Life Cycle Assessment of Municipal Solid Waste Management Scenarios in Faridabad, India

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Abstract

The sustainable management of municipal solid waste (MSW) is a pressing environmental and public health issue in rapidly urbanising regions like India. Faridabad, Haryana, generates around 800 tonnes of MSW daily, with much disposed of through open dumping at the Bandhwari landfill. This practice results in serious ecological and health risks, including groundwater contamination, air pollution, and increased disease prevalence. Life Cycle Assessment (LCA) serves as an effective tool for evaluating the environmental impacts of different waste treatment strategies. This study uses LCA, adhering to ISO 14040 and ISO 14044 standards, to compare five MSW management scenarios for Faridabad, including the prevalent practice of open dumping with partial refuse-derived fuel (RFD) recovery.

Using SimaPro 9.0.0.48 and Eco-indicator 99 (H), this research assesses environmental impacts in four areas: Global Warming Potential (GWP), Acidification Potential (AP), Eutrophication Potential (EP), and Human Toxicity Potential (HTP). Scenario 5 [Material Recovery Facility (20%) + Composting (40% of biodegradable waste) + Anaerobic Digestion (40% of biodegradable waste) + Sanitary Landfill (residual waste)] proves to be the most sustainable option, significantly reducing GWP, EP, and HTP, despite a slight increase in AP. Sensitivity analysis indicates that increasing recycling rates for the prevalent scenario from 20% to 90% can significantly reduce overall environmental impacts. This study underscores the necessity for integrated waste management systems in India, combining recycling, composting, anaerobic digestion, and sanitary landfilling, providing valuable guidance for municipal authorities and policymakers in Faridabad and similar urban environments.

Keywords: *Life Cycle Assessment (LCA); Municipal solid waste management (MSWM); Global Warming Potential (GWP); Acidification Potential (AP), Human Toxicity Potential (HTP); Sanitary landfill*

INTRODUCTION

Background

Municipal solid waste management (MSWM) is a pressing global challenge that requires sustainable solutions across technical, economic, and social dimensions. Rapid urbanization, industrialization, and lifestyle changes have dramatically increased the volume and complexity of waste generated worldwide. The World Bank (2018) estimated that global solid waste generation reached 2.01 billion tonnes in 2019 and is projected to rise to 3.40 billion tonnes annually by 2050. This exponential growth exacerbates environmental pressures, particularly in developing countries where infrastructure for waste management often lags behind population growth and urban expansion.

India exemplifies these challenges. Despite significant advancements in waste management policy, open dumping remains the most prevalent method of MSW disposal. Such practices threaten soil quality, air purity, water resources, and public health, particularly in densely populated urban centers. Cities like Faridabad face acute difficulties in managing waste sustainably, with improper disposal methods leading to pollution, greenhouse gas emissions, and health hazards.

Life Cycle Assessment (LCA) has emerged as a robust methodology to evaluate the environmental impacts of waste management systems. By assessing inputs, outputs, and emissions across a system's entire life cycle, LCA identifies the most sustainable pathways for managing MSW. Applied to MSWM, LCA enables comparisons between traditional disposal methods and integrated waste management scenarios that include recycling, composting, anaerobic digestion, and engineered sanitary landfills.

Study Context

Faridabad, a major industrial hub in the National Capital Region (NCR), produces around 800 tonnes of municipal waste daily. Waste collection and transportation are managed by Eco Green Energy under the supervision of the Municipal Corporation of Faridabad (MCF). The city's waste is largely deposited at the Bandhwari landfill, a site lacking engineered liners, leachate collection, and adequate gas recovery systems. Approximately 3.5 million tonnes of untreated legacy waste have accumulated at this site, contributing to leachate seepage into groundwater, surface water contamination, uncontrolled methane emissions, and health risks to nearby populations.

Recent attempts to process a fraction of waste through a refuse-derived fuel (RDF) plant at the Bandhwari site have been limited in effectiveness. Consequently, evaluating alternative integrated waste management strategies becomes critical for improving environmental outcomes.

Objectives

The objectives of this study are:

- To evaluate the environmental impacts of current and alternative MSWM scenarios in Faridabad using LCA methodology.
- To identify the most eco-friendly scenario that minimises impacts across global warming, acidification, eutrophication, and human toxicity.
- To assess the influence of varying recycling rates (20–90%) on overall environmental performance.
- To provide recommendations for sustainable MSWM practices in Faridabad.

Scope

The scope encompasses the collection, transportation, treatment, and disposal of MSW generated in Faridabad. Using SimaPro 9.0.0.48 software and the Eco-indicator 99 (H) method, environmental impacts are assessed per functional unit of 1 tonne of MSW. Primary data were collected from MCF, while secondary data were sourced from published literature and the Ecoinvent database. The study focuses on four key impact categories: Global Warming Potential (GWP), Acidification Potential (AP), Eutrophication Potential (EP), and Human Toxicity Potential (HTP).

LITERATURE REVIEW

Life Cycle Assessment and Municipal Solid Waste Management

Life Cycle Assessment (LCA) has been widely applied to evaluate waste management strategies globally. Studies from India, Iran, Turkey, China, and Europe consistently demonstrate that integrated systems combining recycling and biological treatments outperform landfilling and incineration in terms of environmental performance (Koci and Trecakova, 2011; Erlandsson and Borg, 2003). For instance, Rana *et al.* (2019) found that scenarios combining composting, anaerobic digestion, and sanitary landfills reduced impacts in India's Tricity region. Similarly, Rajaeifar *et al.* (2015) reported that combining anaerobic digestion with incineration offered the most eco-friendly option for Iranian cities.

Functional Units

Defining a functional unit (FU) ensures comparability across LCA studies. Most MSWM LCAs adopt 1 tonne of MSW as the FU. This approach was also applied in the present study, allowing standardised assessment of treatment alternatives.

LCA Models

Several LCA software tools exist, including SimaPro, GaBi, WRATE, and EASETECH. SimaPro is widely used in MSWM studies due to its flexibility and comprehensive databases (Yadav and Samadder, 2018a). In India, both SimaPro and GaBi have been applied to assess waste strategies in urban contexts (Sharma and Chandel, 2016; Khandelwal *et al.*, 2019).

Sensitivity Analysis

Sensitivity analysis helps evaluate the robustness of LCA results by varying key parameters such as recycling rates, transport distances, or emission factors. McDougall *et al.* (2008) emphasise its importance in determining reliability. Several studies confirm that higher recycling rates significantly reduce greenhouse gas emissions and other environmental burdens (Menikpura *et al.*, 2013; Yay, 2015).

Suitable MSWM Options

Globally, recycling consistently emerges as the most sustainable option, while open dumping is recognised as the least favourable. Composting and anaerobic digestion also offer significant benefits, particularly in reducing methane emissions and recovering resources. However, results vary depending on local conditions such as waste composition, infrastructure, and regulatory frameworks. Integrated approaches remain the most widely recommended strategies (Banar *et al.*, 2009; Gilardino *et al.*, 2017).

MATERIALS AND METHODOLOGY

Study Area

Faridabad is located 32 km south of Delhi, covering 742.9 km² with a population of 1.4 million (2011 census). The city is divided into three administrative zones: New Industrial Township, Old Faridabad, and Ballabhgarh. Waste collection is largely performed by tippers, rickshaws, and compactors, with transfer to the Bandhwari landfill. Fig. 1 shows the administrative boundaries of Faridabad Municipal Corporations boundaries with its wards.

LCA Framework

The LCA applied in this study followed the ISO 14040:2006 and the ISO 14044:2006 standards, encompassing:

- Goal and scope definition

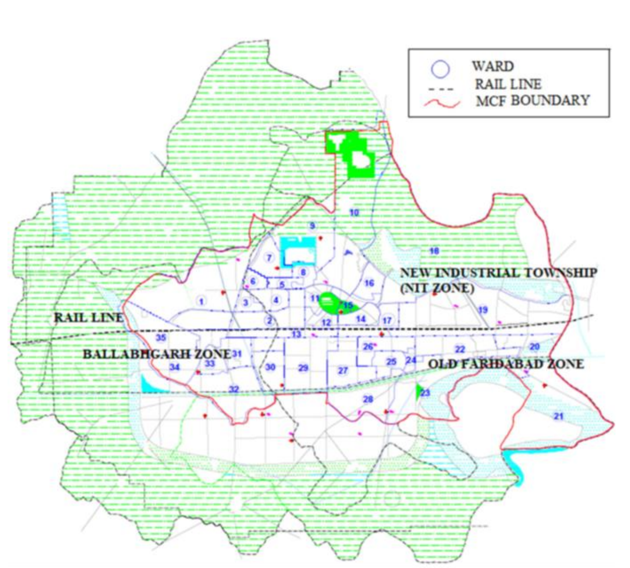

Fig. 1: Administrative boundaries of Faridabad Municipal Corporation with its wards.

- Life Cycle Inventory (LCI)
- Life Cycle Impact Assessment (LCIA)
- Interpretation

The functional unit was defined as 1 tonne of MSW managed in Faridabad. The system boundary extended from collection to final disposal. Fig.2 illustrates the classical MSWM Boundary System (Rana *et al.*, 2019) that includes material recovery facility (MRF) or recycling, composting (COM), anaerobic digestion (AD), incineration, and engineered sanitary landfill (SLF) processes.

Description of Scenarios

In the present study, the following five scenarios for MSWM system have been considered and analysed:

- **Scenario 1** (Prevalent)**:** Open landfill (87.5%) + RDF recovery (12.5%).
- **Scenario 2:** MRF (20%) + SLF (residual).
- **Scenario 3:** MRF (20%) + COM (80% of biodegradable waste) + SLF (residual).
- **Scenario 4:** MRF (20%) + AD (80% of biodegradable waste) + SLF (residual).

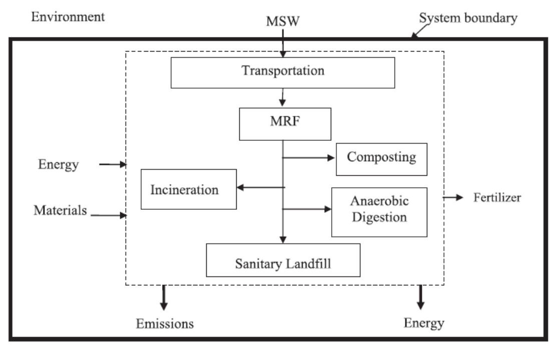

Fig. 2: MSWM Boundary System (Source: Rana *et al.*, 2019).

- **Scenario 5:** MRF (20%) + COM (40% of biodegradable waste) + AD (40% of biodegradable waste) + SLF (residual).

Life Cycle Inventory Data

The MSW from Faridabad city was composed of biodegradable (46.78%), plastics (16.30%), paper/cardboard (9.53%), glass (1.30%), metal (0.46%), and inert (25.63%) (Yadav and Bansal, 2017). The transportation distance of solid waste from transfer station to the SWM process site is considered as 23 kms, which is the distance of current landfill site. The input data for non-renewable sources such as fuel required for transportation and waste management is considered as per the literature, SimaPro dtabase and EcoIndicator 99(H); whereas, the emissions data as obtained from the vehicle kilometers of travel (VKT) method, and the inventory data of environmental emissions from the production of 1MJ (million joules) of electricity and mineral fertilizer production as per SimaPro database. For details, readers are referred to the thesis work of the author (Praveen, 2020).

Life Cycle Impact Assessment (LCIA)

The emissions accounted for inventory stages were divided into four categories of impact, namely Global Warming Potential (GWP, in kg CO_2 eq), Acidification Potential (AP, in kg SO_2 eq), Eutrophication Potential (EP, in kg PO_4^{3-} eq), and Human Toxicity Potential (HTP, in kg 1,4-DB eq).

According to Intergovernmental Panel on Climatic Change (IPCC, 2006), GWP is a measure of the greenhouse gases (GHGs) like CO_2, NO_x, CH_4, CFCs, HCFCs and methyl bromide, emissions collectively expressed in kg CO_2 equivalents.

The contribution of AP impact is the emission of corrosive gasses into the air (like SO_X, NO_X, HCL, HF and NH_4) which is taken up by climatic precipitations and subsequently causing acid raining. These acidifying emissions are expressed in kg SO_2 equivalents.

Eutrophication is caused by too much large amounts of macro-nutrients, the most imperative of which are phosphorus and nitrogen. EP is indicated in kg PO_4^{-3} equivalent.

HTP evaluation intends to estimate the negative effect on people. The principle contributor are heavy metals emitted to air, soil and water. For each toxic substance HTP's are expressed in kg 1,4-dichlorobenzene equivalents.

Life Cycle Interpretation by Sensitivity Analysis

In the present research, the recycling rate is the subject of input parameters for sensitivity analysis. The rate of recycling is defined as the percentage of recycled materials recovered from the waste. For the present study, the materials considered for the recycling are paper, plastics, glass, metals and the total amount of these recyclable materials for MSW composition for Faridabad city is 27.6%. So, different recycling rates of 20%, 50%, and 90% with the prevalent scenario (i.e., *Scenario 1*) were modeled to examine impacts on GWP, AP, EP, and HTP.

RESULTS AND DISCUSSION

Estimated Emissions

The air emissions taken into consideration are GHGs and particulate matter (PM). The Tier I methodology of the IGPCC (2006) was adopted to quantify CH_4 from open landfill and sanitary landfill (SLF) relying on a mass balance approach. The composting (COM) operation emissions measurement was based on carbon and nitrogen balance (Amlinger *et al.*, 2008; Boldrin *et al.*, 2009). The anaerobic digestion (AD) emissions of CH_4 and CO_2 were measured using Buswell equation, and the rest of the emissions were computed from the SimPro database. Table 1 presents the emissions for each of the five scenario.

Table 1: Life cycle inventory emissions (per tonne of MSW) under each scenario.

Substances	Scenario				
	1	2	3	4	5
CH_4 [kg]	33.3	34.2	29.0	26.3	28.3
CO_2, Biogenic [kg]	91.5	93.9	200.8	192.4	181.4
CO_2, Fossil fuel [kg]	13.1	18.4	16.2	35.0	27.5
N_2O [g]	4.4	131.4	300.1	15.4	168.3
SO_X [g]	11.2	10.9	25.1	234.7	128.9
NO_X [g]	302.5	412.2	355.2	449.8	483.3
NH_3 [g]	8.3	15.8	75.8	9.5	36.4
PM [kg]	0.252	0.023	0.019	0.024	0.023

Scenario 1 had the highest CH_4 emissions (33.3 kg/t of MSW), while *Scenario 4* achieved the lowest (26.3 kg/t of MSW). PM emissions were lowest in *Scenarios 3–5* due to improved treatment technologies.

Environmental Impact Analysis

The LCIA of the four categories of impact for each of the five scenarios are analysed and graphically presented hereunder.

Global Warming Potential

The GWP with each of the five scenarios is presented in Fig. 3. *Scenario 1* [prevailing open landfill] produced the highest GHG emissions (1109.69 kg CO_2 eq/t of MSW), followed by *Scenerio 2* [MRF (20%) + SLF (residual)]. This is due to high contribution of CH_4 in landfills with no provision for leachate

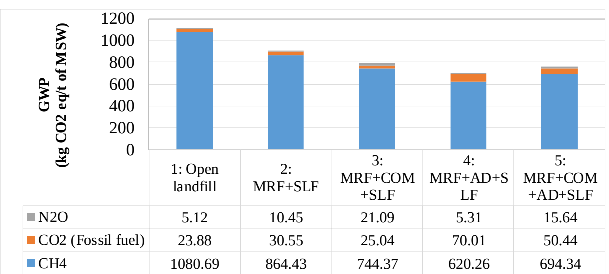

Fig. 3: Global Warming Potential (GWP) of the five scenarios.

collection and treatment, as well as absence of liner in the dumping pit. *Scenario 4* [MRF (20%) + AD (80% of biodegradable waste) + SLF (residual)] yielded the lowest (695.58 kg CO_2 eq/t) due to the reduction of CH_4 during anaerobic digestion. The next best scenario is *Scenario 5* [MRF (20%) + COM (40% of biodegradable waste) + AD (40% of biodegradable waste) + SLF (residual)] with 760.42 kg CO_2 eq/t.

Acidification Potential

Fig. 4 shows the AP with each of the five scenarios. Highest AP is with *Scenario 4* [MRF (20%) + AD (80% of biodegradable waste) + SLF (residual)] accounting for 2.94 kg SO_2 eq/t of MSW due to NO_X and SO_2 emissions from anaerobic digestion. The best results, that is lowest AP is with *Scenario 2* [MRF (20%) + SLF (residual)] accounting for 0.59 kg SO_2 eq/t of MSW due to limited oxidiation of sulphur and nitrogen substances into NO_X and SO_X.

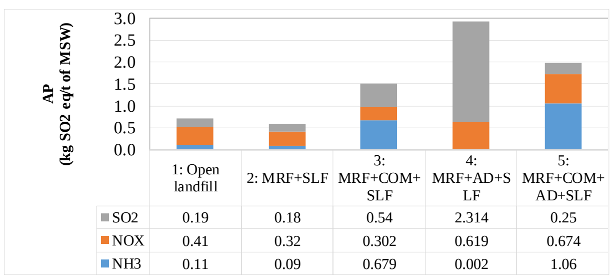

Fig. 4: Acidification Potential (AP) of the five scenarios.

Eutrophication Potential

The results of the EP potential with each of the five scenarios (Fig. 5) reveal that *Scenario 1* has the highest EP (0.591 kg PO_4^{3-} eq/t of MSW due to absence of liner system in the open dump pits which leads to high emissions of total nitrogen and total phosphorous in open dumpsites during biological phase. *Scenario 5* presents the best scenario having the least EP of 0.017 kg PO_4^{3-} eq/t of MSW due to the provision of impermeable synthetic bottom liners in engineered sanitary landfill sites.

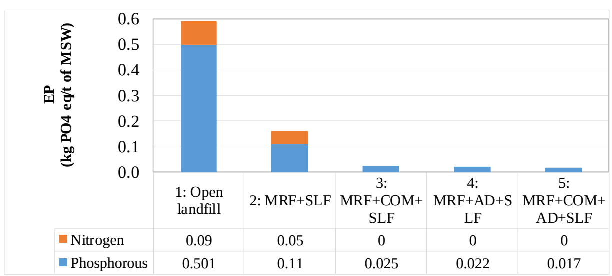

Fig. 5: Eutrophication Potential (EP) of the five scenarios.

Human Toxicity Potential

The HTP with each of the five scenarios is presented in Fig. 6. Emissions of toxins such as PM, SO_X, NO_X and heavy metals are responsible for human toxicity. *Scenario 4* [MRF (20%) + AD (80% of biodegradable waste) + SLF (residual)]

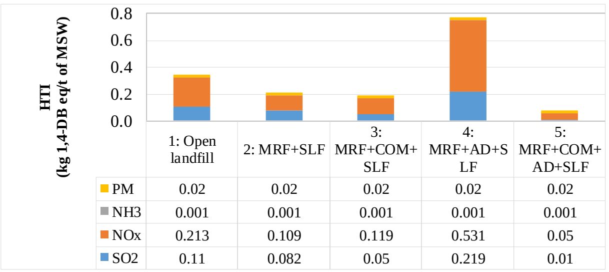

Fig. 6: Human Toxicity Potential (HTP) of the five scenarios.

represents the highest HTP (0.771 kg 1,4-DB eq/t of MSW) due to high emissions of SO_2 and NO_X. *Scenario 5* [MRF (20%) + COM (40% of biodegradable waste) + AD (40% of biodegradable waste) + SLF (residual)], which has the advantage of composting with anaerobic digestion, provides the best results having lowest HTP of 0.081 kg 1,4-DB eq/t of MSW.

The LCIA findings, based on GWP, AP, EU and HTP environmental impact categories, reveals that *Scenario 5* [MRF (20%) + COM (40% of biodegradable waste) + AD (40% of biodegradable waste) + SLF (residual)] has the least overall environmental consequences, and having lower impact on human health, global warming and eutrophication of water bodies, despite some increase in the acidification potential.

Sensitivity Analysis

The results of the impact of different recycling rates of 20%, 50%, and 90% were computed for the prevalent scenario (i.e., *Scenario 1*) for all the four environmental impact categories and are tabulated in Table 2.

Table 2: Environmental impact of different recycling rates for the prevalent *Scenario 1*.

Environmental Impact Category	Recycling Rate		
	20%	50%	90%
GWP (kg CO_2 eq/t of MSW)	1109.69	995.36	912.37
AP (kg SO_2 eq/t of MSW)	0.71	0.64	0.60
EP (kg PO_4^{3-} eq/t of MSW)	0.59	0.516	0.41
HTP (kg 1,4-DB eq/t of MSW)	0.34	0.33	0.19

The results revealed that increasing recycling rates from 20% to 90% reduces the environmental impact potential in terms of GWP, AP, EP and HTP significantly. Thus, the overall environmental benefits will increase as the recycling rate increases. In the prevalent MSW management scenario (*Scenario* 1), increasing the recycling rate from 20% to 90% will result in the reduction of GWP, AP, EP and HTP by 17.8%, 15.3%, 30.9% and 44.8% respectively.

Policy Implications

Findings underscore the importance of transitioning from open dumping to integrated systems. *Scenario 5* demonstrates that combining recycling, composting, anaerobic digestion, and sanitary landfilling provides optimal environmental outcomes. Policymakers should prioritize:

- Source segregation and recycling infrastructure.
- Investments in composting and anaerobic digestion facilities.
- Rehabilitation of legacy waste at Bandhwari landfill.
- Public awareness programs to enhance participation.

Conclusion

This study demonstrates that the existing open dumping practice in Faridabad imposes severe environmental burdens, particularly in terms of greenhouse gas emissions and eutrophication. Life Cycle Assessment reveals that integrated management strategies substantially improve outcomes. Among the scenarios tested, the *Scenario 5* [MRF (20%) + COM (40% of biodegradable waste) + AD (40% of biodegradable waste) + SLF (residual)] emerges as the most sustainable, reducing GWP, EP, and HTP while maintaining manageable acidification levels. Sensitivity analysis confirms that higher recycling rates amplify environmental benefits.

While LCA provides robust insights, limitations include reliance on secondary data and exclusion of economic and social dimensions. Future studies should incorporate cost-benefit analyses and stakeholder perspectives. Nevertheless, the evidence presented here offers a compelling case for adopting integrated MSWM systems in Faridabad, with implications for other rapidly urbanizing Indian cities.

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The present research did not receive any financial support.

Conflict of Interest

The authors declare that there is not any conflict of interests regarding the publication of this manuscript. In addition, the ethical issues, including plagiarism, informed consent, misconduct, data fabrication and/ or falsification, double publication and/or submission, and redundancy has been completely observed by the authors.

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