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Original Article

Life Cycle Assessment of Potential Municipal Solid Waste Management Practices for Itanagar City, India

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Abstract *- This study evaluates the environmental impacts of various Municipal Solid Waste Management (MSWM) scenarios for Itanagar City, governed by the Itanagar Municipal Corporation (IMC), using Life Cycle Assessment (LCA) as an analytical tool. Four waste management scenarios were analyzed: Scenario S1 serves as the baseline, indicating the existing waste management practices; Scenario S2 involves a sanitary landfill without landfill gas capture; Scenario S3 features a sanitary landfill with a 50% landfill gas collection efficiency; and Scenario S4 proposes an Integrated Waste Management approach, incorporating recycling, composting, and inert landfilling. One tonne of Municipal Solid Waste was designated as the functional unit for the assessment. Primary data were obtained through sampling, surveys, and literature review. The scenarios were compared using the Recipe Midpoint H method across five impact categories: Global Warming Potential (GWP100), Human Toxicity Potential (HTP), Particulate Matter Formation Potential (PMFP), Photochemical Oxidant Formation Potential (POFP), and Terrestrial Ecotoxicity Potential (TETP). This analysis was conducted with the help of openLCA software in conjunction with Eco-Invent databases. Results demonstrate that Scenario S1 (baseline) performed worst across most impact categories, while Scenario S2 exhibited the highest Global Warming Potential (2.334×10^3 kg CO_2-Eq) and Photochemical Oxidant Formation Potential (9.499×10^{-1} kg NMVOC-Eq) for each tonne of MSW. In contrast, Scenario S4, which implements an Integrated Waste Management strategy, emerged as the least environmentally damaging across all evaluated categories.*

Keywords *- Life Cycle Assessment, Municipal solid waste management, Itanagar Municipal Corporation, openLCA, Integrated waste management.*

1. Introduction

With the increasing worldwide awareness regarding environmental issues and the observable changes in nature, climate change is inevitably upon us. A major factor driving climate change is the increasing amount and diversity of Municipal Solid Waste [15]. Most Indian cities are undergoing attempts to improve MSWM, but medium- and small-sized towns are not receiving the same level of attention [17]. In a city, the responsibility for Solid Waste Management (SWM) falls under its municipality. In India, on average, the management of solid wastes constitutes 10 to 50 percent of municipalities' budget expenditure [3][8]. The high cost involved in operating and maintenance of waste management facilities effectively often leads to partial neglect in this sector [21]. In recent years, with the government's stringent environmental policy, the study on Municipal Solid Waste (MSW) has garnered growing interest and focus. Numerous local governments across the nation are confronted with the task of discovering more effective approaches to handling MSW. They face the dual challenge of operating within budget limitations while also striving to achieve more stringent environmental objectives.

The influx of people from villages and rural areas into urban establishments has substantially increased the volume of waste generated, exacerbating the existing waste management issues in municipalities [14]. The lack of efficient collection mechanisms means that waste is often left uncollected or improperly disposed of, resulting in its build-up in every corner of the cities [7]. During 2020–21, India generated a substantial volume of solid waste, estimated at 160038.9 Tonnes Per Day (TPD) MSW, as per the annual report by the Central Pollution Control Board (CPCB) on implementing the Solid Waste Management Rules, 2016 [8]. Although there is a collection efficiency of 95.4%, a significant portion of the collected MSW remains unaccounted for, amounting to 31.7% of the total waste collected. This poses a significant challenge for developing countries like India, leading to health issues and environmental pollution. Immediate actions are necessary to manage the rising solid waste generation and implement proper disposal practices to protect public health and the environment [10]. This similar trend can be seen in many Indian cities, and Itanagar is one of them. Identifying the MSW disposal option that has the least environmental impact is a significant developmental challenge for countries in the process of development, such as India [23]. Life Cycle Analysis (LCA) serves as a key resource for policymakers and decision-making bodies to assess the effects on the environment due to various waste management alternatives within a particular area [16]. It facilitates cradle-to-grave analysis of any product life cycle from an environmental perspective, which consists of Material Flow Analysis of all the inputs to a system, like resources and energy, and the subsequent output, like emissions to air, soil, and water, to find out its impacts in each life cycle stage.

For a LCA study in the year 2018 for Dhanbad city, different scenarios for the MSW disposal options were studied, where the Integrated Waste Management option consisting of recycling, composting and inert landfilling was found to be the most environmentally suitable disposal option when compared with open dumping and sanitary landfilling [31]. Similarly, in an LCA study of MSWM generated in Bangalore City, waste-to-energy conversion via bio-methanation was found to be the most preferred option in comparison to open dumps and landfilling options [2]. Six distinct MSWM scenarios were evaluated in 2017 for Mumbai City to assess their environmental implications. Open dumping and bioreactor landfills were included in the baseline scenario.

Along with that, six other waste disposal scenarios were assumed. The author concluded that the integrated MSWM approach that combines multiple waste management strategies to reduce environmental harms and optimize resource efficiency has the lowest impacts and is the most sustainable MSW disposal option [28]. Most of the LCA studies thus carried out are for metro cities (Delhi, Mumbai, Bangalore, etc.) or cities with more than 100 TPD of solid waste generation capacities daily. Only a few or close to nil LCA studies had been done for cities below 2,00,000 population or at all in the entire northeast region of India. Therefore, a lot of waste management practices in towns and cities of northeast India remain under the shadow. Recently, in the year 2021, the National Green Tribunal (NGT) imposed environmental compensation on the municipalities of Itanagar and Pasighat for failing to comply with the SWM Rules 2016 by the Government of India for unsanitary dumping of MSW [20].

For the current LCA study, we have considered the Itanagar Municipal Corporation (IMC) in the state of Arunachal Pradesh. The investigation will be conducted in two distinct parts: the first being deducing the environmental impact (Climate Change Potential-GWP100) caused by the collection and transportation of 1 tonne of MSW to the disposal site from different locations within the IMC jurisdiction, and the second part where we are going to compute the environmental impacts using Recipe midpoint- H for five impact parameters to assess the different waste disposal scenarios assumed for the study area. The baseline scenario is denoted as S1, sanitary landfill without gas recovery: S2, sanitary landfill with 50% gas recovery: S3, and recycling, composting and inert landfilling as S4 to find the best MSWM strategy using LCA as a tool.

2. Materials and Methods

2.1. Study Area: Itanagar Capital Complex

The research work is carried out in Arunachal Pradesh, India, specifically in the Itanagar Capital Region (ICR), positioned at a latitude of 27°06'00"N and a longitude of 93°37'12"E. It encompasses four major town zones: Itanagar, Naharlagun, Nirjuli, and Banderdewa. The Itanagar Municipal Corporation (IMC) assumes sole responsibility for the handling of MSW.

The study area covers approximately 51.4 square kilometres and has a population of 101,772 individuals based on the 2011 census data. The population is projected to reach 149,504 individuals by 2021, assuming a decadal growth rate of 46.9%. As per the annual report by the CPCB, 2020-21, the estimated generation of MSW in the study area is roughly 85 tonnes per day [8].

The study focuses specifically on the municipal region within the jurisdiction of the IMC. This region is divided into 20 administrative wards. The IMC ensures that the 30,646 households within these wards receive door-to-door collection services for MSW disposal. At present the IMC follows the unsanitary means of waste disposal in an open dumpsite located at Chimpu. The total area of the dumpsite is 3ha, and it is an open dumping ground without any sanitary measures taken; topographically, it has elevated sloping grounds that may further facilitate the spread of air and leachate pollution to the nearby surroundings.

2.2. Characterization of MSW at the Disposal Site

The quartering and coning method is utilized for the waste characterization study, and it is also described as one of the best techniques for determining the composition of MSW [9]. It consists of reducing the sample into a more manageable size via quartering and coning of the MSW so that it can be easily classified into various MSW components.

We have taken a total of 10 sample collection points for the estimation of the MSW constituents at the Chimpu dumping site, as shown in Table 1. 10 kg of sample was collected from a mixed MSW pile from each site after the quartering and coning procedure, which was then used to find the physical composition of MSW, after manually segregating into various waste components. Using the composition data of waste from the Chimpu dumpsite, the Degradable Organic Carbon content of the MSW was computed using the IPCC Guideline for National Greenhouse Gas Inventories 2006. The default values of Organic Carbon Content for each fraction and degradability factor of the MSW were sourced from references [4], [13].

Table 1. MSW composition at the CHIMPU dumpsite (IMC)

MSW Samples	Organic Fraction (kg)			Inorganic Fraction (kg)			
	Food/ Vegetable Waste	Paper/ Cardboard	Textiles	Plastic Wastes	Glass	Metals	Others
1.	4.56	2.13	0.00	2.67	0.00	0.10	0.54
2.	3.72	2.48	0.00	2.75	0.60	0.00	0.00
3.	4.13	3.24	0.35	1.82	0.37	0.23	0.00
4.	6.10	2.13	0.00	2.02	0.00	0.00	0.13
5.	5.36	1.87	0.89	1.34	0.56	0.00	0.34
6.	5.88	2.46	0.34	1.21	0.00	0.00	0.00
7.	7.43	0.34	0.00	2.35	0.00	0.00	0.00
8.	7.83	0.68	0.00	1.28	0.00	0.39	0.42
9.	4.26	1.56	0.00	1.54	0.21	0.22	0.54
10.	5.54	1.38	0.00	2.89	0.34	0.33	0.03
MEAN wt. Composition (%)	**54.8**	**18.2**	**1.5**	**19.8**	**2.0**	**1.2**	**2.5**

- Organic Carbon Content = (food waste × organic carbon content) + (paper waste × organic carbon content) + (others × organic carbon content)
  = (0.548×0.50) + (0.182×0.45) + (0.025×0.25)
  = 0.36225
  = 36.23%
- Degradable Organic Carbon = organic carbon content × degradability factor
  = 0.36225 × 0.5
  = 0.181125
  = 18.11%

2.3. Goal and Scope of Study

This study seeks to evaluate the environmental impacts of the waste management strategies currently implemented by IMC by applying an LCA perspective. It also aims to analyze the emissions linked to the collection and transportation of MSW from various locations within IMC to the disposal site. Various MSWM disposal scenarios were assumed in compliance with the CPHEEO manual, part 2 [9].

Based upon the feasibility of the study area, the urban population within the municipality and the composition study of the MSW, the current waste management scenario practiced by IMC is depicted as the baseline: scenario 1; scenario 2 consists of sanitary landfill without gas recovery; scenario 3: sanitary landfill with 50% gas recovery and scenario 4: recycling, composting and inert landfilling. The input-output analysis of various end-of-life scenarios is to be assessed using Life Cycle Inventory Assessment (LCIA) tools to quantify and compare the most sustainable waste management options.

2.4. Functional Unit

The selected functional unit for the LCA study is the one tonne of normalized MSW composition from the waste disposal site, which is then utilized for the comparisons in all four scenarios.

2.5. System Boundary

The system boundary, which serves as a check to expedite the LCA research, comprises all the inputs from the technological and natural resource sectors, as well as the outputs into the environment and any potential negative effects on nature. It includes the complete process within MSWM, beginning with the collection of MSW and ending with its final disposal (end-of-life stage). The collection and transportation play an indispensable function in the management of MSW and is therefore denoted as Scenario 0, which is analyzed separately. Each disposal scenario within the system boundary is an independent variable of its adjacent scenario, and the material flow of waste takes place from top to bottom, as shown in Figure 1. The MSW disposal strategies selected for the study area are- Scenario 1: baseline consisting of open dumping; Scenario 2: landfill without gas recovery; Scenario 3: landfill with 50% gas recovery; and Scenario 4: recycling, composting and inert landfilling.

2.5.1. Scenario 0 (S0): Collection and Transportation

Scenario 0 is the representation of the existing collection and transportation scenario for the MSW collection in the study region by IMC. The MSW collection efficiency of the study area was taken as 88.24% [8]. The wastes are collected manually by the workers from collection points along the national highway or in and around the vicinity of colony roads. The collected wastes are taken off to the disposal ground at the Chimpu dumpsite. The emissions caused by the collection and transportation of per tonne MSW to disposal sites from these four major town zones (Itanagar, Naharlagun, Nirjuli and Banderdewa) are computed in this scenario for the impact category Global Warming Potential- GWP100.

2.5.2. Scenario 1(S1): Baseline Scenario-Open Dumps

The baseline scenario (S1) in the assessment represents the current waste management practiced by IMC, consisting of unsanitary methods for MSW disposal. Based on the environmental SWM performance ranking of states, Arunachal Pradesh is one of the worst-performing in the country. Also, it has been reported that nil solid waste had been processed for the year 2020-21 [8]. In the study area, recycling efforts are limited, with only a few informal sectors and rag pickers participating in recycling activities. We have also observed that open burning of waste is practiced in some of the neighbourhoods, or, in case the waste piles up in places inaccessible by IMC workers, it is often burned off. With the context of the study area, we have taken around 3% of waste that is openly burned off [18] in the baseline scenario. The rest of the waste generated is assumed to be open-dumped without any recycling activity. The emission of water due to the open dump was taken from the leachate composition at the disposal site [26].

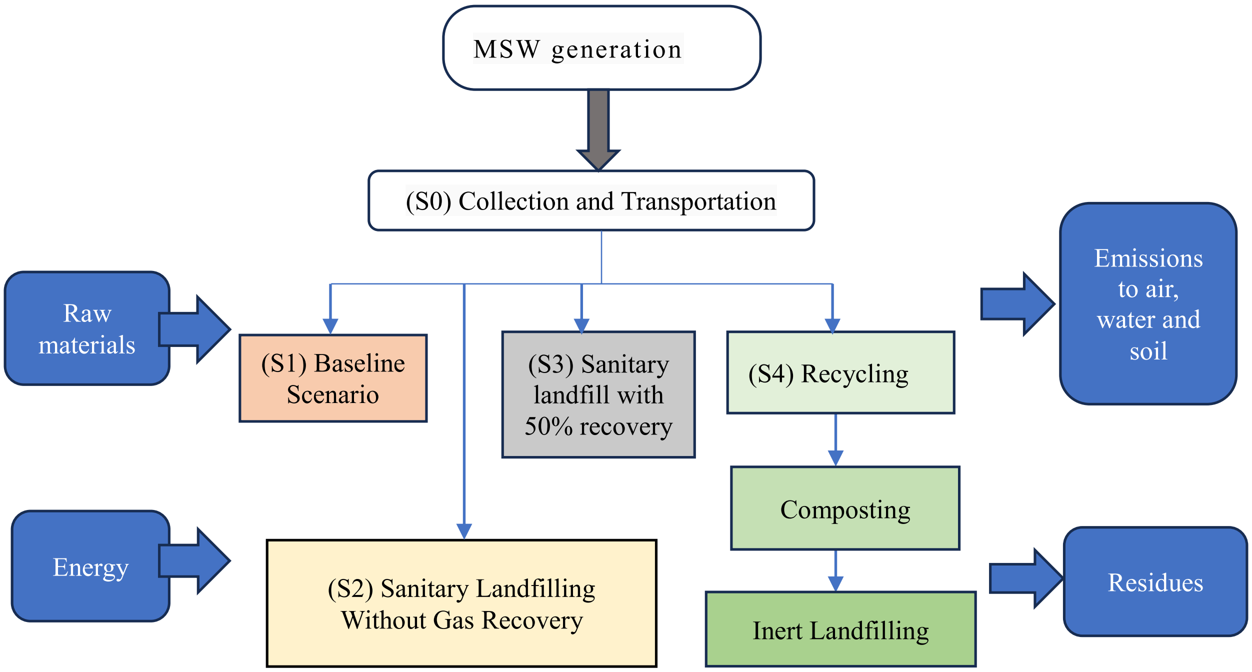

Fig. 1 System boundary of the present LCA study

2.5.3. Scenario 2 (S2): Landfill System without Gas Recovery

This scenario entails waste disposal according to sanitary landfill standards; however, it does not incorporate a system for recovering landfill gas due to financial constraints faced by municipalities. The waste is deposited in a designated area with a protective liner system and daily landfill cover. Within the landfill, waste decomposes anaerobically, resulting in the emission of Landfill Gas (LFG). The amount of LFG released is influenced by the concentration of Dissolved Organic Carbon (DOC) found in the municipal waste [2],[28]. It is assumed that all generated MSW is disposed of in a landfill without any gas collection system in place.

The leachate, which is considered a major emission to water, is being recirculated to enhance biological degradation. We have taken a 2% probability for leakage of leachate in a sanitary landfill. The research does not include emissions from biogenic CO2, as these are considered a natural component of the carbon cycle. The major air emissions from a sanitary landfill mainly come from methane generated during the anaerobic decomposition of waste [6]. This scenario seeks to evaluate the different air and water emissions associated with each tonne of MSW produced.

2.5.4. Scenario 3 (S3): Landfill System with 50% Gas Recovery

This situation closely resembles scenario 2, with the further establishment of the LFG collection system designed to capture the gases produced at sanitary landfill sites. The collected gas can then be converted into a valuable form of energy. It is assumed that the gas collection efficiency is 50%, meaning that half of the LFG produced is successfully captured while the remaining portion is allowed to escape into the atmosphere [4]. Along with the gas recovery system, the setup already incorporates a leachate collection, which is recirculated to stimulate biological degradation. The overall net environmental impacts can be reduced by generating electricity from the captured LFG, which will account for avoided emissions by contributing to the electricity grid.

2.5.5. Scenario 4 (S4): Recycling, Composting and Inert Landfilling

The Integrated MSWM hierarchy outlined by the CPHEEO 2016 report considers recycling of MSW to be the most preferred option [9]. In Scenario S4, specific fractions of the MSW were targeted for recycling: paper/cardboard (18.2%), metals (1.2%), glass (2.00%), plastic (19.8%), and recyclable textiles (1.5%) were all recycled. Composting was used for garden and food waste (54.8%). A landfill without energy recovery was used to dispose of the remaining material, which was categorized as inert waste (2.5%). Since only inert wastes were dumped in the inert landfill, it was anticipated that there would be no emissions. Furthermore, as the study area lacked any recycling plants, it was assumed that the recyclables would be transported to other cities for further processing. This aspect was deemed beyond the system boundary and was consequently excluded from the LCA study.

3. Life Cycle Assessment

Life Cycle Assessment (LCA) is a valuable analytical method for assessing the environmental impacts linked to products, processes, or activities across their full life span, from initial manufacturing to ultimate disposal. This comprehensive method, commonly termed "cradle-to-grave", thoroughly examines the environmental effects at every phase of the product life cycle. When this perspective is utilized in waste management systems, it is often referred to as "waste LCA". This method assesses and compares the environmental impacts of various waste disposal techniques, facilitating more informed and sustainable decision-making [11]. Waste LCA, when conducted for a product or waste material, specifically concentrates on its end-of-life stage. Its main purpose is to compare and evaluate different treatment options available for managing specific materials or types of waste. By employing waste LCA, researchers can analyze and understand the comparative environmental impacts associated with different waste management approaches. Various LCA software tools are available to facilitate the assessment and modelling of Life Cycle Inventory data. These software tools often include comprehensive and widely used LCA databases. OpenLCA is one such interface that is utilized for the current LCA study, it is an open-source sustainability software used by LCA practitioners worldwide, made publicly available under the Mozilla Public Licence, MPL 2.0. The openLCA project and software first emerged in 2006 and is managed exclusively by GreenDelta in Berlin [12],[24].

3.1. Life Cycle Inventory Analysis

For performing LCA of any outcome, the data obtained from the Life Cycle Inventory (LCI) plays a very crucial role. It provides the detailed information needed for the entire evaluation. By gathering LCI data from every phase of a product's life cycle, it becomes possible to obtain an in-depth insight into its environmental effects [11]. This process relies solely on LCI databases. In the context of waste management studies, it involves an input-output analysis of different waste treatment processes analyzed within LCA scenarios, taking into account the resources and energy consumed as inputs and the discharges released into soil, air, and water during its end-of-life phase. Furthermore, it highlights the advantages of retrieving recyclable wastes and the energy or electricity generated through different waste treatment processes, which are recognized as avoided impacts. The LCI databases were sourced from onsite investigations, existing literature on prior LCA studies, and repositories such as openLCA and Eco-Invent. Obtaining sufficient inventory data in the IMC region proved to be quite challenging, owing to the absence of sufficient data and research related to waste management.

3.1.1. Collection and Transportation of Wastes

Currently, the IMC operates with a fleet consisting of 36 Tata 912 LPK model vehicles, 6 JCB/loaders, and 2 other vehicles for waste collection purposes [8]. The Tata 912 LPK model, also known as a mini dumper, has a capacity of 3 tonnes and consumes fuel at a rate of 7-9 km/l. To determine the energy used in transporting municipal waste from the generation facility to the disposal location, average distances of 15.9 km, 21 km, 26 km, and 36 km from the dump site were considered using Google Earth for four major town zones Itanagar, Naharlagun. Nirjuli and Banderdewa, respectively. The distance of town zones from disposal sites along with their average fuel consumption, is provided in Table 2. The compacted truck has a waste density of approximately 450 kg/m³, based on the national average for MSW density in India, which ranges from 450 to 500 kg/m³ [9]. With a volume of 5 m³ per truck, this translates to a capacity of roughly 2.3 tonnes of MSW for each trip. By assuming a fuel efficiency of 8 km/l of diesel used by the truck and considering the Higher Heating Value (HHV) of diesel fuel at 36.7 megajoules per litre [2], the energy required to transport MSW across the four average distances was calculated. Additionally, the emissions released from the combustion of one litre of diesel for MSW transportation were obtained from the Eco-Invent database [2].

Table 2. Diesel usage for transporting 1 tonne of MSW across four average distances within the IMC jurisdiction

IMC Zones	Mean Distance in km	Mean Distance (to and fro) in km	Fuel Consumed (litres/tonne of MSW)
Itanagar	15.9	31.8	1.72
Naharlagun	21	42	2.28
Nirjuli	26	52	2.82
Banderdewa	36	72	3.91

3.1.2. Open Burning

In the context of the study area, open burning is considered for the burning of MSW (yard wastes, plastics, paper, rubbers, etc.) in outdoor open spaces, which results in atmospheric pollution. The burning of MSW in open spaces and public places is considered illegal in India. But still, according to the CPCB annual report 2018-19, about 3% of MSW is openly burned off in India. It has been noted that in the IMC region, waste that accumulates in hard-to-reach areas inaccessible by IMC workers is frequently burned off. The percentage of burning MSW in open spaces for the study area is considered to be the same as that of the national average i.e.

3% utilized for the assessment of Scenario 1: baseline scenario. Different emissions caused by the MSW open burning had been sourced from [2],[30].

3.1.3. Open Dumping

To evaluate methane emissions from open dumps, the Tier 1 method described by the Intergovernmental Panel on Climate Change (IPCC) 2006 was employed, relying on a mass-balance approach. The emission of greenhouse gases from landfills is computed using the IPCC Tier 1 formula, where the cumulative sum of total Municipal Solid Waste (MSW_t) generated and the Degradable Organic Carbon (DOC) content are crucial factors for determining emissions [28].

$$CH_4 \text{ emissions (kg/ton of MSW)} = (MSW_t \times MSW_f) \times MCF \times DOC \times DOC_f \times F \times (16/12 - R) \times (1 - OX)$$

As per IPCC, 2006 default values for computation of tier 1 methodology (for uncategorized waste in open dumps:

- Methane Correction Factor, MCF = 0.6
- Fraction of organized carbon dissimilated, $DOC_f = 0.77$
- Oxidation factor, OX = 0
- Fraction of MSW disposed at landfill, $MSW_f = 100\%$
- Fraction by volume of CH4 in landfill gas, F = 50%
- Recovered methane, R= 0

The CO2 emission is considered to be biogenic and was not included in emissions to the air. Default values from LCA databases are to be used for other air emissions. Major emissions to water due to open dumps are caused by Landfill leachate. It consists of high organic and inorganic impurities, which are released mainly due to dumping organic wastes [26]. The values for emissions to water were obtained from leachate composition in Table. Emissions from the management of MSW in open dumping grounds were not considered in the study [2], [28]. According to estimates from the CPCB, the production of leachate from one tonne of MSW can vary between 0.2 to 0.6 cubic meters [9], depending on various factors like waste composition and the prevailing weather conditions. Based upon the topology of the dumpsite and the weather and rainfall conditions of the study area, we have assumed an upper value of 400 litres of leachate production per tonne of MSW when disposed of in open grounds.

3.1.4. Sanitary Landfills

For estimating CH_4 (methane) emissions from sanitary landfills, the study utilized the default methodology, which is similar to that used for open dumps. The MCF was taken to be 1.0, as per the default value provided by IPCC 2006 for sanitary landfills. It was estimated that 50% of the landfill gas emitted is utilized for generating electricity in scenario 3, while the remaining 50% is released into the atmosphere, contributing to GHG emissions [28]. In terms of leachate management, it was assumed that a leachate collection system is provided in the sanitary landfill. The collected leachate is recirculated within the landfill to stimulate biological degradation, and eventually, it is disposed of in a separate sludge disposal system. The probable leakage of leachate in a sanitary landfill was taken as 2%. The waste composition, landfill design, and management techniques used are some of the variables that might affect how much energy is needed to handle one tonne of MSW in a sanitary landfill site. Studies, however, have calculated the overall energy demand for handling one tonne of MSW in a sanitary dump site can range from 100-200 kilowatt-hours (kWh) per ton, which is equivalent to 360-720 megajoules (MJ) per ton [2],[18]. The emissions to the soil were not considered in the sanitary landfill.

Table 3. Characteristics of leachate obtained from the Chimpu landfill site [26]

Chemical Parameters	mg/l*
pH	6.71
Conductivity, µS/cm	1109.66
TDS, ppm	870
BOD_5	42
COD_5	140
Chloride	223.82
Calcium	85.41
Sodium	240.17
Potassium	215.08
Sulphate	260
Nitrate	4.21
Total phosphorus	2.15
Iron	10.1
*Other than pH and conductivity	

3.1.5. Composting

Municipal Solid Wastes can be effectively dealt with by composting organic fractions [9],[17],[18]. Scenario 4 consists of windrow composting of organic fraction of MSW. Drawing from the existing literature and the waste characterization assessment of the IMC region, assumptions were made regarding the inventory data for the composting process. The compost produced accounted for an avoided emission with 20% assumed production efficiency under good operational conditions; the windrow compost plant receiving an organic fraction of MSW has a typical efficiency of around 18%–20% [9]. The leachate produced is recirculated in the windrow to maintain a balance in moisture content and nutrient availability for bacterial decomposition. The energy consumption for managing windrow composting of 1 tonne of MSW, which includes sorting of biodegradables, can range from 10-35 kWh/ton, depending on the specific equipment, process, and conditions used [4],[25]. Diesel consumption for turners and other heavy equipment was assumed to be 100.8 MJ/tonne of MSW input for composting. The compost thus produced can be utilized to substitute N-P-K fertilizers in agricultural fields and generate revenue via selling it [5],[25].

Overall, compost comes under avoided emission as it helps reduce the net environmental impacts by replacing fertilizer production.

3.1.6. Recycling

In LCA studies, recycling is associated with product sustainability as it facilitates the cutback of the use of raw virgin material during product manufacturing and also reduces the load from MSW fractions that end up in landfills. In scenario 4 of the study, recycling was considered for specific fractions of MSW: paper/cardboard (18.2%), plastics (19.8%), glass (2.0%), metals (1.2%) and textiles (1.5%). For recycling, the MSW is often sent to Material Recovery Facilities (MRFs), where they are segregated and compacted accordingly [1]. The amount of electricity and diesel consumption associated with the machinery operations of the MRFs are taken as 31.2kwh/ton and 3.21 L/ton [31]. As there is no recycling plant within the system boundary, only the energy consumption during the sorting of MSW at the Material recovery facility was considered.

4. Results

The findings of this study are categorized into two sections: the first part focuses on the collection and transportation of MSW to disposal sites, identified as scenario 0; the second part analyzes different end-of-life scenarios for various disposal methods.

4.1. Collection and Transportation, Scenario 0

For collection and transportation, the functional unit considered was 1 tonne of MSW generated, which is being transported to the Chimpu dump site from four major town zones, namely Zone 1: Itanagar, Zone 2: Naharlagun, Zone 3: Nirjuli and Zone 4: Banderdewa. The input provided was the energy utilized for the to and fro movement of the vehicle from respective town zones using diesel as a fuel for each tonne of waste transported, and the output was the emissions produced from the consumption of the diesel fuel. The impact parameter Global Warming Potential 100 (GWP100) was utilized for the comparison of different zones, which is a measure in kilogram CO_2/KG emission for a period of 100years [4],[31], where we found that zone 4 (1.8641×10^1 kg CO_2-eq) to be the highest contributor in terms of GWP 100 for transportation of one tonne of MSW when compared to other zones as shown in Figure 2. The main contributor to the GWP-100 is due to the release of fossil CO_2 from the combustion of diesel.

4.2. End-Of-Life Scenarios Comparison (S1, S2, S3 and S4)

In the second section of the study, the waste disposal scenarios: S1: baseline, S2: sanitary landfill without gas recovery, S3: sanitary landfill with 50% landfill gas recovery and S4: recycling, composting and inert landfilling. The outcomes of the four MSW disposal scenarios were evaluated and compared using the Recipe midpoint H methodology. This analysis focused on five impact categories, as outlined in Table 4. For the impact parameter Global Warming Potential-100 (GWP) measured over 100 years (kg CO_2 per kilogram of emission), scenario S2 has the highest contribution to global warming at 2.3345×10^3 kg CO_2-equivalent as shown in Figure 3. This is followed by S3 at 1.1725×10^3 kg CO_2-equivalent, S1 at 1.39425×10^3 kg CO_2-equivalent, and finally S4 at 1.0511×10^1 kg CO_2-equivalent. S2 is a landfill without a methane recovery system, and the main contributor to global warming was found to be methane emission. In scenario S3, it has been assumed that 50% of methane emission from the LFG is collected and utilized to generate electricity as an avoided emission to the grid, subsequently reducing its GWP compared to S2. In scenario S4, the main GWP contributor is due to the utilization of energy in MRF facilities for segregation and inert landfilling, and the impact value is the lowest for scenario 4.

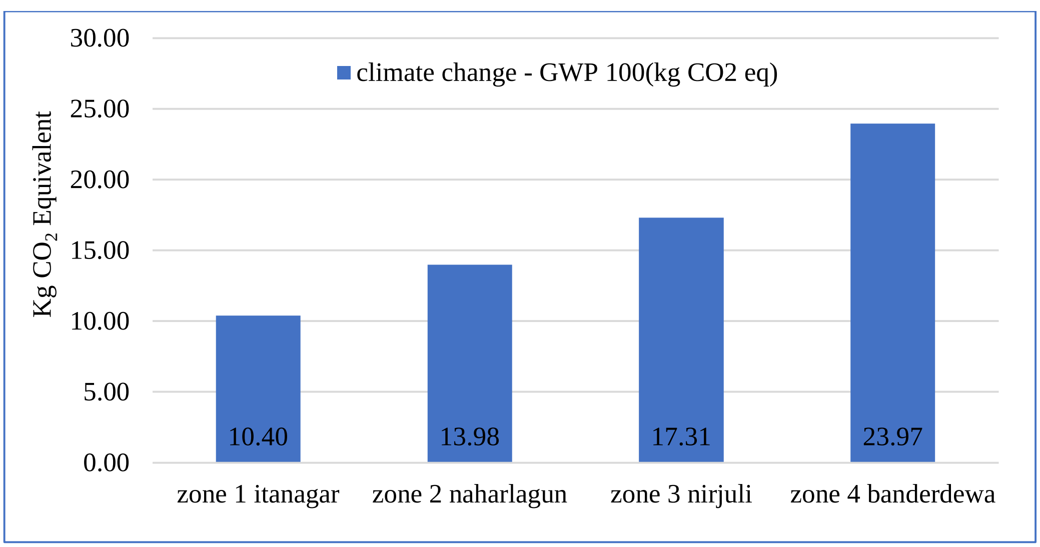

Fig. 2 Climate change- GWP100 impact category for collection and transportation of per tonne MSW from different town zones within IMC

Table 4. Result of LCA impact analysis of different waste disposal scenarios using recipe midpoint H method for five impact categories

Indicator	Scenario 1	Scenario 2	Scenario 3	Scenario4	Units
Global Warming Potential-GWP100	1394.3	2334.5	1172.5	10.511	kg CO_2-Eq
Human Toxicity Potential-HTP	7.23895×10^{-2}	0.0270873	0.027087	0.027087	kg 1,4-DCB-Eq
Particulate Matter Formation Potential-PMFP	1.8018×10^{-2}	5.0498×10^{-3}	5.0498×10^{-3}	5.0498×10^{-3}	kg PM^{10}-Eq
Photochemical Oxidant Formation Potential-POFP	0.645177	0.94997	0.48052	1.1076×10^{-2}	kg NMVOC-Eq
Terrestrial Ecotoxicity-TETP	2.09139×10^{-4}	1.17997×10^{-5}	1.1799×10^{-5}	1.1799×10^{-5}	kg 1,4-DCB-Eq

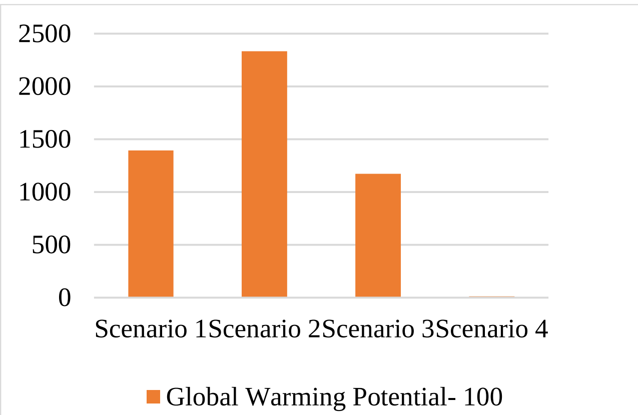

Fig. 3 Climate change- GWP 100 category for different scenarios

Human Toxicity Potential (HTP) measures the harmful effects of toxic compounds like 1,4-dichlorobenzene, which is a toxic compound that may potentially be harmful when released into the environment or comes in contact with any human. In Scenario 1 (S1), the highest HTP value was observed, primarily due to the open burning of MSW, which releases 1,4-dichlorobenzene. This practice significantly contributes to human health risks. In contrast, the other scenarios do not involve the open burning of MSW, and their HTP contributions are mainly linked to fossil fuel combustion, as illustrated in Figure 4.

Particulate Matter Formation Potential (PMFP) refers to the generation of particulate matter in the atmosphere through specific activities or processes. In Scenario S1 (1.8018×10^{-2} kg PM_{10}-Eq), we assumed 3% of MSW is openly burned, releasing PM_{10}, $PM_{2.5}$, and other secondary particulate matter. This results in S1 having the highest PMFP values, as depicted in Figure 5. In contrast, Scenarios S2, S3, and S4 primarily derive their PMFP from diesel fuel combustion. Diesel engines emit not only particulate matter but also NO_x and VOCs, which can further contribute to secondary particulate matter formation. These emissions from diesel combustion are significant contributors to poor air quality, particularly in urban environments.

Photochemical Oxidant Formation Potential (POFP) refers to the ability of certain substances or atmospheric conditions to generate photochemical oxidants, primarily ozone (O_3), in the presence of sunlight. The analysis revealed that in Scenario S2, which involves sanitary landfilling with daily cover, the primary contributors to POFP are the utilization of fossil fuels like diesel for landfill management and the release of landfill gases like methane and VOCs, resulting in 9.4997×10^{-1} kg of NMVOC released, as illustrated in Figure 6. Scenario S2 shows a higher POFP compared to the baseline Scenario S1, where the main source of POFP is from the burning of MSW in the open environment, contributing to 6.4518×10^{-1} kg of NMVOC. The Terrestrial Ecotoxicity impact parameter evaluates the potential toxicity of various chemicals and VOCs released from dumping sites to the surrounding environment, posing risks to both plant and animal life. Key contributors to terrestrial ecotoxicity include pesticides, heavy metals, industrial chemicals, and Persistent Organic Pollutants (POPs), which can accumulate in the soil and adversely affect organisms. This assessment expresses values in terms of 1,4-dichlorobenzene equivalents per kilogram of emission. In the baseline scenario where open dumping is practiced, the potential for terrestrial ecotoxicity was identified as the highest, measuring up to 2.0914×10^{-4} kg of 1,4-DCB equivalent, as depicted in Figure 7.

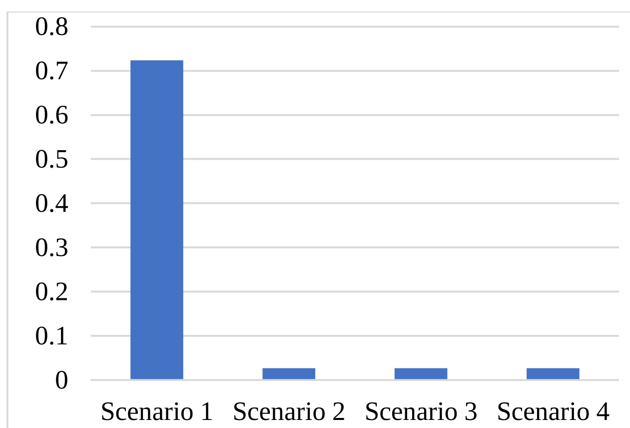

Fig. 4 Human toxicity potential for different scenarios

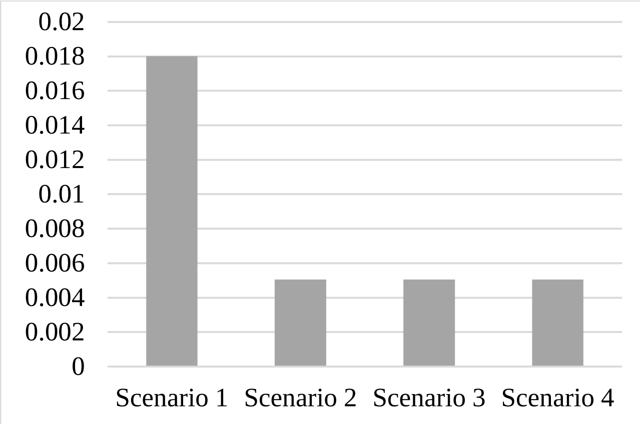

Fig. 5 Particulate matter formation potential for different scenarios

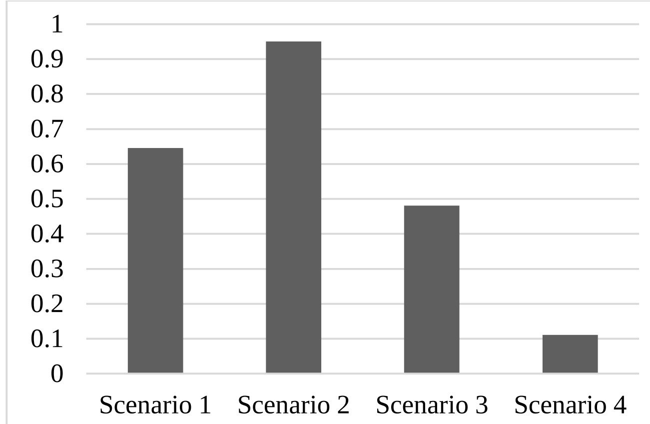

Fig. 6 Photochemical oxidant formation potential for different scenarios

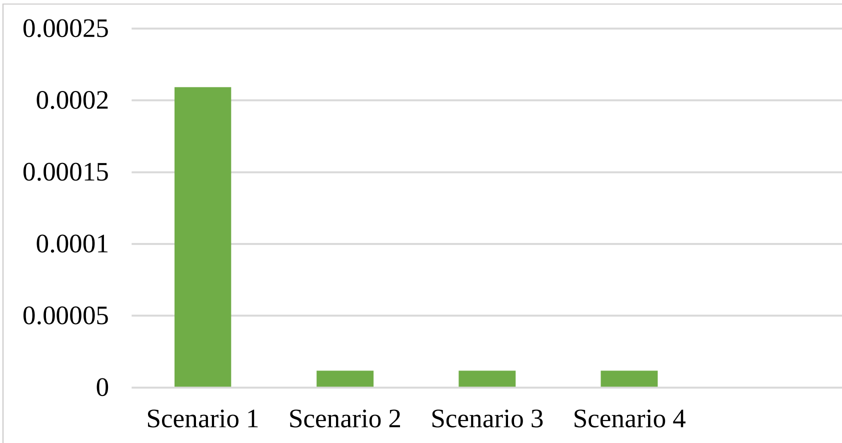

Fig. 7 Terrestrial ecotoxicity for different scenarios

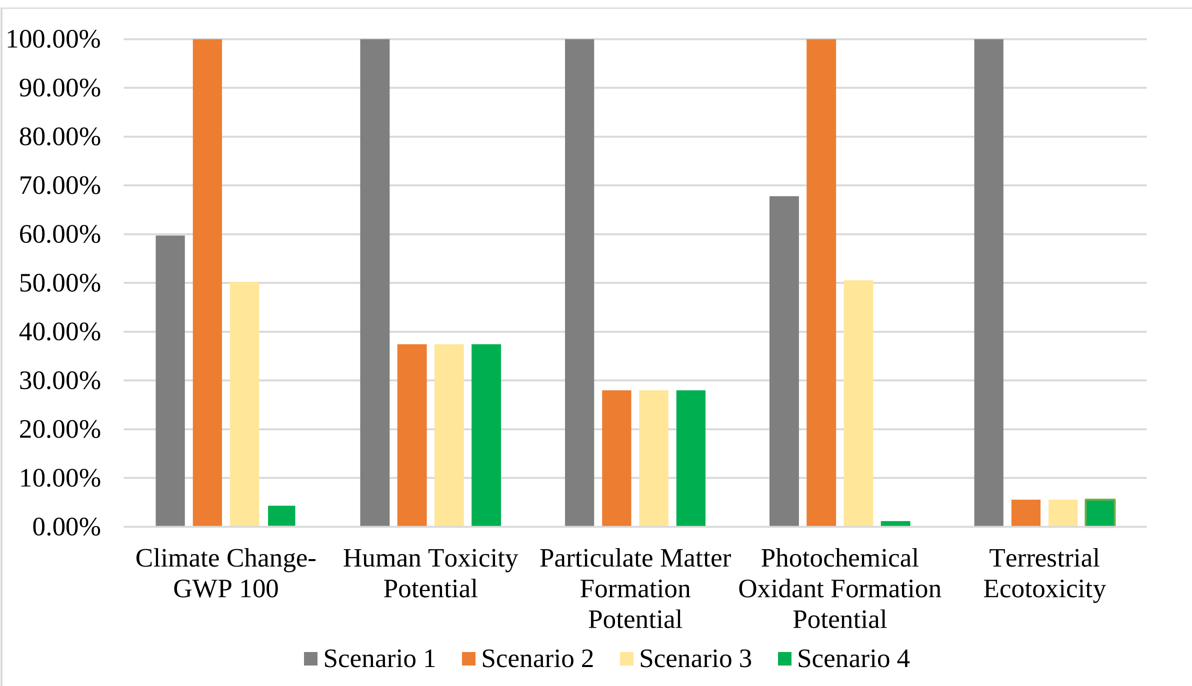

Fig. 8 Relative indicator results for various scenarios with the maximum values for each impact category normalized at 100%

The baseline scenario, referred to as Scenario 1, was identified as the most environmentally damaging when compared to the other scenarios. Figure 8 presents the normalized values of each scenario, with the maximum values within each impact category set at 100% for comparative analysis. Scenario 4, which incorporates an Integrated Waste Management approach, exhibited the least environmental footprint in all the impact parameters. For the impact category GWP 100 and POFP scenario 2 consisting of landfill without LFG recovery was found to be the worst performing. By adopting scenario 4, the IMC can effectively address its escalating MSW handling and disposal challenges. This approach would significantly reduce environmental degradation caused by the current MSW management practices in the region.

5. Discussion

Although several limitations must be noted, the current LCA study offers us important insights into the environmental impacts of various MSWM strategies for the Itanagar Capital Region. Due to the unavailability of primary data and resource constraints, secondary data sources were used for certain processes, potentially introducing uncertainty. The study did not consider various trace gaseous air emissions from open dumps and sanitary landfills. The functional unit focuses on per-tonne waste impacts, which may not fully capture site-specific variations. Assumptions regarding the output emissions, degradation rates, and process efficiencies represent average conditions that might differ from actual operational parameters, creating scope for uncertainties [22]. Additionally, due to the geographic scope of the data obtained from LCA databases, the findings may not entirely represent the studied region with different waste characteristics or management systems. Future studies can be improved by incorporating primary data collection and sensitivity analysis across different scenarios to enhance the robustness of the LCA study.

The findings of this research can provide a useful source for studies on waste management in cities across northeast India or other hilly regions that share similar demographics, cultural practices, and food habits. These areas often exhibit comparable waste composition and face common challenges such as rapid urbanization and shifting waste generation trends. LCA studies like this one can be instrumental in designing MSW disposal options and evaluating various alternatives, along with their associated limitations and advantages. Such an approach can facilitate informed decision-making, ensuring adherence to the SWM Rules, 2016, while promoting sustainable and environmentally sound waste management practices.

6. Conclusion

This LCA study evaluated the four waste management scenarios to determine their environmental impacts. The baseline scenario S1, which consists of the current MSWM employed by the IMC, exhibits the highest effects on HTP, PMFP, and TETP impact categories, mostly due to the open dumping of MSW without any processing. Scenario S2, which includes landfilling without gas capture, exhibited the most significant effects regarding GWP 100 and POFP, attributable to significant methane emissions and heavy machinery use. However, when 50% of landfill gas is captured, as seen in Scenario S3, these impacts notably decrease. The reliance on landfilling fails to capitalize on the recycling and composting potentials of organic waste. Conversely, Scenario S4, which incorporates an integrated approach of recycling, composting, and inert landfilling, demonstrated a minimal environmental footprint in most of the assessed impact parameters. By successfully adopting scenario 4, IMC can effectively improve its waste management strategy in compliance with the SWM Rules 2016. Furthermore, by implementing an Integrated Waste Management (IWM) approach, IMC can support a circular economy within its waste disposal framework, which can significantly reduce its environmental liabilities. Additionally, waste collection and transportation analysis of the IMC exhibits that zone 4 (Banderdewa) resulted in the highest impact on the GWP 100 impact category per tonne of waste when compared to other zones, highlighting inefficiencies. This emphasizes the importance of MRFs as temporary pilot stations that can accommodate the diversion of huge quantities of recyclables from the disposal sites, further highlighting the importance of the IWM approach. Increased distances between collection and disposal sites further amplify the environmental burden associated with fossil fuel consumption utilized during transportation.

6.1. Recommendations

- Source Separation: The segregation of waste at the generation stage should be encouraged to improve recycling rates and reduce contamination. Source separation can increase the efficiency of downstream processes and can significantly diminish the environmental footprints of waste processing facilities by lowering the energy needed for sorting and other operations.
- Optimization of waste collection and transportation: collection and transportation being an integral part of waste management when utilizes fossil fuel as a source of energy becomes an environmental burden. Optimized routes, deploying fuel-efficient or electric vehicles, or increasing collection efficiency should be incorporated from the loading to unloading of MSW at the disposal site.
- Integrated Waste Management: An optimal waste disposal strategy would involve the separation of waste into recyclables and organic components right at the source of MSW generation points. The collected trash can then be combined with MRFs and composting sites. Waste reduction and recycling activities can significantly lower the environmental impacts when compared to other

disposal options. Adopting an Integrated Waste Management system can greatly decrease emissions linked to the management of MSW.

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