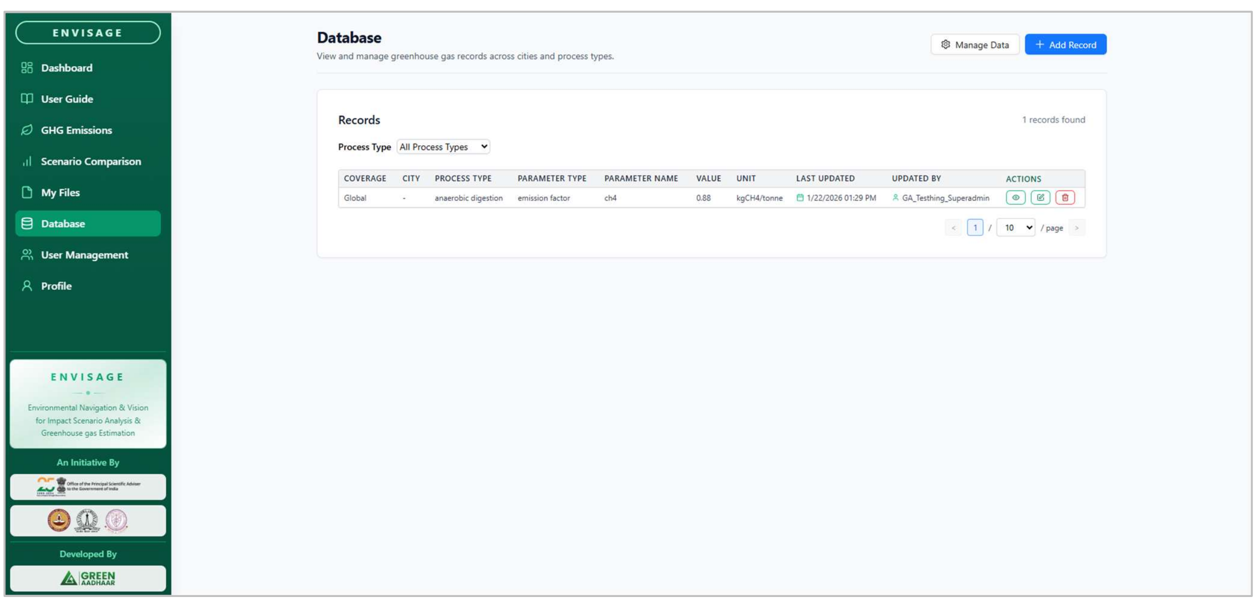


Figure 19. Database

- ## User Management

Purpose: *To create, modify, and deactivate user accounts and manage assigned permissions.*

Access to this module is restricted to the Superadmin role. The menu item is visible only to users with the user’s module permission.

Viewing Users

Navigate to User Management. The table displays each user's name, email address, assigned city, role, and module permissions.

Creating a New User

1. Click Add User.
2. Complete the user creation form with the following information:
   - Full name, email address, initial password, and mobile number
   - Assigned city and role (Superadmin, Admin, or Regular)
   - Accessible cities (for non-Superadmin roles)
   - Module permissions (auto-populated based on role; adjustable as required)
3. Click Save to create the account.

Modifying and Removing Users

- To edit user details, role, or permissions, click the Edit icon on the relevant row, make the required changes, and save.
- To deactivate or remove a user account, click the Delete icon and confirm the action.
- To assign a new password to a user, click Reset Password.

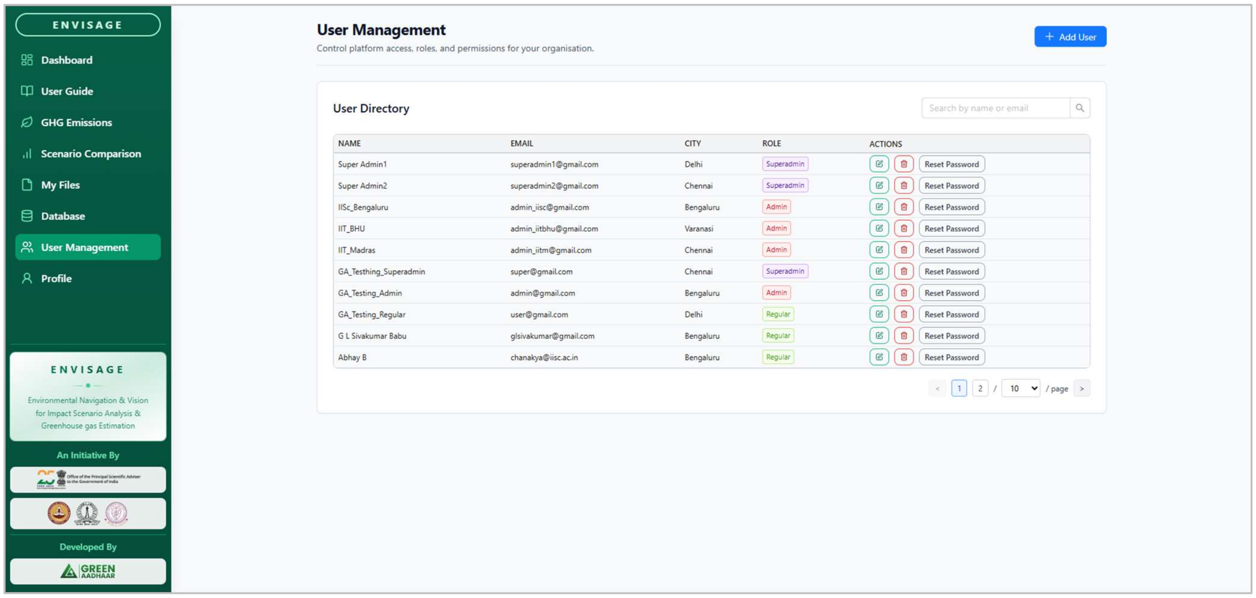


Figure 20. User management

- **Profile**

Purpose: To maintain city baseline profile data, configure language preferences, and terminate the user session.

Profile Header

The profile header displays your name, email address, and a Logout button. Refer to Section 11 for session termination procedures.

Language Settings

Select English or Hindi from the language dropdown. The interface updates immediately upon selection.

City Baseline Data

The Profile module stores default reference data for your assigned city, organised into the following sections:

Section	Contents
City Data	City name, population, area, number of wards, total waste generation, and preferred treatment methods
Waste Composition	Default percentage shares for all twelve waste material categories

Transportation	Default vehicle type and fuel type selections
Composting	Default compost production rate, utilisation percentage, operational fuels, and transport settings
Anaerobic Digestion	Default energy product type, fossil fuel displacement, and digestate recovery parameters
Recycling	Default material composition percentages and energy input parameters
Incineration	Default incineration type, net calorific value, and energy recovery configuration
Landfill	Default landfill type, gas recovery settings, and disposal timeline parameters

Saving and Resetting Profile Data

Action	Procedure
Save	Click Save to persist all profile section data to the database.
Reset Profile	Click Reset Profile to clear all fields to empty default values. A confirmation prompt will be displayed.

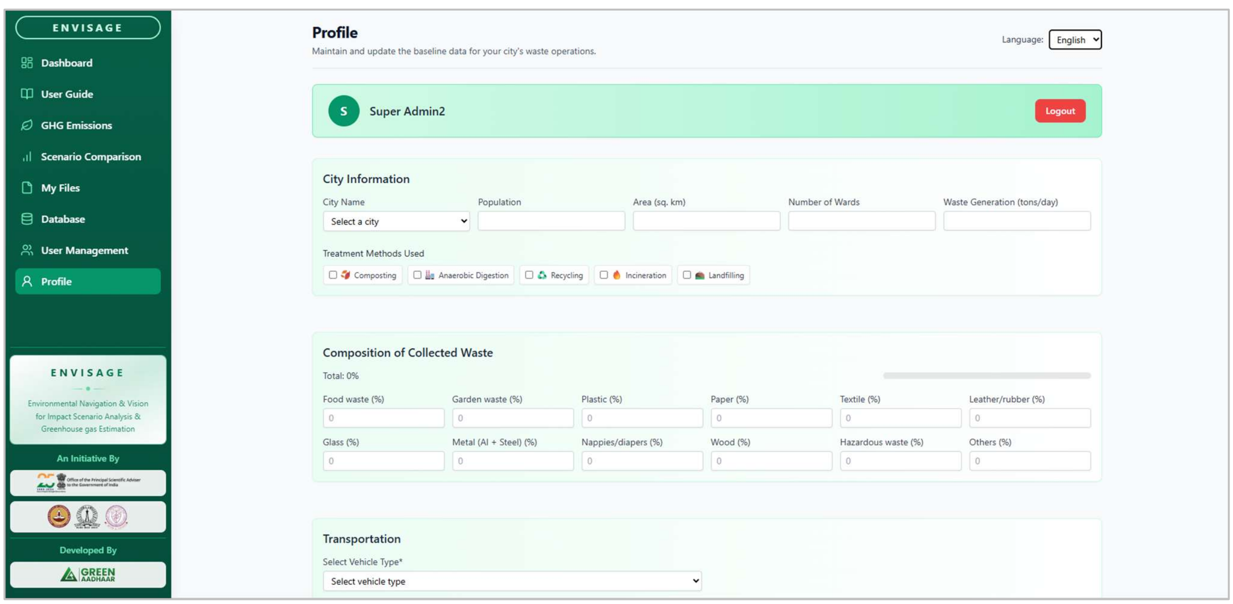


Figure 21. User profile

7. CALCULATION METHODOLOGY — TECHNICAL OVERVIEW

This section provides a concise explanation of how ENVISAGE computes GHG emissions. Detailed emission factors are stored in backend reference data files and aligned with applicable IPCC guidance.

- ## General Accounting Framework

The application quantifies emissions by pollutant – methane (CH_4), carbon dioxide (CO_2), nitrous oxide (N_2O), and black carbon (BC) – and converts them to carbon dioxide equivalents (CO_2e) using Global Warming Potential (GWP100) factors as follows:

Greenhouse Gas	GWP100 Factor
CO_2	1
CH_4 (biogenic)	28
CH_4 (fossil)	30
N_2O	265
Black Carbon (BC)	590 (reported as mass in kg; excluded from CO_2e totals)

Gross Emissions represent total direct and indirect releases from waste operations.
Avoided Emissions represent GHG reductions achieved through material substitution, energy recovery, or fertiliser displacement.
Net Emissions = Gross Emissions minus Avoided Emissions.

- ## Transportation

Emission sources include fuel combustion during waste collection (petrol, diesel, CNG), grid electricity for electric collection vehicles, and transfer station fuel and electricity use.
Formula for fuel combustion emissions:
Emissions (kg CO_2e/tonne) = Sum of [Fuel Consumption x Energy Content x Emission Factor] divided by Waste Handled

Black carbon emissions from diesel vehicles are calculated using vehicle-class-specific factors (older trucks versus modern trucks). Transportation generates gross emissions only; no avoided emissions are credited.

- **Composting**

Emission sources: operational fuel combustion and grid electricity; process CH_4 (IPCC default: 0.88 kg CH_4/tonne, biogenic); process N_2O (IPCC default: 0.30 kg N2O/tonne). Avoided emissions are credited for chemical fertiliser production displaced by compost application:

Avoided = (Compost kg/tonne divided by 1000) x (Utilisation % divided by 100) x Fertiliser Emission Factor

- **Anaerobic Digestion**

Emission sources: operational fuel combustion and grid electricity; biogenic CH_4 leakage (IPCC default value from reference data).

Avoided emissions are credited for: grid electricity displaced by biogas-generated power; fossil fuel displaced by recovered heat or direct biogas use; and fertiliser production displaced by digestate or compost application.

- **Recycling**

Emission sources: per-material processing energy (fuels and electricity) for formal and informal collection streams, weighted by material composition percentages.

Avoided emissions are credited for virgin material production avoided through recycling:

Avoided = (Composition % divided by 100) x (Recyclability % divided by 100) x Virgin Production Emission Factor

Supported materials: paper, plastic, aluminium, steel, and glass.

- **Incineration**

Emission sources: process CH_4 and N_2O from incineration type-specific factors; fossil CO_2 from waste carbon content (calculated as: Dry Matter x Total Carbon Fraction x

Fossil Carbon Fraction x Oxidation Factor); auxiliary fuel combustion; and grid electricity use.
Avoided emissions are credited for heat recovery displacing fossil fuel combustion and for electricity generation displacing grid power.

- **Landfilling**

Emission sources are the most complex of all pathways and include biogenic CH_4 from the IPCC First Order Decay (FOD) model over a 100-year horizon; open burning emissions where applicable; and operational fuel combustion and electricity use.
The FOD model computes methane generation from degradable organic carbon (DOC) in landfilled waste, adjusted by the following parameters:

- Waste-specific organic carbon decay rate (k)
- Methane correction factor (MCF) according to landfill type
- Oxidation factor applied to uncaptured gas
- Annual waste deposition growth rate

Avoided emissions are credited for landfill gas collection and utilisation for heat generation, LPG substitution, or grid electricity generation.

- **Upstream and Downstream Transportation**

When users enable the Input Transportation or Output Transportation options on treatment method forms, the application makes additional API calls to quantify logistics emissions separately from process emissions. These results appear in the Upstream/Downstream chart on the Results page.

Output Units

Metric	Unit
CH_4, CO_2, N_2O – per ton and cumulative total	kg CO_2e
Black Carbon (BC) – per ton and cumulative total	kg (mass; not converted to CO_2e)
Net Emissions	kg CO_2e

8. RECOMMENDED END-TO-END WORKFLOW

The following procedure represents the standard workflow for conducting a complete GHG assessment using ENVISAGE:

1. Log in to the application using your assigned credentials.
2. Consult the User Guide module to familiarise yourself with the application's capabilities.
3. Configure your city baseline data in the Profile module.
4. Open the GHG Emissions Calculator and complete the multi-step wizard: Initial Data Entry, Transportation, Treatment Method Forms, and Results.
5. Save the completed scenario from the Results page using Save Scenario.
6. Open the Scenario Comparison module, load the saved scenario as the BAU baseline, and define one or more alternative scenarios for comparison.
7. Review comparative results and save the comparison dataset if required.
8. Download PDF reports or JSON data from My Files as needed.
9. Log out from the Profile module upon completing your session.

9. DATA VALIDATION RULES

The application enforces the following validation rules. Non-compliance with these rules will prevent the user from proceeding to the next step.

Validation Rule	Applicable Module(s)	Consequence if Violated
Waste composition percentages must total exactly 100%	GHG Emissions; Scenario Comparison	Next button disabled; error message displayed
Allocated waste quantity must not exceed formally collected waste	GHG Emissions; Scenario Comparison	Next button disabled; input field error displayed
Sum of formally collected, informally collected, and	GHG Emissions	Input field validation error displayed

uncollected waste must not exceed total generation		
At least one treatment method must be selected	GHG Emissions	User cannot proceed to Step 1
A scenario name must be provided when saving	Results pages	Save modal validation error displayed
Privacy Policy and Terms & Conditions acceptance is mandatory	Login page	Form submission blocked

10. TROUBLESHOOTING AND FREQUENTLY ASKED QUESTIONS

Q1: Certain menu items are not visible after login.

Answer: Menu visibility is determined by your assigned role and module permissions. Contact your system administrator to verify your access configuration.

Q2: The Next button is greyed out on the GHG Emissions initial page.

Answer: Review the validation error messages displayed below the button. Common causes include waste composition not totalling 100%, or the allocated waste quantity exceeding the formally collected waste figure.

Q3: Calculation results show zero for a selected treatment method.

Answer: Verify that waste was allocated to the relevant treatment method on the initial data entry page, and that all required fields on the corresponding treatment form have been completed.

Q4: The application redirected me to the Login page unexpectedly.

Answer: Your session token may have expired, or the server returned an authentication error. Log in again to continue. Unsaved form data within the current wizard session may have been lost.

Q5: A scenario has been deleted. Can it be recovered?

Answer: Deletion is permanent and cannot be undone. To prevent data loss, maintain local JSON backups of all critical scenarios using the Download function in My Files.

Q6: Can the application be used without an internet connection?

Answer: No. ENVISAGE requires a continuous network connection to the backend calculation server. Offline operation is not supported.

Q7: Which IPCC guidelines does the tool reference?

Answer: The tool incorporates IPCC default emission factors for waste treatment processes (composting, anaerobic digestion, and the landfill First Order Decay model), GWP100 conversion factors, and regional default waste composition data for South-Central Asia. The application does not currently classify results by GHG Protocol Scope 1, 2, or 3 categories.

11. SESSION TERMINATION — LOGOUT

Standard Logout Procedure

1. Navigate to Profile from the sidebar.
2. Locate the Logout button in the profile header card (top-right area of the page).
3. Click Logout to terminate the session.

System Actions upon Logout

Upon logout, the application performs the following operations in sequence:

4. Removes the access token from browser local storage.
5. Clears cached user profile and permission data.
6. Resets the authentication state.
7. Redirects to the Login page via the route protection mechanism.

Conditions for Automatic Logout

The system will log out the user automatically under the following conditions:

- The JWT token expires during an idle or inactive period.
- The permission verification request fails on application load.
- Any authenticated API request returns HTTP 401 (Unauthorised).

Security Recommendations

- Always log out explicitly when using shared or public computers.
- Do not share your credentials with other users under any circumstances.
- Report suspected unauthorised access to your system administrator immediately.

APPENDIX A — WASTE COMPOSITION CATEGORIES

Category	Description
Food	Food waste and kitchen scraps (organic fraction)
Garden	Yard and garden trimmings (leaf litter, grass clippings)
Plastic	Plastic materials of all polymer types
Paper	Paper and cardboard (all grades)
Textile	Textile and fabric waste
Rubber	Rubber and leather items
Glass	Glass containers and construction glass
Metal	Ferrous and non-ferrous metals
Nappies	Disposable diapers and sanitary products
Wood	Wood and timber waste
Hazardous	Hazardous waste fractions (batteries, chemicals, e-waste)
Others	Residual and unclassified waste fractions

APPENDIX B — TREATMENT METHODS SUPPORTED

Method	Process Description
Transportation	Collection and transfer of solid waste from generation points to treatment or disposal facilities. Always included in calculations.
Composting	Aerobic biological decomposition of organic waste fractions to produce stabilised compost for land application.
Anaerobic Digestion	Anaerobic microbial breakdown of organic waste to produce biogas and digestate.
Recycling	Recovery and reprocessing of recyclable material fractions to substitute virgin material production.
Incineration	High-temperature combustion of waste with optional heat and electricity recovery.
Landfilling	Controlled disposal of residual waste in engineered or unmanaged land disposal sites.

APPENDIX C — GLOSSARY OF TERMS

Term	Definition
BAU	Business-as-Usual; the reference scenario representing current or baseline waste-management practices, used as the comparator in scenario analysis.
CO_2e	Carbon dioxide equivalent; the standard unit for expressing the combined warming impact of different greenhouse gases relative to CO_2.
DOC	Degradable Organic Carbon; the fraction of carbon in landfilled waste that is subject to biological decomposition under anaerobic conditions.
FOD	First Order Decay; the IPCC methodology for modelling the generation of methane from landfilled organic matter over time.
GHG	Greenhouse Gas; gases that trap heat in the atmosphere, including CO_2, CH_4, N_2O, and others.
GWP	Global Warming Potential; a factor that converts emissions of a specific greenhouse gas to an equivalent mass of CO_2 over a defined time horizon (typically 100 years).
IPCC	Intergovernmental Panel on Climate Change; the United Nations body responsible for assessing the science related to climate change and providing international reference guidelines.
JWT	JSON Web Token; a compact, cryptographically signed token used for secure user authentication and session management.
LFG	Landfill Gas; gas produced by the decomposition of organic waste in landfills, primarily comprising methane (CH_4) and carbon dioxide (CO_2).
MCF	Methane Correction Factor; a parameter in the FOD model that accounts for the degree of anaerobic conditions in a given landfill type.
MSW	Municipal Solid Waste; solid waste generated by households, commercial establishments, and institutions within a municipality.
RBAC	Role-Based Access Control; a security model that restricts system access based on a user's assigned organisational role.

Volume III

Overall Project Outcomes and Recommendations

Office of the Principal Scientific Adviser
to the Government of India

Chapter 1
Recommendations

1.1 Introduction to the Recommendations

1.1.1 Purpose of the recommendations section

This section translates the study findings into actionable measures for improving municipal solid waste management performance in urban local bodies, corporations and cities. It identifies priority interventions that can reduce environmental burdens, strengthen data reliability, and support evidence-based decision-making.

1.1.2 Linkage between LCA findings and decision-making

The recommendations are grounded in life cycle assessment outcomes, wherein the approach aligns operational choices with measurable impacts such as greenhouse gas emissions, resource recovery efficiency, and disposal-related losses. The basic framework of the Life Cycle Assessment (LCA) model for Solid Waste Management (SWM) assessment is depicted in Fig. 1.1. The model's key outputs including emissions from different processes, material flows and environmental impacts can be the deciding factors to choose the right combination of technologies for treating wastes before performing a technoecomic assessment.

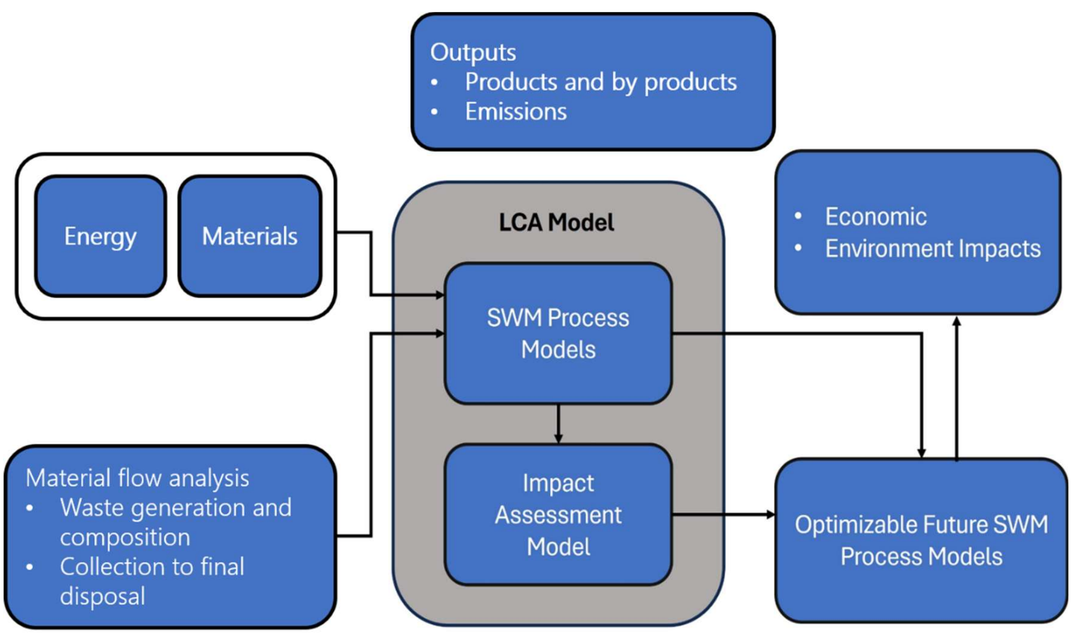


Fig. 1.1 Life cycle assessment (LCA) framework for solid waste management processes

Basis for Recommendations

- Major findings from the LCA study

  The LCA methodology identified the principal environmental hotspots across the municipal solid waste processing system, with treatment-stage emissions and unmanaged disposal accounting for the largest share of greenhouse gas (GHG) burdens. Quantitative results show that processes, which fail to capture methane (landfills, poorly managed biogas systems) and high-carbon thermal treatments without emission controls, are dominant contributors to global warming potential. Secondary impacts arise from material losses and low recovery rates, which amplify resource depletion and embodied emissions across the waste supply chain. These findings indicate that targeted interventions at disposal and recovery nodes will yield disproportionate environmental benefits.

- Environmental hotspots across the waste management chain

  Hotspots concentrate where organic degradation, uncontrolled combustion, or inefficient energy recovery occur, specifically open dumping, unmanaged landfills, and sub-optimally operated biogas and composting facilities. Collection and transportation contribute non-trivial emissions where routing inefficiencies, vehicle idling, and high diesel dependence persist; however, their relative impact is lower than that of disposal-stage methane emissions. Contaminant flows (heavy metals, plastics in organics) create localized toxicity and reduce the efficacy of biological treatments, shifting the burdens downstream and increasing treatment energy demands. Prioritizing interventions to reduce methane emissions and improve material purity will therefore address both climate and local environmental objectives.

- Importance of data quality, interpretation, and system boundary consistency

  Robust interpretation of LCA results requires consistent functional units, transparent system boundaries, and reliable empirical input data; inconsistencies across these elements introduce large uncertainties that can misguide policy. Gaps in plant-level operational reporting, variable waste composition datasets, and non-standardized emission factors undermine comparability between cities and technologies and reduce confidence in scenario ranking. Harmonizing data collection protocols, documenting boundary choices, and applying validated, context-specific emission factors are essential to produce policy-relevant LCA outputs that can reliably inform technology selection and investment decisions.

1.1.3 Scope of recommendations for planning, policy, and operations

The recommendations cover strategic planning, institutional governance, data systems, and facility-level operations. They are intended to support both immediate corrective actions and longer-term transitions toward low-emission, circular, and data-driven waste management systems.

1.2 Key Challenges Identified

A major limitation in the study context is the absence of complete, city-level, facility-level, and process-specific datasets needed for robust life cycle assessment. This constraint weakens scenario comparison, reduces transparency, and limits the precision of environmental burden estimation. This can be specifically grouped under the following categories.

1.2.1 Inconsistencies in waste generation and composition data

Reported values for waste generation and composition often vary across agencies, seasons, and survey methods, making cross-site comparison difficult. Such inconsistency affects model reliability and can lead to misleading conclusions regarding treatment suitability and emissions performance. Typically, the ULBs in India depend hugely on historic thumb-rule estimates of waste composition in a specific region over different periods of the year. This does not include the varying waste composition due to rapid urbanization, and evolving regulations on waste management practices. This reduces the accuracy of the emissions from various processes predicted by the LCA models.

1.2.2 Gaps in plant-level operational reporting

Operational reporting from treatment facilities is frequently incomplete, especially for throughput, rejects, energy use, methane capture, and residue management. These gaps prevent accurate benchmarking of plant performance and obscure the real process efficiency and environmental impact of the system.

1.2.3 Lack of reliable emissions data

Direct emissions data for biogas units, composting facilities, waste-to-energy plants, and landfills remain limited or highly uncertain. As a result, emission inventories often rely on secondary factors, reducing confidence in policy-level interpretation and technology ranking.

Daily monitoring of the gaseous, liquid (leachate) and solid residue emissions vis-à-vis the type/composition of waste processed will have a direct impact on the emissions outcome from LCA model.

1.2.4 Actual waste handled vs installed plant capacity

A persistent mismatch exists between installed treatment capacity and actual waste received or processed, which affects both technical performance and environmental accounting. This mismatch indicates the need for capacity-linked planning based on waste composition, segregation levels, and realistic generation trends rather than nominal design values. Owing to the ever-increasing volume of wastes, the processing plant may get overloaded that would typically limit its performance. On the other hand, plants operating under-capacity, either due to low amount of incoming wastes or due to diversion of wastes to other processes, are operated infrequently in batch mode, which also limits the efficiency.

Fig. 1.2 illustrates how the above-mentioned challenges can hinder the assessment of waste management systems.

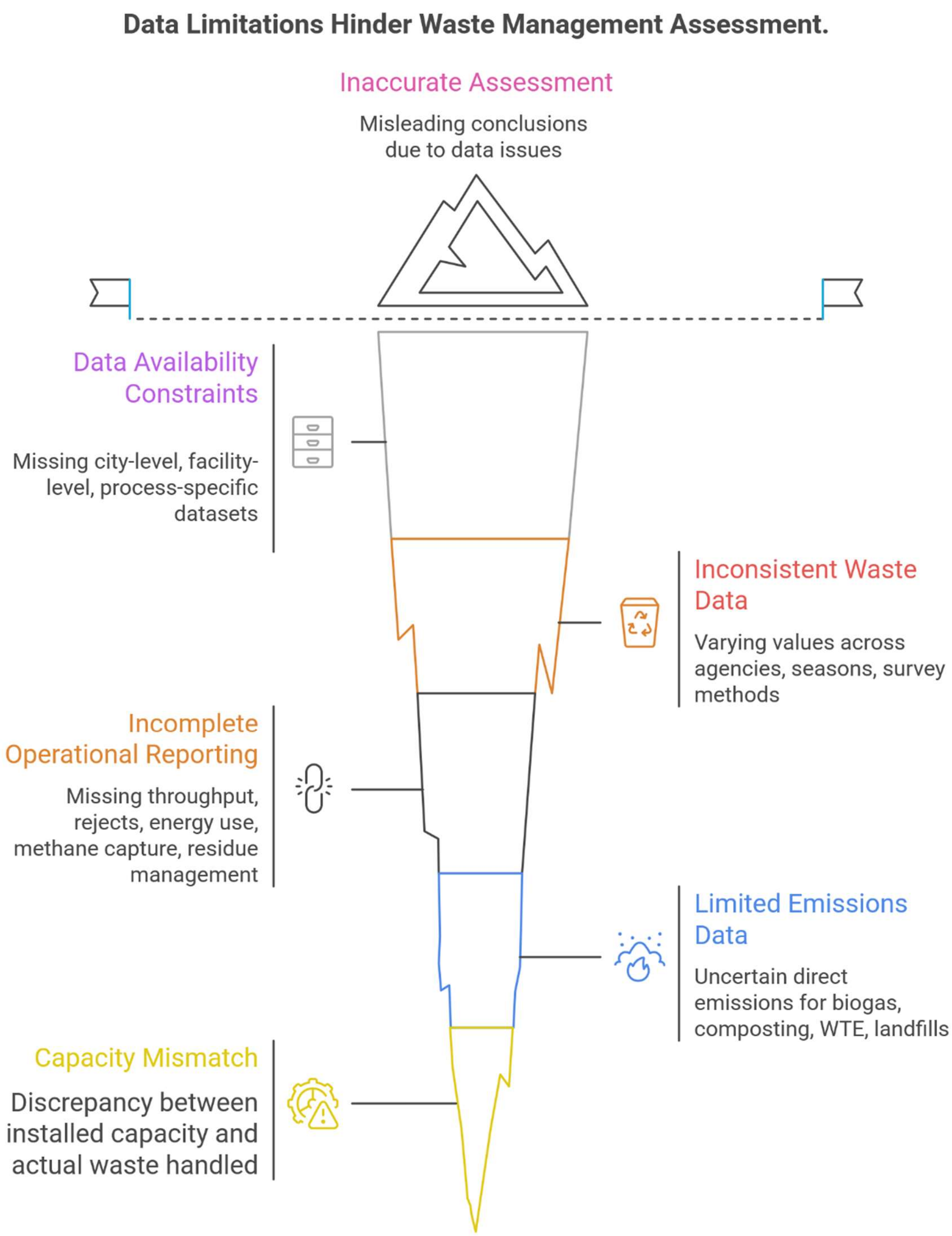


Fig. 1.2 Effect of data quality challenges and limitations on SWM assessment

1.3 Recommendations for Data Collection and Monitoring

1.3.1 Standardization of data collection and reporting

A standardized data collection protocol should be established across municipalities, treatment facilities, and regulatory agencies to ensure consistency in LCA inputs. Uniform definitions, units, sampling procedures, digitalization of data collection and entry, and standardized reporting formats are essential to improve comparability and reduce uncertainty in environmental assessments. A common reporting framework should be adopted across urban local bodies, plant operators, and regulatory institutions to minimize discrepancies in waste, energy, and emissions datasets. Uniform reporting will improve traceability, support centralized databases, and create a stronger foundation for consistent LCA-based policy evaluation.

The possible improvements to overcome data and reporting gaps in MSW management practices and their LCA studies is illustrated in Fig. 1.3.

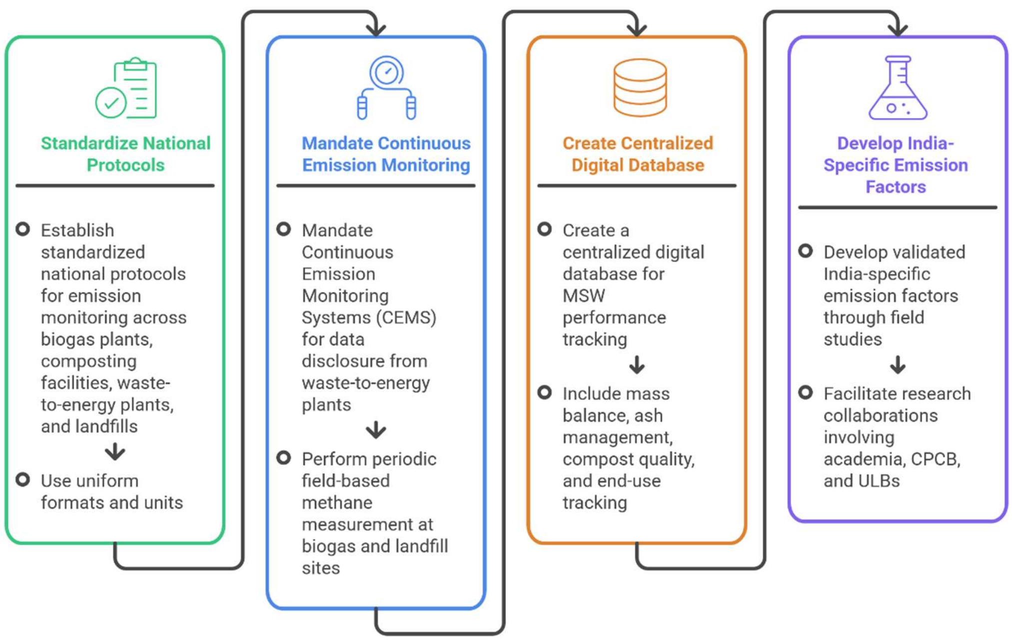


Fig. 1.3 A standardized approach to address data reporting gaps in LCA of SWM facilities

Importantly, all operational and environmental data should be reported in a form compatible with well-defined LCA functional units, such as per ton of waste treated or per unit of service delivered. This will enable consistent comparison across technologies, cities, and scenarios while improving the interpretability of results for policy and planning.

1.3.2 Periodic measurement of waste quantity and composition

Waste quantity and composition should be measured periodically rather than estimated through static or thumb-rules or experience. Seasonal, spatial, and source-specific characterization is necessary because composition variability strongly influences technology performance, emissions, and resource recovery potential. This requires a reasonable mass balance between the overall waste collected in an urban local body (ULB) vis-à-vis the individual fractions diverted to different processes. This also helps in assessing the unprocessed fraction ending up in a landfill/dumpsite. Digitalization of waste collected, segregated, transported, processed is necessary to avoid data manipulations often done through hand written records. This is being carried out in certain ULBs in India using softwares developed by private companies and start-ups (example: https://greenaadhaar.com/). This is aimed at better traceability of the wastes, evaluating the extent of segregation involved, and assessing the energy incurred in the collection and transportation processes. This also helps in better and automated compliance of the stakeholders, and greatly benefit the ULB in proper planning of waste conversion / disposal.

1.3.3 Methane and GHG monitoring

Biogas plants and gas purification systems should be subjected to routine methane leakage monitoring to capture fugitive emissions that are often overlooked in operational reporting. Improving leakage quantification is critical because even small methane losses can substantially alter the climate performance of the biomethanation systems. Landfill systems should incorporate systematic monitoring of methane generation, capture efficiency, and recovery performance. Such monitoring is necessary to distinguish between nominal landfill gas potential and actual field conditions, thereby improving both emissions accounting and recovery planning.

Similarly, composting facilities should monitor CH_4, N_2O, and NH_3 emissions under actual operating conditions, as these emissions significantly affect both climate and air-quality outcomes. Reliable field data are needed to evaluate process efficiency, optimize aeration and moisture management, and generate context-specific emission factors. Many institutional and micro-composting centers do not possess this data on a daily / weekly / monthly basis as a means of performance and emission assessment. Most of the small-to-medium sized (10-100 tons/day waste handling capacity) waste-to-energy plants, and thermal processing facilities adopting pyrolysis or torrefaction do not report the gaseous emissions on hourly / daily basis that gets recorded on a common portal. Gaseous emissions within the PCB-prescribed norms depend on both process efficiency as well as the efficacy of the emission control units installed downstream of these processes / reactors. Periodic maintenance of the emission control units (like cyclones, electrostatic precipitator, bag filters, wet/dry scrubbers) is essential to keep the emissions within norms.

1.4 Recommendations for Digital Data Management

1.4.1 Digitalizing data collection

Digitalization should be bottom-up, i.e. digitalization efforts must begin right from waste collection on the ground. This includes integration of weighbridge records, adoption of QR code-based and AI-enabled tools to classify the waste based on composition to minimize manual reporting errors and improve traceability across the waste value chain. GPS-enabled route monitoring, and vehicle-level operational tracking to capture real-time waste movement, fuel usage and service efficiency are also essential to accurately account for the energy consumption, which is a key input to LCA models. Automated capture of vehicle identity, trip count, waste quality vs quantity, and destination can significantly enhance data reliability and reduce dependence on fragmented paper-based manual recording systems. This integration would strengthen accountability in waste collection, classification and transport, while generating reliable primary data for activity-based emissions estimation.

1.4.2 Centralized digital database

A centralized digital database should be established to consolidate municipal solid waste data on mass flows, composition, treatment performance, emissions, ash management, compost quality, and end-use pathways. Such a platform would improve data accessibility, reduce fragmentation across ULBs, and provide a common evidence base for LCA-informed planning and regulatory review. While Swachh Bharat Mission has a nation-wide portal encompassing the waste generation and processing statistics across all the registered ULBs, it also suffers from periodic updating of data in those facilities, which results in sparse datasets. More importantly, the data entered in the portal need to be aligned with LCA-specific inputs as mentioned in Section 1.3.

1.4.3 Longitudinal life cycle and environmental assessment

Digital platforms should maintain structured historical records to support trend analysis, scenario comparison, and long-term environmental performance assessment. Archived datasets are essential for evaluating policy effectiveness over time and for enabling dynamic, evidence-based updates to LCA assumptions and planning strategies. It is also essential that the LCA-based digital platform is interoperable with municipal and national platforms such as Swachh Bharat Mission to harmonize reporting, benchmarking, and policy oversight. Integration with broader urban governance systems can strengthen continuity between local operational data and national-level sustainability, climate, and waste management targets.

1.5 Recommendations for Segregation and Material Flow Management

1.5.1 Strengthening source segregation

Source segregation should be treated as a foundational intervention rather than a supportive measure both at household and commercial levels, because it directly determines the environmental and operational performance of downstream treatment systems. The latest Solid Waste Management Rules (2026) enforces waste segregation into four streams, viz., wet wastes that are potentially compostable or digestable, dry wastes including recyclables that are processed at material recovery facilities, sanitary wastes and hazardous / special care wastes. Strengthening segregation at household and commercial levels can improve material quality, reduce contamination, and increase the effectiveness of composting, biomethanation, recycling, and energy recovery pathways. It is also necessary to track the fate of the segregated fractions after collection, as oftentimes they tend to get mixed in a dumpsite. While the informal sector (kabadiwalas, local scrap collectors, informal recyclers) plays a key role in segregation and repurposing and recycling of the dry wastes (like metals, plastics, papers, glass) in India, the mix-up of hazardous and sanitary wastes along with other mixed fractions is not uncommon. Therefore, tracing and ensuring that the segregated fractions travel segregated until the end of value-chain is key to reap the benefits.

1.5.2 Technology-linked segregation

Segregation of wastes after disposal is a capital-intensive operation. Therefore, segregation at source is the most preferred approach. Nevertheless, mix-up of different waste streams post-collection also occurs in the transfer stations in the intermediate stages of the waste value chain. Segregation targets should be defined in relation to the requirements of the dominant treatment technology rather than through a uniform city-wide benchmark. A technology-linked approach ensures that the quality of segregated waste aligns with process needs, thereby improving treatment efficiency, reducing reject rates, and enhancing environmental outcomes. More important is the regular monitoring of contamination levels in segregated waste streams to assess the practical effectiveness of segregation systems and identify recurring material quality issues. Such monitoring is especially important because different technologies are sensitive to different contaminants, and unmanaged contamination can significantly reduce recovery efficiency and environmental benefits.

Based on the case studies of Delhi and Varanasi, it is found that adopting a three-tier waste segregation model with low, medium and high extent of segregation is better to route the wastes to the respective waste conversion processes. Highly segregated wet and dry waste fractions are conducive to composting and material recovery, respectively, while less segregated wastes end up in the landfills/dumpsites or gets diverted to waste-to-energy plants. It is worthwhile to note that too much inerts affect the throughput of any waste conversion process, while the presence of wet wastes or high moisture (>10-15%) increase the energy requirements of any thermochemical waste-to-energy process, thereby reducing the process efficiency and adversely affecting the emissions. The presence of non-biodegradable matter like plastics also reduces the throughput of biological processes like digestion and composting.

1.5.3 Ward-level and seasonal waste composition studies

Waste composition studies should be carried out at ward level and across seasons continuously to capture local and temporal variability that is often masked in city-averaged datasets. This finer-resolution evidence is essential for selecting appropriate technologies, calibrating policy thresholds, and improving the reliability of LCA-based planning in data-poor urban contexts. The composition metrics could include basic ones like moisture, ash, fractional characterization and calorific value to more detailed assessments including CHNS/O elemental composition, biochemical/plastic characterization, emission calculations, etc. This is a stage where the students of different levels, especially of high/higher secondary school and college undergraduates, can be deployed to collect waste data, characterize them and develop datasets. The integration of such datasets for a city / district / state will be valuable to develop well-founded deep learning AI models. This would promote a deeper engagement of corporation/ULBs with institutions to solve a fundamental problem for a national cause.

1.5.4 Improving logistics efficiency

Collection, routing and transportation systems should be (re)designed to reflect material flow requirements, segregation status, and destination-specific logistics rather than generic transport routines. Such optimization can reduce fuel use, avoid unnecessary handling, improve service efficiency, and generate more accurate data for both operational management and environmental assessment. Such a waste generation-utilization-logistic optimization will minimize overall emissions involved in all the unit processes in solid waste management. While it is a complicated task to optimize the logistics of waste collection and transportation in real time at a corporation level, efforts are needed to study this optimization problem at the level of ULB, and translate it to a bigger city scale.

1.6 Recommendation on Treatment Technologies

Based on the extensive LCA study and discussion with the experts, the recommendations on the various treatment technologies are summarized in Table 1.1. Segregation needs to be strengthened to facilitate efficient waste treatment including recycling and reuse. Moreover, resource recovery and nutrient recovery efficiency benchmarking needs to be evolved for Indian conditions. It should be noted that *Successful solid waste treatment isn't just about choosing the right technology; it's about mastering its day-to-day operation.*

Table 1.1 Recommendation on various treatment technologies

Technology	Recommendation
Bio-methanation	• Best option for wet wastes • Maximize energy recovery (as CBG, cooking gas, electricity, etc) and by-products • Align with existing policy such as SATAT, FOM, and LFOM • Needs to be augmented with other byproducts to make them viable at the lower end of the scale while FOM (fermented organic manure) and LFOM (liquid FOM) need to be give a boost in order to greatly reduce carbon-and resource footprint • Digestate valorization to biochar and other liquid fuel products needs detailed studies though thermochemical technologies
Composting	• Compost plant can be integrated with biogas recovery from leachate • Improve economic viability by increasing compost yield, generating revenue from leachate, and with Government support
MRF/Recycling	• MRF and recycling are used interchangeably, while they are indeed very different! • While Material Recovery focuses on the segregation of dry wastes and sorting them into recyclable materials, recycling is actually the conversion of the segregated dry waste fractions into value-added products through various technologies

	• Dry wastes and MRFs need to be made viable at the lower end of the collection by innovations in aggregation as well as in recycling technologies
Waste-to-Energy (WtE)	• Best for high calorific value waste and low moisture content waste • Carbon capture followed by sequestration or utilization from WtE would lead to drastic decrease in carbon footprint, although it is capital-intensive • Continuous emission monitoring and recording alongside proper maintenance of the emission control units is necessary to meet the norms
Other recycling technologies	• Some of the recycling technologies like pyrolysis are shown to be effective for well-sorted plastic wastes containing mainly olefinic plastics with negligible halogenated plastics and contaminants • However, their technoeconomics and the use of the oil product for refinery applications seem to be the major bottlenecks
Landfill	• High calorific value and wet-wastes ending up in landfills must be minimized and eventually avoided • Open dumping and simple passive venting of landfill gases from sanitary landfill must be avoided *(existing landfills)* • Leachate recirculation and reuse, biogas, and nutrient recovery must be prioritized *(existing landfills)*
Biomining	• Recycling of legacy wastes need to be boosted through higher levels of innovations • The power consumption and mechanical efficiency of the trommels and other machineries must be optimized
Leachate treatment	• The practice of treating leachate to drinking water standards must be discontinued, as this quality level is not required for typical on-site or industrial reuse

1.6.1 Biomethanation

Biomethanation should be prioritized for source-segregated organic waste because it offers simultaneous benefits in waste stabilization, renewable energy generation, and nutrient recovery. The environmental performance of these systems can be significantly improved by maximizing useful biogas utilization as compressed biogas (CBG), cooking fuel, or electricity, while rigorously controlling fugitive methane emissions across digestion and purification stages. Digestate valorization is a key area needing innovative processing and conversion to value-added products (including biochar and biofuels) as this would positively improve the technoeconomic viability of the business. Some of the emerging processes include hydrothermal liquefaction and carbonization, although these are presently at a low TRL for digestate management.

Our LCA study demonstrates that simple energy recovery pathways particularly electricity generation and direct cooking deliver substantial climate mitigation. In contrast, purification-intensive pathways such as upgraded biomethane for cooking or vehicle fuel offer lower benefits due to methane slip and higher energy inputs, especially at medium scales within 100 TPD waste input. Economically, large-scale biogas plants integrated with digestate valorization are essential for financial sustainability. Larger capacity units, especially at 500 TPD and above, demonstrate strong returns on investment and short payback periods (< 5 years).

1.6.2 Composting

Composting remains an appropriate treatment option for biodegradable waste streams where feedstock quality is maintained and process control is adequate. It is also the only viable process to generate value from biogas digestate. However, the market price of fermented organic manure (FOM) and liquid fermented organic manure (LFOM) are low, i.e. INR 0.5-4/kg for FOM and INR 10-20/liter for LFOM, for any business of MSME scale to be viable. This is a domain where Government subsidies are necessary for businesses to reap the benefit of setting up a biogas unit for solid waste management. Furthermore, its environmental and economic performance can be improved through better segregation, enhanced compost yield, and integration of leachate management or biogas recovery options where feasible.

Our study shows that the environmental sustainability of organic fraction of MSW (OFMSW) composting systems is governed not only by waste stabilization but also by the effective valorization of compost leachate. By integrating leachate-based energy recovery into the life cycle boundary, the analysis highlights a major opportunity to enhance the climate performance of composting facilities. In fact, composting combined with anaerobic digestion of leachate and biogas-to-electricity generation is the best option from both environment and LCA perspective. Importantly, the compost utilization rates, transport distances, and energy recovery efficiency are decisive factors determining the climate viability. These findings indicate that composting systems must be designed as integrated circular economy infrastructures rather than standalone treatment units.

1.6.3 Waste-to-energy systems

Waste-to-energy should be considered primarily for high-calorific, low-moisture residual waste that cannot be effectively diverted through biological or material recovery pathways. The climate burden of such systems can be reduced substantially through improved feedstock control, higher conversion efficiency, and the future integration of carbon capture, utilization, or sequestration measures. Our analysis based on LCA reveals that while carbon capture utilization (CCU)-integrated systems exhibit the highest theoretical environmental mitigation potential, their practical performance is constrained by operational, infrastructural, and market limitations. The financial viability is strongly dependent on waste quality, with positive returns achievable only for high-calorific value (>2150 kcal/kg), low-moisture (<20%) waste streams. Accordingly, carbon capture technologies cannot be considered standalone solutions; their effective deployment requires upstream measures such as improved source segregation, waste pre-treatment, and system integration. These findings should be interpreted as forward-looking potential within the limitations identified, highlighting that aligning waste management practices with feedstock quality improvement is essential for realizing the environmental benefits of advanced WtE systems while maintaining financial sustainability in India.

A detailed account on the WtE plants in India by the Center for Financial Accountability (2022) shows that WtE plants cannot function without large monetary grants from Government and high tariff for sale of power generated from the units. Despite the minor concessions by the Government, the existing plants only run with the help of debt financing, while some have already filed bankruptcy (https://www.cenfa.org/wp-content/uploads/2022/12/INDIAS-WASTE-TO-ENERGY-PARADIGM.pdf). One of the reasons is also attributed to the poor understanding of waste composition at the design stage leading to over-design of the unit for a larger capacity, while only a fraction of the total waste, i.e. non-recyclables, is really combustible owing to its reasonable calorific value. In order to match-up the capacity, many plants ended up burning the organic and the dried composed fractions.

The few yet key reasons for the poor success rate of WtE plants in India, especially from the technological viewpoint, include the following. These are also highlighted in the reports submitted by this project team:

- High heterogeneity of wastes including a substantial fraction of wet wastes, hazardous and chemical wastes and inerts, which adversely affect the process efficiency
- Frequent faults with and poor maintenance of the emission control units, which is exacerbated by the large variability in waste composition
- Lack of periodically monitored data of emission characteristics (of gases, leachates and hazardous ash) to guide the operations, online assessment and real time trouble shooting of emission control units

1.6.4 Landfill and landfill gas management

Landfill management should move away from open dumping and passive venting toward engineered containment, methane recovery, and controlled leachate handling. Our LCA studies suggest that landfill-based energy recovery substantially enhances both the environmental and economic performance of municipal solid waste management systems. Open dumping exhibits the highest global warming impact, whereas electricity generation from landfill gas substantially reduces the emissions through avoided coal-based power generation. Bio-CNG production for vehicle and cooking fuel also achieves significant emission reductions, although its environmental performance is lower than that of electricity generation due to the energy-intensive processes involved in upgrading and compression. Endpoint results show that electricity generation is the only scenario with an overall net negative environmental impact. Economic analysis proves that this option yields the highest revenue surplus along with shortest payback period (< 4 years), and a positive net present value when carbon credits and tax revenues are included. These findings highlight electricity generation as the most effective pathway for landfill decarbonization, underscoring the critical role of fiscal incentives in enabling sustainable, circular waste management systems in India. Therefore, existing landfill sites should prioritize landfill gas capture, leachate recirculation and electricity generation as the key decarbonization efforts to reduce long-term environmental burdens and improve site stability.

1.6.5 Biomining systems

Biomining interventions should focus not only on waste excavation and land reclamation but also on improving the operational efficiency of mechanical systems used during processing.

Optimization of trommel performance, energy use, and material separation efficiency is necessary to reduce the environmental burden of biomining and improve recovery outcomes. These interventions directly impact the quality of refuse derived fuel (RDF), a high calorific value feedstock for WtE plants, and recyclable fractions that can be diverted to MRF. Without verifiable performance metrics, such as stabilization thresholds (Moisture < 25%, Organic content < 10%) and defined drying periods (8–12 weeks), biomining risks "secondary landfilling" and sub-optimal recovery. To achieve a true circular economy, our study recommends mandating a minimum resource recovery rate of >50% by mass and improving RDF quality through standardized pre-processing. Financial analysis at sites like Mandur reveals that biomining is not self-sustaining through material recovery alone. Economic feasibility is entirely contingent on land reclamation credits and avoided costs (e.g., tipping fees and long-term maintenance). Furthermore, carbon credit potential is highly sensitive to landfill age; younger sites offer significant methane avoidance, while sites over 40 years old may reach carbon-neutral states where operational emissions offset savings.

1.6.6 Leachate treatment and reuse systems

Leachate treatment strategies should be aligned with realistic reuse objectives rather than unnecessarily targeting drinking water quality where such standards are not required. Current frameworks predominantly advocate for "treatment for disposal"; however, a strategic shift is required toward "treatment for valorization," where leachate is managed as a resource stream rather than a waste liability. Sustainable treatment strategies must prioritize nutrient recovery, water reuse, energy generation, and adaptive system design tailored to landfill age and leachate characteristics. Formal guidelines are needed to promote the reuse of treated effluent for non-potable applications such as dust suppression, industrial washing, or greenbelt irrigation to significantly reduce freshwater demand. For young and compost-derived leachate, anaerobic digestion presents a viable pathway for energy recovery, thereby lowering the net operational energy footprint. To enhance process efficiency, sustainable pretreatment methods, such as the addition of biochar or garbage enzymes can be integrated to improve biodegradability and minimize reliance on intensive chemical dosing. Conversely, for stabilized (aged) landfill leachate, the dependence on membrane systems should be reduced by strengthening upstream treatment through advanced oxidation processes like UV, ozone, or Fenton oxidation. Additionally, constructed wetlands offer a cost-effective tertiary polishing step, reducing treatment costs while enhancing the removal of nutrients and residual organics. Finally, continuous monitoring coupled with modular upgrades (e.g., adjustable biological stages or

RO capacity) is essential to ensure system adaptability as leachate characteristics evolve over the landfill's lifecycle.

The following key insights emerge from the above discussion, especially on technology selection and optimization:

- It is vital to match treatment technologies with waste characteristics in order to improve the process efficiency, environmental performance, reduce process failures and avoid the lock-in to unsuitable infrastructure
- It is also essential to improve the operational efficiency of the existing waste processing and treatment assets before deciding to spend the capital on newer infrastructure. In many existing facilities, improvements in segregation quality, process throughput, energy use, and emission control can deliver faster and more cost-effective environmental gains.
- The overall technoeconomic viability of waste processing units is hinged on effective by-product valorization. These include compost as manure, bio-gas as fuel, recovered materials, upgradation of landfill gas, biochar for soil amendment and carbon credits, and ash in construction materials. Just like a hydrocarbon refinery, wherein even a drop of crude oil is not wasted in a barrel, a waste refinery should be implemented. While there are existing models of such integrated facilities on paper, commercial realization is still a long way to go.

Overall, technology planning should be guided by circular economy principles that prioritize waste prevention, minimization of losses in the waste collection, processing and conversion value chain, material recovery, product valorization, and reduced dependence on disposal. Embedding these principles within infrastructure decisions can improve long-term resource efficiency and shift municipal systems from end-of-pipe management toward regenerative waste governance.

1.7 Policy and Institutional Recommendations

1.7.1 Development of standardized national monitoring protocols

A national monitoring protocol should be developed to harmonize data collection, emissions measurement, and reporting practices across waste treatment and disposal systems. Standardized protocols are necessary to improve comparability, strengthen regulatory oversight, and ensure that LCA-based evaluations are founded on consistent and policy-relevant evidence.

1.7.2 Roles of CPCB, ULBs, operators, and academic institutions

Effective implementation requires clearly defined institutional roles for central regulators, urban local bodies, facility operators, and academic or research institutions. While regulatory agencies should lead standard setting and compliance oversight, local bodies and operators must ensure data generation and disclosure, and academic institutions can support method development, validation, and field-based research.

1.7.3 Mandatory disclosure of environmental performance data

Environmental performance data should be disclosed in a mandatory and structured manner to improve transparency, accountability, and public-sector decision quality. Regular disclosure of mass balance, emissions, energy consumption, rejects, and recovery outcomes would reduce information asymmetry and create a more credible basis for planning and policy evaluation.

1.7.4 Incentives for segregation, resource recovery, and emissions reduction

Policy frameworks should combine regulatory measures with targeted incentives that reward source segregation, material recovery, renewable energy generation, and measurable emissions reduction. Such incentives can accelerate system improvement by aligning financial signals with environmental performance and by encouraging operators to move beyond compliance-driven minimum standards.

1.7.5 Capacity building for LCA-informed planning

City-level implementation of LCA-informed planning requires sustained capacity building in data handling, emissions accounting, technology assessment, and interpretation of environmental results. Strengthening institutional and technical capability at the municipal level is essential to convert analytical tools into routine planning instruments rather than one-time assessment exercises.

1.8 Recommendations for LCA-Based Planning Tools

Rapid city-level GHG screening tools should be used as frontline decision-support instruments to compare alternative waste management scenarios before undertaking detailed project reporting (DPR) and techno-economic assessments. A versatile and robust tool like ENVISAGE can be positioned as a rapid city-level GHG screening tool for comparing municipal solid waste scenarios before detailed technology assessments. Such tools can help cities identify high-emission practices, prioritize low-carbon interventions, and accelerate early-stage planning where time and data are limited. Integrating such a tool with other waste monitoring, collection and segregation tools that are developed, and in use, by private companies by ULBs can be done to improve the accuracy of the LCA outcomes.

ENVISAGE can serve as a digital decision-support tool that converts complex waste-system data into comparable environmental indicators for technology selection and policy review. When integrated with standardized reporting, it can improve transparency, support evidence-based prioritization, and help cities align operational choices with low-emission and circularity goals. Fig. 1.4 depicts the homepage and dashboard of GHG calculator tool developed by the team, tentatively named ENVISAGE.

The use of such apps can strengthen planning by storing and using historical waste and emissions data for trend analysis, scenario comparison, and longitudinal evaluation. This strengthens the ability of decision-makers to assess whether system changes are delivering sustained environmental gains over time rather than only short-term improvements. It is worthwhile to note that such screening tools should complement, rather than replace, detailed LCA studies, by serving as an initial filter for identifying priority scenarios and technology pathways. ENVISAGE should be used as a frontline screening platform that complements, rather than replaces, a detailed LCA activity. By filtering the obviously unviable options at the pre-assessment stage, it can guide which scenarios warrant deeper LCA analysis, thereby improving analytical efficiency and ensuring that detailed studies focus on the most policy-relevant pathways.

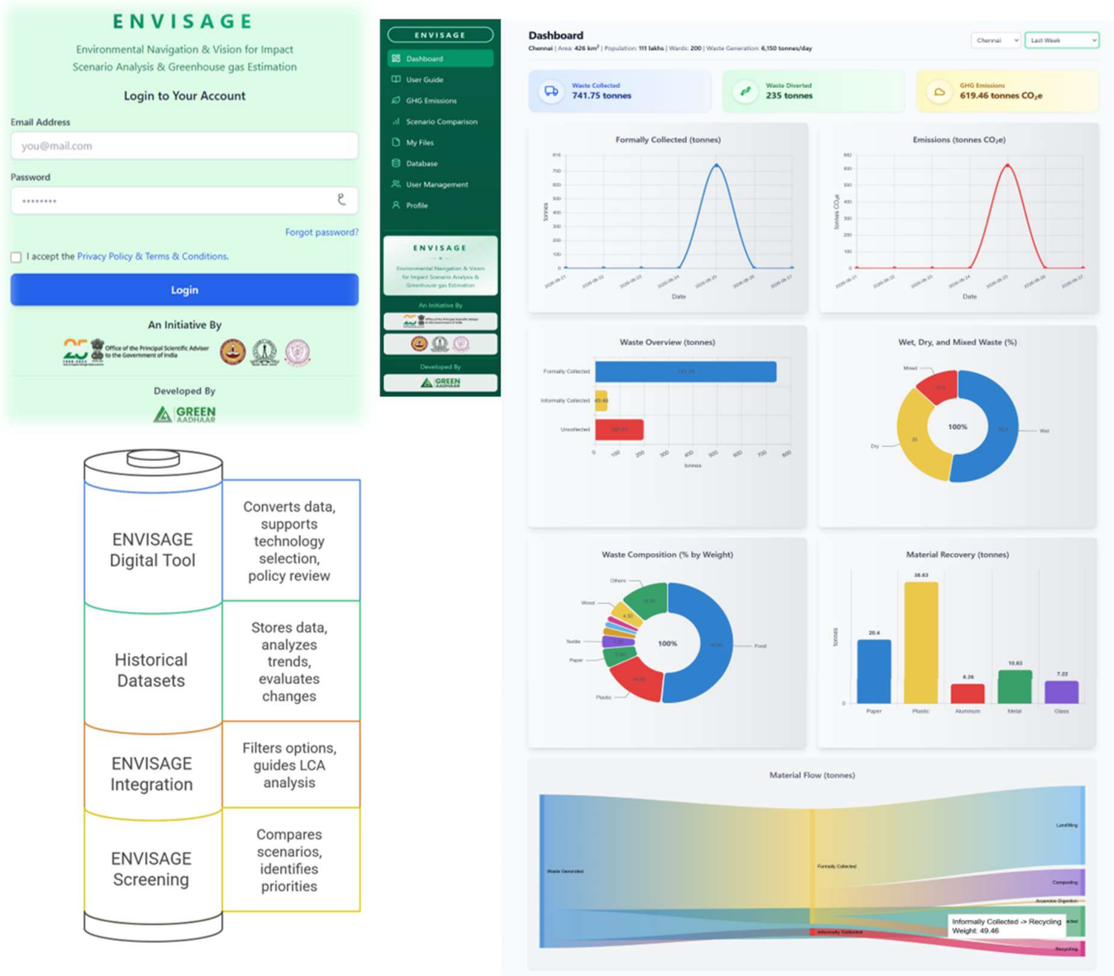


Fig. 1.4 A glimpse of GHG Calculator tool ENVISAGE

1.9 Implementation: Prioritization and Roadmap

Building on these insights, this study proposes a phased future roadmap for transforming India's solid waste management system.

- High-impact immediate actions

  Priority should be given to interventions that can deliver measurable environmental gains with minimal delay, particularly enforcement of source segregation in line with SWM Rules (2026), operational optimization, and improved data monitoring. These measures can reduce emissions quickly while creating the evidence base needed for more capital-intensive reforms. It is also necessary to determine the GHG emissions for the BAU (business-as-usual) scenario in cities of all tiers, corporations, ULBs using a simple calculator like ENVISAGE to estimate the base case emissions. Typical scenarios can also be evaluated to understand the best waste management practice before even floating a DPR.

- Medium-priority institutional and technical actions

  Medium-priority actions should focus on strengthening institutional systems, digital reporting, and technology-specific improvements that require coordination but not full system overhaul. This includes creation of standardized monitoring and reporting protocols, centralized digital databases, and enhanced facility performance tracking. It is also necessary at this stage to evaluate the technoeconomics of the best cases identified by the GHG calculator, develop DPRs and allocate funding and resources towards implementation.

- Long-term infrastructure and policy transitions

  Long-term actions should address structural transitions such as engineered landfill systems, expanded resource recovery infrastructure, and market integration for recovered products. These measures are essential for locking-in sustained emissions reduction and circularity benefits. Prioritization of the technology should be based on a combination of environmental benefit, implementation cost, technical readiness, and institutional feasibility. Actions that offer high emission reduction potential and can be implemented within the existing administrative and operational capacities could be advanced first.

Recommendations should be sequenced across short-, medium-, and long-term horizons to maintain continuity between immediate improvements and systemic transformation. This phased approach ensures that early operational reforms support infrastructure and policy changes rather than working in isolation. Fig. 1.5 illustrates strategically phased action plan for implementing the recommendations for improving the MSW management practices in India.

Fig. 1.5 Strategic phased action plan for solid waste management transformation in India

- In the short term (0–1 year), priority should be given to strict enforcement of source segregation, digitalization of waste collection, movement and segregation, optimization of existing plant capacities, strengthening of data monitoring systems, and establishment of BAU scenarios of GHG emissions across different cities to support informed decision-making.
- The medium term (1–3 years) should focus on expanding treatment infrastructure, improving operational efficiencies, and maximizing resource recovery and utilization, supported by robust market mechanisms for recovered products.
- In the long term (3–7 years), the LCA-based evidence should lead to a shift from disposal-oriented practices to a resource-efficient, technology-driven, and circular waste management system. This includes a transition towards engineered landfill systems with proper environmental controls, power generation from landfill gas, widespread adoption of biomethanation and composting for wet waste streams, and maximum resource recovery from different non-biodegradable wastes, alongside the development of sustainable financing mechanisms such as carbon credits.

1.10 Conclusions

Evidence-based recommendations are essential to ensure that municipal solid waste planning moves beyond conventional practice toward environmentally justified and performance-oriented interventions. By grounding decisions in life cycle assessment, operational data, and system-specific realities, such recommendations improve the credibility, defensibility, and long-term relevance of policy and investment choices. The value of the study lies not only in identifying environmental hotspots, but in converting those findings into implementable actions across planning, technology, and governance domains. The following are the expected outcomes when the recommendations are implemented at scale.

- **Better data reliability and transparency**

  Implementation of the proposed measures is expected to improve the reliability, consistency, and transparency of waste management data across cities and facilities. Stronger data systems will reduce uncertainty in environmental assessment and provide a more credible foundation for planning, compliance, and policy review.

- **Better accuracy and robustness of LCA studies**

  More standardized and field-validated datasets will enhance the accuracy, comparability, and interpretive strength of future life cycle assessment studies. This will allow LCA results to move from indicative analysis toward a more robust basis for technology evaluation and policy prioritization.

- **Reduction in GHG emissions and environmental burdens**

  Improved segregation, optimized treatment performance, methane capture, and better resource recovery are expected to reduce GHG emissions and associated environmental burdens across the waste management chain. These gains are particularly significant where current systems remain dependent on open dumping, passive landfilling, or poorly controlled biological treatment.

- **Improved and well-grounded technology choice**

  A more data-driven and LCA-informed planning framework will support better alignment between waste characteristics, treatment choices, and operational strategy. This is expected to improve overall system performance by reducing technology mismatch, increasing recovery efficiency, and strengthening long-term environmental outcomes.