

Greenhouse Gas Emissions from Municipal Solid Waste Management: A Review of Global Scenario



Meenu Gautam and Madhoolika Agrawal

Abstract Increases in the population and prosperity are significant contributors to waste generation. Globally, ~2.01 billion metric tonnes of municipal solid waste (MSW) are produced annually, which are expected to upsurge by two folds in 2050, thereby raising a matter of concern in future. The chapter aims to assess the greenhouse gas (GHG) emissions from MSW management and its subsequent impacts on socioeconomic status of people and ecological systems. The study also includes mitigation strategies to reduce emissions of GHGs from waste management. The life cycle assessment of MSW management in relation to GHG emissions discloses that more than 50% of the collected waste is not managed properly instead openly burned or dumped at landfills in most developing countries. Moreover, nearly 10–40% is processed through recycling and composting. Total GHG (CH₄, CO₂, and N₂O) emissions from waste management contribute approximately 5% of overall GHG emissions into the atmosphere. Methane generation exclusively accounts for 1–2% of GHG release from the process of waste management. The emitted GHGs lead to global warming, climate change, and adversely affect the living organisms on the earth. Therefore, sustainable management of the system from collection to treatment and disposal with special emphasis on GHGs emission minimization is essential to sustain the available resources and safeguard the environment. The study highlights the strategies such as 5-R principal, waste segregation at household level, use of natural gas-based vehicles, advanced modifications in the system of waste management in developing countries, utilization of compost and residue as manure, and reclamation of abandoned landfill sites to mitigate the emissions for sustainable progression of the nations. The review also provides a basis for decision-makers in local, national, and regional levels to formulate and execute strategies and policies for mitigating GHG emanations during MSW management.

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1 Introduction

Solid waste refers to any unwanted solid materials of everyday use that are generated by community activities. Of the total solid waste generated worldwide, ~70% constitute municipal solid waste (MSW) [78]. Increase in population and prosperity are the two critical drivers for waste generation, thereby making MSW management one of the key challenges of the twenty-first century [22]. Globally around 2.01 billion tonnes (Bt) of MSW are generated annually, of which East Asia and Pacific stands at the top (23%) followed by Europe and Central Asia (20%), and South Asian countries (17%) in terms of MSW generation (Fig. 1a) [78].

Worldwide waste generation per person per day averages 0.74 kg and ranges widely from 0.11 to 4.54 kg [78]. Waste generation, however, depends on several factors such as population, development, and income level of the nation, etc. There is generally a positive correlation between waste generation and income level (Fig. 1b). High-income countries generate about 683 million tonnes (Mt) of MSW [78]. Since, all the countries want to progress in all the possible ways to provide quality of life to their citizen; there are increases in industrialization, urbanization, and commercialization with simultaneous increase in population. Thus, when looking forward, the MSW generation has been projected to increase to 3.40 Bt by the end of 2050 [78]. The fastest-growing regions will be the Middle East as well as North Africa, South Asia, and Sub-Saharan Africa where total waste generation is expected to increase by 2, 2, and 3 folds, respectively by 2050.

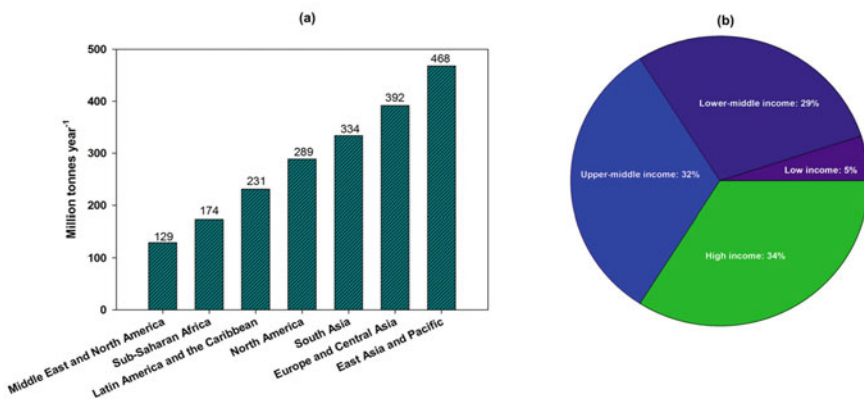


Fig. 1 Amount of municipal solid wastes generated from different regions of the world (a) and percentage contribution in waste generation based on the global economy (b) (based on the data from [78])

Composition of generated MSW can be categorized into organic and inorganic. Organic fraction of the waste mainly includes food wastes (mixed), plant materials, paper and cardboard, textile and gunny bags, animals' wastes and decomposed garbage, etc. (Table 1, Fig. 2) [34]. Whereas, inorganic fraction of MSW encapsulates construction wastes, plastics, glass, metals, rubber, thermacole, electronic wastes (e-waste), multilaminates, ashes, and other processed trashes having inorganic constituents (Table 1, Fig. 2). Percentage contribution of both organic and inorganic fractions in MSW generated from different areas of the world is illustrated in Table 2 [44]. Composition of MSW is greatly influenced by geographical loca-

Tables 1 Sources of organic and inorganic constituents in municipal solid waste

Type	Sources
Organic	Food material, garden trimmings, branches, grass cuttings, raw peelings, bagasse, organic residues, animal excreta, decomposed garbage. residues from slaughterhouses, etc.
Paper and cardboard	Cardboard, newspapers, wrapping paper, paper scraps, telephone books, magazines, bags, boxes, shredded paper, paper disposables
Plastics	Bottles, containers, packaging, bags, toys and lids, etc.
Glass	Bottles, light bulbs, broken glassware, cultured glass, etc.
Metals	Container, foil, tin, nonhazardous aerosol can, appliances, railing, vehicle, and other utilities
Others	Leather, textiles, multilaminates, rubber, e-waste, building and construction waste; appliances, ash, and other inert materials

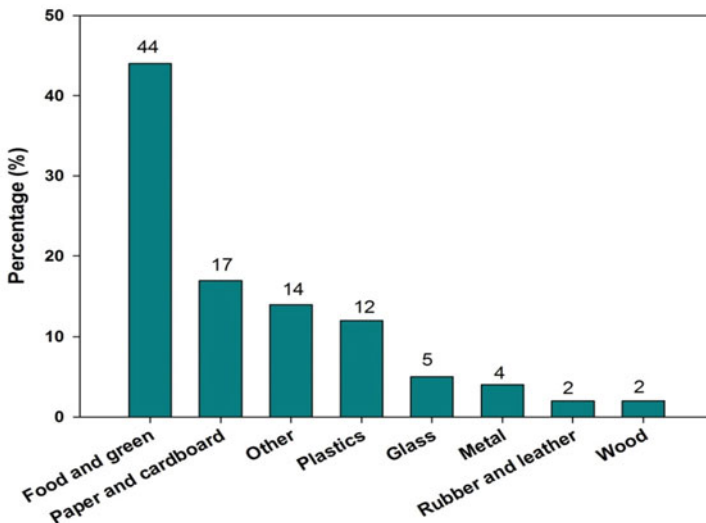


Fig. 2 Percentage of food and green, paper and cardboard, plastics, glass, metal, rubber and leather, wood, and miscellaneous constituents in MSW worldwide (based on the data from [34])

Table 2 Percentage contribution (%) of food, garden, paper and cardboard, wood textile, nappies, rubber and leather, plastic, metal, glass, and other miscellaneous materials (mean value) in municipal solid waste from collection to disposal at landfill sites across different regions of the world

Region	Food waste	Garden waste	Paper and cardboard	Wood	Textiles	Nappies	Rubber and leather	Plastics	Metals	Glass	Other
<i>Asia</i>											
Central	30.0	1.4	24.7	2.5	3.5	0	0	8.4	0.8	5.9	23.0
Eastern	40.3	0	20.4	2.1	1.0	0	0	6.5	2.7	4.3	22.9
South-Eastern	49.9	1.0	11.2	0.8	0.4	0	0	10.2	4.2	3.7	18.6
Southern	66.1	0	9.2	0	1.2	0	0.4	7.0	0.9	1.5	13.9
Western	42.2	3.2	15.3	0.8	3.0	0.4	0.3	17.2	2.5	3.4	11.8
<i>Africa</i>											
Northern	50.4	0	12.1	0	5.8	0	0	13.8	4.4	3.3	10.5
Eastern	44.4	6.9	10.4	0.5	3.0	0	0.4	8.0	2.6	2.1	21.7
Middle	28.4	0	8	0	1.3	0	0	7.1	1.4	1.1	52.7
Southern	24	0	14.5	0	5.5	0	0	26.5	6.5	9.0	14.0
Western	53.9	0	7.5	0	1.9	0	0	6.4	2.7	1.3	26.5
<i>Europe</i>											

(continued)

Table 2 (continued)

Region	Food waste	Garden waste	Paper and cardboard	Wood	Textiles	Nappies	Rubber and leather	Plastics	Metals	Glass	Other
Eastern	31.8	2.4	17.1	2.5	3.1	0.1	0.5	4.6	0.7	1.8	35.3
Northern	30.3	5.2	13.8	1.8	3.2	1.2	0	4.9	1.4	4.3	34
Southern	35.8	1.4	21.4	1.2	2.8	1.1	0.2	14.1	2.0	3.5	16.7
Western	33.2	2.7	17.2	2.3	5.9	3.0	0	20.5	1.5	1.4	12.3
<i>America</i>											
Central	62.7	0	12.6	0.3	2.2	0	0	10.3	2.7	3.3	6
Southern	54.1	3.3	12.4	0	1.7	1.9	0.6	13.7	2.0	3.0	7.2
North	20.2	6.8	23.3	4.1	3.9	0	1.6	15.8	6.4	4.2	14.0
Australia and New Zealand	25.9	12.2	12.0	6.5	2.9	3.5	0	8.3	1.8	2.8	24.1

Source: IPCC [45]

tion, cultural norms, economic development, energy sources, and climatic conditions [34]. High-income nations have higher consumption of inorganic supplies (such as plastics, laminated paper, glass, and metals); hence have high generation of inorganic/recyclable waste. While, low to middle income countries have high organic fraction in MSW, i.e., 40–85% compared with 28% in high-income countries [34].

Climate of the region also influences the composition of the wastes [34]. Precipitation and humidity play crucial role in waste composition, particularly when measured by mass because of absorption of moisture from the atmosphere [34]. Waste of dry region has low moisture content and vice versa. For an instance, [68] showed that in Muscat, Sultanate of Oman, 33.6% by weight and 16.7% by volume of MSW were generated in winter, and 22.8% by weight and 7.8% by volume in summer. Physical properties of MSW show density, volatile solid, ash, and moisture content in the range of 65–480 kg/m³, 69–86%, 0–68%, and 2–91%, respectively (Table 3). Chemical properties such as electrical conductivity, pH, contents of carbon, oxygen, hydrogen, sulfur, chlorine, organic carbon, organic nitrogen, phosphorous and potassium, C/N ratio, fixed residue, and calorific value of MSW from different countries are presented in Table 3. Chemical composition of MSW in West Bengal exhibited high moisture, ash, and inorganic contents, while contents of nitrogen, phosphorus, and potassium were relatively low [74].

Tremendous generation of MSW has creating and likely to create a massive problem in upcoming future. Improper management of MSW has severe negative consequences on the environment as well as human health [75]. The disintegration of waste into harmful chemical constituents is a common source of environmental pollution and is severe mainly in developing nations. Severe negative consequences of MSW disposal were described in various cities of different countries such as China [10], India [80], Malaysia [51], and Thailand [11]. Poor management of MSW has become an inevitable challenge for governments of many Asian and African countries [24].

Management of MSW generally involves segregation at source point, door-to-door collection, transportation, storage, segregation at storage house into biodegradable and nondegradable wastes (plastics, metals and glass), material recycling, anaerobic digestion and composting of organic wastes, incineration/thermal treatment for waste-to-energy recovery and finally the residues are disposed at landfill sites. However, the above-mentioned sequence of waste management varies with countries, states, and cities. Figure 3 shows percentage contribution of various treatment processes in waste management globally [34]. Furthermore, Fig. 4 depicts the MSW treatment contribution by various countries across the world. In developed countries, wastes management is strictly complied with the norms, regulations, and policies of IPCC and EPA. While, the developing countries like China, India, South Africa, Nepal, Pakistan and Bangladesh, etc., are yet to be in strict alignment with the IPCC and EPA protocols. In these regions, currently more than 50% of the waste is openly dumped and the waste growth curves are likely to have vast insinuations for the environment, health, and prosperity, which necessitate a quick call for appropriate and urgent actions.

Tables 3 Physicochemical properties of municipal solid waste from collection to disposal at landfill sites

Properties	Range	References
Moisture content (%)	2–93	[36] ¹ ; [73] ² ; [74] ³ ; [6] ⁴ ; [21] ⁵ ; [53] ⁶ ; [29] ⁷ ;
Volatile matter (%)	2–83.32	[36] ¹ ; [82] ⁸ ; [53] ⁶ ; [102] ⁹ ; [87] ¹⁰
Ash content (%)	1–76.8	[59] ¹⁵ ; [36] ¹ ; [74] ³ ; [102] ⁹
Density (kg m ⁻³)	65–480	[74] ³
pH	4.4–8.12	[73] ² ; [74] ³ ; [82] ⁸ ; [21] ⁵
Electrical conductivity (dS m ⁻¹)	0.19–0.29	[82] ⁸
Carbon content (g kg ⁻¹)	21–64.32	[36] ¹ ; [74] ³ ; [102] ⁹
Nitrogen content (g kg ⁻¹)	0.96–5.11	[36] ¹ ; [74] ³ ; [102] ⁹ ; [87] ¹⁰ ; [52] ¹¹
C/N ratio	13.0–30.94	[18] ¹² ; [73] ² ; [65] ¹³ ; [71] ¹⁴
Hydrogen content (g kg ⁻¹)	0.1–9.2	[36] ¹ ; [74] ³ ; [102] ⁹
Oxygen content (g kg ⁻¹)	0.07–44.24	[36] ¹ ; [74] ³ ; [87] ¹⁰
Sulfur content (g kg ⁻¹)	0.05–5	[36] ¹ ; [74] ³ ; [52] ¹¹
Organic carbon (%)	0–27.6	[74] ³
Organic nitrogen (%)	0.34–0.70	[74] ³
Phosphorous (P ₂ O ₅) (%)	0–0.82	[74] ³ ; [65] ¹³ ; [52] ¹¹
Potassium (K ₂ O) (%)	0–0.83	[74] ³ ; [65] ¹³ ; [52] ¹¹
Calcium (CaO) (g kg ⁻¹)	0–14.9	[18] ¹²
Magnesium (MgO) (g kg ⁻¹)	0–3.33	[18] ¹²
Chlorine content (%)	0.39–2.48	[6] ⁴ ; [102] ⁹
Fixed residue (%)	3.2–87.13	[74] ³ ; [102] ⁹
Calorific value (kcal kg ⁻¹)	900.61–4568.7	[6] ⁴ ; [65] ¹³ ; [87] ¹⁰

1: South Africa; 2: Iran; 3: Bangladesh; 4: Turkey; 5: Germany; 6: The USA; 7: Island of Crete, Greece; 8: Mauritius; 9 and 15: China; 10: Thailand; 11: Africa; 12: Spain; 13: India; 14: Pakistan

Greenhouse gas (GHG) emission from various anthropogenic sources is an important global issue considering the environmental health. Per capita annual carbon dioxide (CO₂) emission increased from 2.2 tonnes (t) in 1990 to 7.5 t in 2014, with a growth rate far higher than the world's average per capita level [44]. China followed by the USA and India are the largest contributors of GHG emissions (Fig. 5) [44]. According to [96], waste is the largest research area of focus for emission followed by energy reduction in the world. It is expected that waste sector including solid and wastewater treatment contributes 3–4% to the global anthropogenic GHG emissions [25]. Municipal solid waste sector is the fourth largest contributor to global GHG emissions accountable for approximately 5% of the global greenhouse budget [39]. This 5% consists of methane (CH₄), carbon dioxide (CO₂), nitric oxide (N₂O), and fluorinated gases (such as perfluorocarbons (PFCs), hydrofluorocarbons

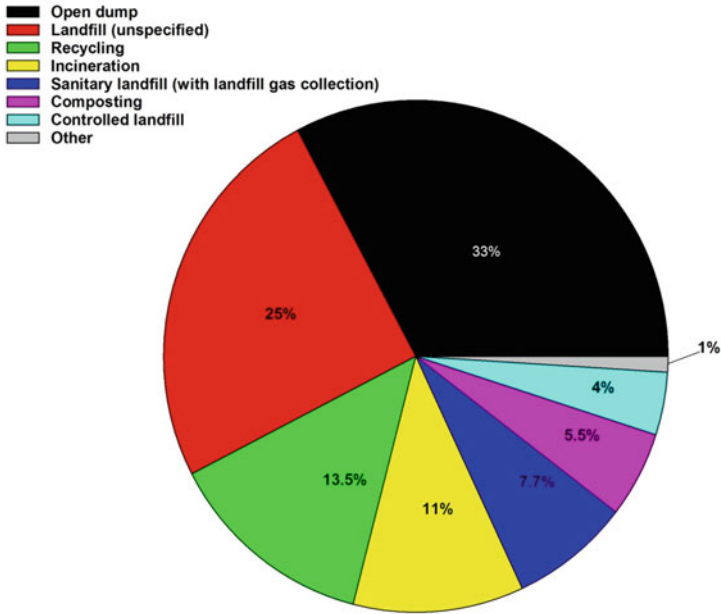


Fig. 3 Various treatment processes and their percentage contribution in municipal solid waste management globally (based on the data from [34])

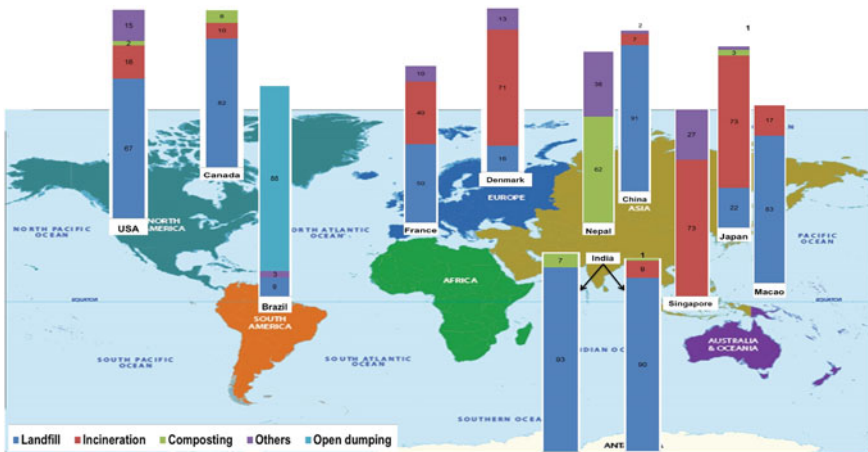


Fig. 4 Percentage contribution of various treatment processes (composting, incineration, open dumping, landfill, and other miscellaneous processes) in management of municipal solid waste in different regions of the world (Modified from [98])

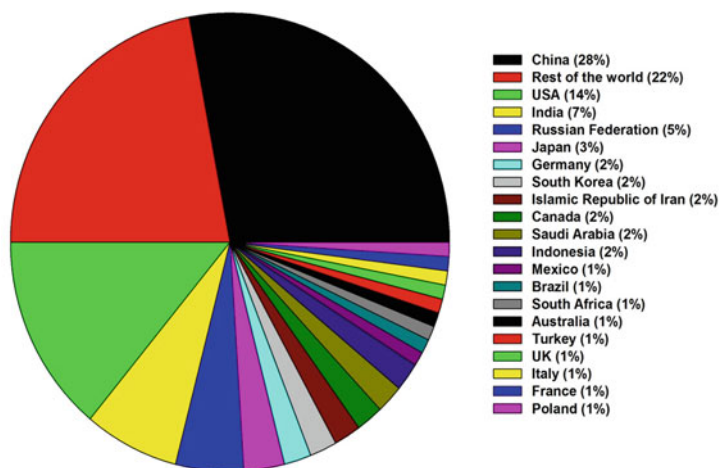


Fig. 5 Percentage contribution of different countries in greenhouse gas emissions from municipal solid waste management (adapted from [44])

(HFCs), chlorofluorocarbons (CFCs), sulfur hexafluoride (SF_6), and nitrogen trifluoride (NF_3). Moreover, CH_4 , CO_2 , and N_2O are dominant GHGs from waste sector [92].

Municipal solid waste releases a gaseous mixture predominantly of CH_4 , CO_2 , and N_2O generated by microbial decomposition of carbon as well as nitrogen-containing compounds and combustion along the hierarchy of waste management (waste generation, storage in bins, collection, transportation, disposal, recycling, composting/incineration, and final disposal at landfill sites). Composting, incineration, and landfills are the chief sources of atmospheric emissions (CH_4 , CO_2 , volatile organic compounds, noxious gases and fumes, etc.). Manfredi et al. [60] stated that mixed wastes are solely responsible for direct emissions of GHG up to $300 \text{ kg CO}_2\text{e t}^{-1}$. Its contribution to GHG emissions reaches $\sim 3\%$ worldwide and up to 15% in developing economies [4]. Thus, the appropriate selection of waste processing techniques via integrated waste management system having negligible emissions and consequent impacts is imperative.

The chapter thus aims to describe the emission scenario of greenhouse gases from varying processes involved in municipal solid waste management through life cycle assessment approach and the subsequent impacts on socioeconomic and ecological systems. The study also includes the mitigation steps for sustainable management of municipal solid waste to reduce greenhouse gas emissions.

2 Literature Search

Worldwide datasets on MSW generation, waste composition, and greenhouse gas productions during waste management system were collected from peer-reviewed literatures available at the Web of Science (accessed till the end of July 26, 2020), official sites of World Bank, IPCC, EPA, IEA [46, 47], NASA, NOAA and national monitoring web networks of USA, China, and India. Published papers from 2001 to 2020 were considered for the global MSW generations' and GHG emissions' scenario. Data from table, text, and figures were extracted for the accomplishment of this review study. Specific keywords such as MSW, life cycle assessment, landfills, GHGs, CH₄, CO₂, N₂O, effects of GHGs, and mitigation strategies were used to access the search engines and other web networks.

3 Methodologies for the Estimation of GHG Emission

The inventory by the IPCC enlists various calculation methods for the emissions of GHGs from waste disposal [39, 40]. The IPCC describes four main types of GHGs accounting such as national accounting, corporate-level accounting, life cycle assessment, and carbon trading methodologies [25]. Many academics have followed the IPCC guidelines in calculating GHG emissions from MSW management [39, 40]. Carbon factor used in calculation varies with the type of vehicles and treatment procedures, and the factors used in GHG computation are derived from the Waste and Resources Assessment Tool (WRATE) version 2 and the Department of Energy and Climate Change data [30]. To study the GHG emissions from landfill sites, LandGEM modeling is widely used [9].

Existing literature on quantification of GHGs during MSW management in both developed and developing nations were surveyed with a particular focus on the life cycle assessment [9, 16, 61]. Figure 6 shows generalized framework in estimating GHG emanations from MSW management for both developing and developed nations. However, huge differences in quantitative estimation of GHG emissions between developed and developing nations are because of lack of resources, information, mandatory obligations, and expertise [92]. Overall assessment of GHG releases through the entire management system of MSW, i.e., collection, transportation, storage, intermediate facilities (material recovery, composting, incineration and/or thermal treatment), and landfill sites are analyzed using GHG calculator. The GHG calculator is an Excel-based tool to estimate GHG emissions [30]. It measures CH₄, CO₂, and N₂O emissions, expressing them as CO₂e emissions or savings, depending upon how the waste is managed [30]. There are different carbon modules in the GHG calculator; each contains information about the CO₂e performance of each waste management system.

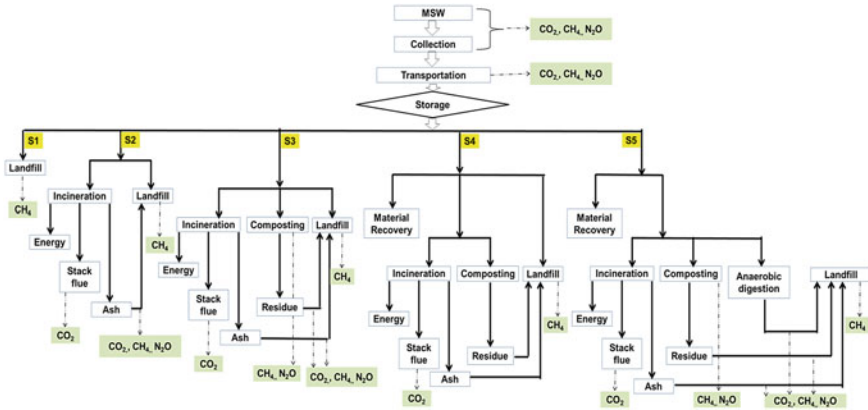


Fig. 6 Scenarios in life cycle assessment of municipal solid waste management (from collection to landfill wastes) with respect to major greenhouse gas emissions (CO₂, CH₄, and N₂O). CO₂: carbon dioxide; CH₄: methane; N₂O: nitric oxide; S1: scenario 1; S: scenario 2; S3: scenario 3; S4: scenario 4; S5: scenario 5

4 Life Cycle Assessment of MSW Management

Life cycle assessment (LCA) is a science-based cumulative approach to enumerate the impact of the entire system, process, or product on the environment [12]. It is the computer-aided tool that is increasingly used for sustainable management of MSW since 1995, specifically in decision-making and adoption of management strategies [32]. LCA is ideal in MSW management because of wide variations in geographical location, properties of the wastes, energy resource, limited availability of disposal sites, market size of the product resulting from the wastes, and in reducing local pressure and waste management cost [62]. Cumulatively, LCA is essential to evaluate, identify the hotspots, and diagnose the possible improvements on reducing and controlling the environmental impacts of GHG emissions along the waste treatment hierarchy. Based on International Organization for Standardization (ISO) 14040 and 14044 [48, 49] and International Reference Life Cycle Data System (ILCD) Handbook [23], LCA has following four sections.

4.1 Goal and Scope Definition

It is the first stage in the LCA of MSW management [48]. The scope and goal may vary from general (e.g., testing the validity of the “hierarchy of waste”) to specific (e.g., comparing the environmental performances of several possible designs for a MSW management system in particular community) assertions. Many studies have been conducted based on different goals and scopes of MSW management. These include identification of options for minimizing the adverse environmental impact,

energy consumption, and economic costs; to reveal the plausibility and limitations of economic information in MSW management; to bring out the comparative assertions in regulation of MSW management and to evaluate the compatibility of LCA with the hierarchy of MSW management [12]. The present study, however, infuses the LCA of MSW management with GHG emissions from cradle to grave for clear understanding of gaseous emissions (Fig. 6).

4.2 Functional Unit and System Boundaries

Functional unit is a well-defined and measurable phase [48]. It provides a basis to understand and compare the results of LCA at general and specific levels [48]. While a system boundary defines the unit processes, i.e., stages, inputs as well as outputs within the system. It comprises the total elements of the system upon which the computations of impacts are based. The LCA of MSW management system ensures the GHG emissions out of the inputs at various stages of management systems (Fig. 6). In addition, both are allied to the generation of useful products such as compost, heat and electricity. More specifically, it includes management of one tonne of MSW with specific composition over a definite period of time to compare the alternative scenarios [94]. Functional unit and system boundaries are comprised of following five scenarios for clear illustration of baseline to advanced management processes.

4.2.1 Scenario 1

It is a baseline scenario for developed and developing nations, where maximum proportion of MSW after collection is dumped to landfill sites having no provision for leachate and gaseous collection. Landfill sites at baseline scenario may or may not have gas flares. Thus, there is more harmful impact of scenario 1 on the environment because of maximum releases of GHGs (CH_4) from the landfill sites (Fig. 6).

4.2.2 Scenario 2

Incineration or thermal treatment facilities equipped with baseline scenario led to recovery of energy from MSW with subsequent generation of flue gas and ash. Relatively less proportion of waste is generally utilized for energy recovery due to high waste generation and less capacity of the incinerator [72]. In this scenario also maximum proportion of MSW is disposed without proper pretreatment to landfills, which consequently leads to high GHG emissions (Fig. 6).

4.2.3 Scenario 3

Composting and incineration units are facilitated with scenario 2, which carries out segregation of wastes into inorganic and organic followed by aerobic digestion of biodegradable fraction and recovery of energy from nonbiodegradable. The outputs of the scenario are GHGs, flue gas, compost, and residues from incinerator (Fig. 6). The scenario minimizes the waste generation to landfill and GHG emissions compared with scenario 2.

4.2.4 Scenario 4

Scenario 4 supports the material recycling of waste along with composting and incineration. Material recycling unit reduces the amount of the wastes to a significant level through the recovery of reusable plastics, glass, and metals. Recovery of recycling materials followed by composting of biodegradable waste and incineration of remaining waste leads to disposal of the relatively less fraction of MSW (compost and residues from incineration) at the landfill (Fig. 6). In this case, emitted CH_4 is harnessed for energy recovery and thus reduces landfill GHG emissions.

4.2.5 Scenario 5

This is the progressive scenario widely practiced in developed countries and in some cities of developing countries to manage MSW. The scenario is the combination of previous four scenarios where after collection, transportation and recycling of materials, equal proportions of biodegradable waste are subjected to anaerobic digestion and composting followed by incineration and waste disposal at landfill sites (Fig. 6). Intermediate treatment processes from collection to disposal site reduce the GHG emissions and landfill waste to a great extent. Landfills are further inculcated with more advanced system of methane collection and energy generation units.

4.3 *Life Cycle Inventories (LCI)*

System boundaries are further divided into foreground and background systems [5]. Foreground system is allied to the generation of useful products such as electricity and compost along with simultaneous emissions to air (e.g. GHG emissions), water and soil during material recycling, composting, anaerobic digestion, and disposal at landfill. Background system incorporates the utilization of resources (MSW, energy, storage containers, and vehicles) to the foreground system [5]. These inputs and outputs are quantified and qualified during LCI of the various processes involved in MSW management. Collection of MSW can either be in mixed or segregated forms. However, wastes in segregated form from point source are highly encouraged

as it leads to successful material recovery. There are certain parameters such as selective collection system, storage containers (made of High Density Polyethylene (HDPE), fiberglass, and steel materials), collection frequency, distance covered, type of collection truck (pneumatic, top, rear, and side loader), fuel of collection truck (diesel and natural gas), density and fraction of wastes, size, and filling percentage of container influence the collection and storage of MSW and thereby affecting the LCI.

4.4 Life Cycle Impact Assessment (LCIA) and Sensitivity Analysis

This is the evaluation of the environmental burden and benefits. It is primarily based on following six impact categories, i.e., global warming ($\text{kg CO}_2 \text{ (eq) t}^{-1}$), abiotic depletion (MJ), acidification ($\text{kg SO}_2 \text{ (eq) t}^{-1}$), nutrient enrichment ($\text{kg PO}_4 \text{ (eq) t}^{-1}$), photochemical ozone creation ($\text{kg C}_2\text{H}_4 \text{ (eq) t}^{-1}$), and human toxicity potentials (DCB (eq)).

4.5 Life Cycle Interpretation (LCIP)

LCA in MSW management is a challenging task because its management facilities require large land area, consume nonrenewable resources (electricity and fuels), and emit pollutants as well as leachates. On other hand, MSW management generates useful products such as reclaimed plastic, paper and cardboard, glass, compost as fertilizer and thermal treatment of wastes produces heat and electricity. Besides, landfilling that is the most widely used method for the management of MSW in most of the countries has a lot of uncertainties related to time frame of the impact. Thus, waste management system itself puts enormous pressure on natural environment. Therefore, there are certain approaches to amplify the LCA approach to manage MSW and GHG releases from the system UNEP [89]:

- Reconsidering the product and analyses the functional unit in detail
- Reducing the consumption of raw material and energy
- Replacing the traditional consumables with less harmful raw materials and energy-efficient production methods
- Recycling of materials
- Repair and redesigning products for reuse.

5 Greenhouse Gas Emissions from MSW Management System

Greenhouse gases are the prime cause of global warming and climatic change, which are subsequently affect the ecological balance and cause abiotic resource depletion, etc. [55]. Global warming is the result of increasing temperature due to emissions of GHGs such as CO₂, CH₄, and N₂O. The LCA of MSW management clearly exemplifies the points of emission of major GHGs such as CH₄, CO₂, and N₂O (Fig. 6). Thus, waste collection, transportation, anaerobic digestion, composting, incineration, and landfill contribute significantly to GHG emissions during waste management process.

5.1 GHG Emissions from Waste Collection and Transport Systems

Greenhouse gases (mainly CO₂ and small amounts N₂O and CH₄) are released in the process of waste collection and transportation due to combustion of fuel. Collection rates have been much lower in developing nations as compared with their developed counterparts. For instance, Organisation for Economic Co-operation and Development (OECD) countries have collection rates varying from 90 to 100%, while developing countries have comparatively low collection rates [67]. Lower collection rates however cause less GHG emissions and vice versa because aerobic digestion of uncollected waste may lead to no CH₄ generation, rather CO₂ is emitted [5, 95]. In developing countries, methods adopted for the collection of waste might not be technologically advanced are causing less GHG emissions. In many African and Asian countries, manpower is employed in waste collection such as wheelbarrows, animal-drawn carts, pedal tricycles and push carts, etc., which are not fuel-based vehicles and thus result in no GHGs emission [8, 37]. For developed countries, GHG emissions ranged between 5 and 50 kg CO₂e t⁻¹ of wet waste [19].

In European nations, on an average 7.2 kg CO₂e t⁻¹ of waste was produced during MSW collection and transportation [81]. In the UK transportation and waste segregation resulted in 14,234 and 13,323 t CO₂e of GHG emissions, respectively [16]. The GHG emission of waste in developing countries such as Saudi Arabia was nearly 24935 t CO₂e in Saudi Arabia [97]. Waste collection along with transportation in Taipei city of Taiwan accounted for 15.53 kg CO₂e t⁻¹ of waste [25]. The emissions from transportation of collected MSW to landfill in Beijing, China varied from 91.49 t CO₂e to 102.69 t CO₂e under the five scenarios of LCA, thereby accounting for 0.56–2.15% of GHG emissions during whole management process [96].

5.2 GHG Emissions from Waste Segregation and Material Recycling Facilities

Waste segregation and recycling replace the raw materials in production, reduce the cost incurred and energy consumption in production processes, and minimize the GHG emissions during further management processes [5]. The MSW is maximally contributed by organic wastes such as domestic and agricultural wastes, and recyclable materials as stated previously [34]. Organic wastes have high proportion of moisture content whose treatments consume more energy and thus there are more gaseous emissions. Similarly, in the process through recovery of recyclable materials such as glass, metals, and plastic, quality cascading occurs in many countries at large scale, which is energy consuming [96]. Nonetheless, most developed countries and some developing nations have implemented comprehensive recycling programs for recycling of materials in order to reduce the burden on MSW management. All these lead to indirect energy conservation and great reduction in GHG emissions. [81] thoroughly addressed the GHG emissions' benefits from recycling across the European Union (EU). Pimenteira et al. [69] quantified GHG emission reductions from recycling in Brazil. At Beijing in China, total GHG emanations from incineration were reduced by 0.0251 t CO₂e after sorting and recycling of MSW at material recycling facility [96].

5.3 GHG Emissions from Composting and Anaerobic Digestion

Several developed and developing nations practice anaerobic digestion and composting of mixed biodegradable waste fractions (kitchen, garden and agricultural wastes, etc.). Generally, composting is applicable to dried waste, while anaerobic digestion is more suited for wet waste [5]. Composting decomposes waste into CO₂, water, and compost with high humic acid content, whereas anaerobic digestion of waste in the absence of air leads to CH₄ generation. Composting is relatively cost-effective and sustainable approach in managing MSW in developing countries, and yields compost. Depending on compost quality and properties of soil, there are several probable applications for MSW compost in agriculture and horticulture to stabilize and improve soil quality [13]. Xin et al. [96] reported that compost is the fraction of MSW, which emits least GHGs and further reported that the GHG emissions t⁻¹ of waste composting is only 0.177 t CO₂e in China. A study conducted by [61] in Queensway, UK found that GHG emissions from normal composting release 470 kg CO₂e t⁻¹ of waste, while solid anaerobic digestion batch with inoculum and postcomposting reduce the generation to 382 kg CO₂e t⁻¹ of waste. Kristanto and Koven [54] reported that GHG emissions from anaerobic digestion and composting resulted in net emissions of GHG of 40 and 340 t CO₂e day⁻¹ in Depok, Indonesia.

5.4 GHG Emissions from Incineration and Thermal Treatments

Incineration or thermal treatment unit consists of a fuel chamber where fossil fuel such as natural gas/oil is used only for the startup and shutdown of the operations. Besides, it is composed of a combustion chamber for transformation of waste into ash and flue gas. The combustion chamber is equipped with an airflow passage, which provides oxygen for combustion. The thermal energy generated from the combustion of waste is transferred to steam in the boiler segment through superheater tubes, which is further used in electricity generation and heating. The hot flue gas is then passed through flue gas purification system (facilitated with water scrubber) for cleaning and lowering of temperature before being emitted to the atmosphere. The emitted gas consists of CO₂, N₂O, NO_x, NH₃, and organic C. Methane generation during waste incineration process is minimum and only arises in exceptional cases (from remain over waste in waste bunker), therefore quantitatively it is not regarded as climate relevant. In incineration unit, CO₂ constitutes the main climate-relevant emission. Moreover, the residues of the process include ash and flue gas purification residues. However, incineration is still not an ideal technology for municipal solid waste in many developing nations due to high proportion of food waste and moisture content. In Germany, incineration of 1 t of MSW was generally associated with the release of nearly 0.7–1.2 t of CO₂ [93]. Bogner et al. [5] estimated the release of GHG from waste incineration approximately 40 Mt CO₂e year⁻¹. The CO₂ emission from incineration unit in European Union was reported as 9 Mt CO₂e year⁻¹ [20].

5.5 GHG Emissions from Landfill

Landfills are the significant contributors to anthropogenic climate change and one of the primary sources of global GHG emissions specially CH₄, accounting for 1–2% of total emissions [101]. The yet another large source of releases of CH₄ and N₂O from the waste sector is leachates from landfill sites [101]. The landfill GHG emissions are mainly influenced by landfill volume, age of the disposed waste, temperature, and moisture content [101]. In addition, fates of the carbon in the waste including carbon sequestered in landfills, in CO₂ from collection, decomposition, combustion and oxidation as well as in CH₄ emitted to the atmosphere, are the major determinants of GHG productions from landfills [101]. Therefore, different stages of MSW management also influence the emissions of GHGs from landfill sites [91]. Bogner et al. [5] reported that landfill CH₄ emission in Europe, the USA, and South Africa in the ranged between 0.1 and 1.0 t CH₄ ha⁻¹ day⁻¹. Since 2009, British landfill greenhouse gas emissions have declined. Tiseo [86] found ~50% reduction in GHG emissions from 2009 (29 million metric tonne (MMt) CO₂e year⁻¹) to 2018 (14.1 MMt CO₂e year⁻¹) in the UK with the lowest emission recorded in year 2016 (13.9 MMt CO₂e year⁻¹). In a study conducted by [33] on landfills in

different countries reported that CH₄ emission flux rates in South Africa, Japan, Florida, Taiwan, Thailand, Mexico, and Malaysia were 31.0, 0.21–266, 37.5, 0.38–89.5, 1030.6, and 0–1112 mg m⁻² min⁻¹, respectively.

6 Case Studies

6.1 GHG Emissions from MSW Management in China

Liu et al. [58] analyzed the properties of MSW and GHG emissions during waste management in different areas of China through LCA approach using EaseTech software. The organic fraction and moisture contents in waste varied from 50 to 70% and >50%, respectively. It was revealed that GHG emissions during scenario 1 (landfilling with flaring) and 2 (landfilling with biogas recovery) were 192 and 117 kg CO₂e t⁻¹ of waste, respectively. Scenario 4, i.e., incineration with 19% energy recovery rate led to a substantial decrease in gaseous emissions (–124 kg CO₂e t⁻¹ of waste) and thus net GHG emission was 32 kg CO₂e t⁻¹ of waste. Due to the high consumption of energy and inevitable leakage of N₂O and CH₄ in the treatment process, the fifth scenario (anaerobic digestion of the biodegradable portions along with incineration of components having high calorific value followed by residue landfilling) resulted in GHG release of 67 kg CO₂e t⁻¹ of waste.

Yu and Zhang [100] reported a gradual increase in the amount of MSW generation in Beijing from 1993 to 2013 having food waste as the most substantial component over the earlier decade. The study showed a substantial increase in GHG emission during the waste management from 1950 (6000 t CO₂e year⁻¹) to 2013 (2145000 t CO₂e year⁻¹) [100]. However, the scenario study showed reduction of 9.8, 22.7, and 4.5% GHG emissions through three techniques, i.e., energy recovery in incineration, gas flaring at landfills, and CH₄ recovery from landfill sites, respectively. The study recommended that utilization of wastes in ratio of 3:3:4 by composting, incineration and landfill can efficiently reduce the gaseous emission by 41% in the coming future [100].

6.2 GHG Emissions from MSW Management in the USA

Direct GHG emissions scenario of 2018 showed that CO₂ (2714003580 Mt CO₂e) is the highest emitted GHG followed by CH₄ (226971856 Mt CO₂e) and N₂O (28672148 Mt CO₂e) [91]. Waste sector stands at sixth position in terms of GHG emissions, i.e., on an average 108.9 MMT of GHG is emitted from 1498 facilities [91]. Table 4 shows GHG generations during the course of MSW management in the USA from 1990 to 2018 [90].

Table 4 Greenhouse gas emissions (MMt CO₂e) from municipal solid waste management sector in the USA from 1990 to 2018

GHGs emissions	1990	2005	2014	2015	2016	2017	2018
<i>CO₂</i>							
Fossil fuel combustion (<i>transportation, electric power generation, industrial, residential, commercial and US territories</i>)	4740.0	5740.0	5184.0	5031.8	4942.2	4892.2	5031.8
Petroleum systems	9.6	12.2	30.5	32.6	23.0	24.5	36.8
Natural gas systems	32.2	25.3	29.6	29.3	29.9	30.4	35.0
Incineration of waste	8.0	12.5	10.4	10.8	10.9	11.1	11.1
<i>CH₄</i>							
Landfills	179.6	131.3	112.6	111.3	108.0	107.7	110.6
Composting	0.4	1.9	2.1	2.1	2.3	2.4	2.5
Petroleum systems	46.1	38.8	43.5	40.5	39.0	38.7	36.2
Field burning of biomass	0.3	0.4	0.4	0.4	0.4	0.4	0.4
Natural gas systems	183.3	158.1	141.1	141.9	135.8	139.3	140.0
Petroleum systems	NA	NA	NA	NA	NA	NA	NA
<i>N₂O</i>							
Composting	0.3	1.7	1.9	1.9	2.0	2.2	2.2
Incineration of waste	0.5	0.4	0.3	0.3	0.3	0.3	0.3
Field burning of agricultural residues	0.2	0.2	0.2	0.2	0.2	0.2	0.2
Petroleum systems	NA	NA	NA	NA	NA	NA	0.1
Natural gas systems	NA	NA	NA	NA	NA	NA	NA

Source US EPA [91]; NA: data not available

Lee et al. [56] used US-based annual figures during the period of 1990–2012 in order to substantiate the causal relationship between MSW management and GHG emissions. He implied that consistent increase in per capita generation of MSW in the USA from 1990 (208.3 kg) to 2012 (250.9 kg) was accompanied with concurrent increase in its recovery rate from 33.3 to 86.6% (increased by 160%). In addition, he marked a successive reduction in GHG emission from MSW management sector, i.e., 165 Tg CO₂e in 1990 to 124 Tg CO₂e in 2012. The study thus implies that decrease in waste generation with simultaneous increase in recycling rate could decrease the GHG releases from waste sector more efficiently.

A study conducted on waste-to-energy conversion technologies by [57] showed that landfill emissions of GHGs differ considerably by wastes' type. The study reported 65% reduction in GHGs from wood waste (i.e., from the amount of 2412 to 848 kg CO₂e t⁻¹ dry mass), while 4% reduction in emission from food waste (i.e., from the amount of 2708 to 2603 kg CO₂e t⁻¹ dry mass) [57]. However, LCA of

waste-to-energy recovery reveals that cumulative application of gas collection from landfills and power generation can reduce GHG emissions from food waste by 44% (i.e., from 2708 to 1524 kg CO₂e t⁻¹ dry mass) when compared with conventional landfilling of MSW [57].

6.3 GHG Emissions from MSW Management in India

Generation scenario of MSW in different states of India shows that Uttar Pradesh followed by Tamil Nadu, Maharashtra, Karnataka, and Delhi are the major contributors of generated MSW India. Ahluwalia and Patel [2] showed a trend of MSW generation in top five metropolitan cities as the highest in Delhi followed by Mumbai, Kolkata, Chennai, and Bengaluru in India (Table 5). In India, >60% of MSW constitutes organic material [8] (Fig. 7a). As per statistic 2014, MSW was majorly contributed by 51% biodegradable wastes, 10% plastics, 7% paper, and 32% other wastes such as textile, glass, metal, drain slit, street sweeping, and inert materials [70].

Annual report of 2016 from Municipal Corporation of different cities showed that door-to-door collection of wastes from households was facilitated in most of the cities in India and percentage of collected wastes varied from 25 to 100% depending upon the available resources [2] (Fig. 7b). While, more than 50% of waste segregation at source was expedited at Bengaluru and Mysuru of Karnataka, Pune of Maharashtra, Indore of Madhya Pradesh, Tirunelveli of Tamil Nadu, Alappuzha of Kerala, and Panaji of Goa. Installed capacity of compost plant in 20 states of India varied from 90 to 4,88,400 t year⁻¹ [17]. Furthermore, installed capacity of Biomethanation plants in Pune, Bengaluru, Solapur, and Chennai were 300, 250, 400, and 30 t day⁻¹ [2]. Capacity of refused derived fuel in various cities in India was varied from 200 to 500 t day⁻¹ [2]. Waste to energy recovery plants with capacity of 1300–2000, 1000–2400, 300, 600, and 70 t day⁻¹ were installed with electricity generation unit of 14–24, 11–20, 2.9, 9, and 1.75 MW in Delhi, Hyderabad, Chennai, Jabalpur, and Shimla [2]. Total number of known landfill sites in different cities of India varies from 1 to 3 [14], and the amount of wastes discarded to landfills by different states is illustrated in Table 5. Emanations of GHGs during the management of MSW in varying regions of India are detailed in Table 6 [31]. Ahluwalia and Patel [2] reported that the emissions of GHGs from landfill sites in Delhi, Mumbai, Chennai, Bengaluru, Pune, Indore, and Chandigarh were 643.7, 920.8, 535.3, 337.3, 74.9, 56.2, and 36.1 kt CO₂e day⁻¹, respectively.

Table 5 Total municipal solid waste generation in different states of India from 2011 to 2015

States	Solid waste generation (tonne day ⁻¹)				Wastes disposed to landfill (%)			
	2011	2013	2014	2015	2011	2013	2014	2015
Andaman & Nicobar	117	126	130	134	100	96	96	96
Andhra Pradesh	16,152	17,724	8,335	8,739	77	47	23	94
Arunachal Pradesh	116	128	134	141	100	42	100	100
Assam	944	1,021	1,061	1,101	92	90	100	82
Bihar	3,912	4,291	4,486	4,684	100	100	100	100
Chandigarh	441	476	494	512	32	47	49	51
Chhattisgarh	1,912	2,122	2,230	2,340	87	92	92	65
Dadra & Nagar Haveli	55	81	95	108	100	100	100	100
Daman & Diu	82	129	153	177	100	100	100	100
Delhi	10,013	10,808	11,215	11,629	81	62	71	72
Goa	526	576	602	629	100	68	70	71
Gujarat	8,178	8,981	9,393	9,813	89	85	72	74
Haryana	3,986	4,447	4,684	4,926	100	87	96	96
Himachal Pradesh	200	211	217	222	23	29	42	44
Jammu & Kashmir	1,953	2,146	2,245	2,346	84	85	86	100
Jharkhand	2,980	3,250	3,389	3,530	98	98	98	98
Karnataka	9,889	10,769	11,220	11,679	79	81	73	69
Kerala	7,696	9,346	10,197	11,066	77	95	96	96
Lakshadweep	16	19	21	23	74	100	100	100
Madhya Pradesh	7,251	7,810	8,096	8,387	87	90	100	100
Maharashtra	18,407	19,747	20,434	21,131	89	76	71	67
Manipur	170	190	200	210	99	100	100	100
Meghalaya	217	236	246	256	54	59	78	86
Mizoram	153	166	173	180	100	100	100	100
Nagaland	104	121	130	138	100	85	100	100
Odisha	2,706	2,921	3,032	3,144	99	99	100	99
Puducherry	540	588	613	638	100	100	100	98
Punjab	5,469	5,892	6,108	6,329	100	99	94	100
Rajasthan	7,135	7,734	8,040	8,352	100	94	94	94
Sikkim	73	98	110	124	56	100	100	100
Tamil Nadu	18,612	20,097	20,858	21,632	97	92	92	93
Telangana	NA	NA	7,511	7,862	NA	NA	60	60

(continued)

Table 5 (continued)

States	Solid waste generation (tonne day ⁻¹)				Wastes disposed to landfill (%)			
	2011	2013	2014	2015	2011	2013	2014	2015
Tripura	413	487	526	565	90	100	52	56
Uttar Pradesh	20,135	21,816	22,677	23,553	100	76	77	92
Uttarakhand	1,014	1,122	1,178	1,234	100	100	100	100
West Bengal	15,924	17,282	17,978	18,686	96	92	95	95

Source GHG Platform, India [31]

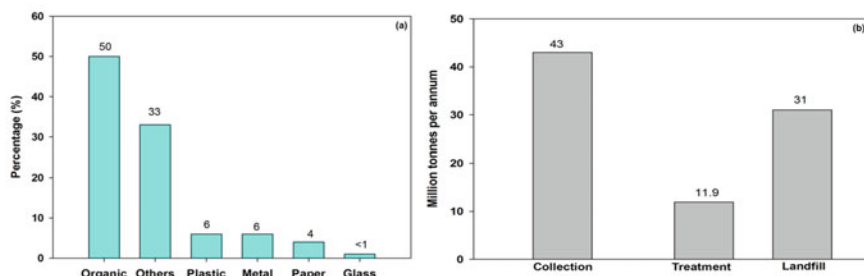


Fig. 7 Percentage contribution of organic and inorganic constituents in MSW generated from India and various treatment processes in the management of municipal solid waste (Source [8])

7 Ecological and Sociological Threats of GHG Emissions

The GHG emissions have far-ranging effects on the environment as well as socio-economic facets due to their global warming as well as climate change potential, which subsequently affect ecological balance, change the biodiversity pattern, cause atmospheric pollution, and affect plant's and animals' health.

7.1 Global Warming

The GHG gases, in particular CO₂, are the most important anthropogenic gas whose atmospheric concentration has increased since preindustrial era [91]. Global atmospheric concentration of CO₂ has increased from a 354.39 to 414 ppm in past 10 years with simultaneous increase in concentrations of CH₄ and N₂O, which absorb outgoing radiant energy, thereby causing a decadal increase in atmospheric temperature by 0.33°C thus causing “Global Warming” [84]. The 100-year time horizon global warming potential (GWP) of CO₂, CH₄, and N₂O is 1, 28, and 265, respectively [42]. It is an amount of the energy absorbed by the emissions of 1 tonne of

Table 6 Total greenhouse gas emissions (t CO₂e per year) from municipal solid waste management in different states of India from 2011 to 2015

States	2011	2012	2013	2014	2015
Andaman & Nicobar	7,852	8,243	8,631	9,018	9,404
Andhra Pradesh	10,25,723	10,80,031	11,36,206	11,16,290	9,78,483
Arunachal Pradesh	7,000	7,410	7,834	7,611	8,164
Assam	62,809	66,051	69,314	72,604	75,926
Bihar	2,32,070	2,38,824	2,46,591	2,55,249	2,64,696
Chandigarh	26,154	24,447	23,101	23,312	23,795
Chhattisgarh	98,367	1,05,937	1,13,576	1,21,295	1,29,107
Dadra & Nagar Haveli	2,950	3,311	3,808	4,424	5,144
Daman & Diu	2,991	3,309	3,795	4,429	5,192
Delhi	6,10,636	6,38,815	6,67,456	6,80,558	7,12,649
Goa	34,435	36,396	38,402	40,270	42,367
Gujarat	4,17,262	4,33,590	4,51,332	4,70,339	4,90,485
Haryana	2,24,434	2,36,735	2,49,829	2,63,645	2,78,120
Himachal Pradesh	14,598	13,301	12,234	11,607	11,729
Jammu & Kashmir	1,24,559	1,31,506	1,38,663	1,46,021	1,53,572
Jharkhand	1,44,498	1,54,315	1,64,055	1,73,754	1,83,445
Karnataka	6,35,002	6,67,723	7,01,152	7,35,280	7,70,099
Kerala	4,62,821	5,01,480	5,45,873	5,95,354	6,49,379
Lakshadweep	930	1,001	1,083	1,174	1,273
Madhya Pradesh	4,63,048	4,81,145	4,99,869	5,19,180	5,39,043
Maharashtra	11,65,966	12,17,766	12,69,926	13,22,524	13,75,627
Manipur	10,918	11,576	12,267	12,989	13,740
Meghalaya	14,506	14,596	14,775	15,248	16,330
Mizoram	9,909	10,423	10,943	11,471	12,006
Nagaland	6,440	6,928	7,458	8,026	8,630
Odisha	1,52,486	1,58,378	1,64,523	1,70,901	1,77,493
Puducherry	34,819	36,621	38,460	40,337	42,251
Punjab	3,51,000	3,67,654	3,84,449	4,01,409	4,18,552
Rajasthan	3,76,944	3,90,384	4,04,732	4,19,895	4,35,799
Sikkim	3,751	3,938	4,227	4,870	5,584
Tamil Nadu	10,86,464	11,32,475	11,79,835	12,28,477	12,78,343
Telangana	–	–	–	–	85,330
Tripura	22,849	24,503	26,365	28,413	28,956

(continued)

Table 6 (continued)

States	2011	2012	2013	2014	2015
Uttar Pradesh	11,25,600	11,68,378	12,13,518	12,60,806	13,10,060
Uttarakhand	54,898	59,177	63,464	67,771	72,106
West Bengal	9,01,414	9,37,633	9,75,680	10,15,397	10,56,653
Total GHG emission	99,16,101	103,73,999	108,53,428	112,59,950	116,69,533

Source GHG Platform, India [31]

a gas over a given period of time with respect to the emissions of 1 tonne of CO₂. The higher is the GWP more is the absorbance of energy by the gas [91]. Increased concentrations of GHGs increase the temperature of the atmosphere leading to the warming of the earth's surface [84].

7.2 Carbon Cycle

Carbon dioxide, CH₄, and N₂O gases undergo natural cycle [84]. For instance, exchange of CO₂ between the atmosphere and the earth's surface involves several processes like respiration, photosynthesis, decomposition, and combustion. Relatively, constant amount of CO₂ is essential to carry out balanced carbon cycling in natural environment; however, its increased concentration due to anthropogenic input is sufficient enough to disrupt natural cycling [84].

7.3 Climate Change

Increase in the concentrations of GHGs and temperature is leading to global change in climatic pattern change (appropriately referred as “forcing climate change”) to restore the balance between incoming and outgoing solar radiations. The forcing climate change is causing a change in cloud cover, wind speed, snowfall and rainfall pattern, sunshine hours and has also affected the normal weather pattern. Cumulatively, the change has knocked a drastic shift in climatic and weather pattern throughout the world [28, 66]. Forcing climate change has profound impacts on both terrestrial as well as aquatic ecosystems including world's oceans and their ecosystems.

7.4 Effects on the Aquatic Ecosystem

Studies have shown that since 1955, oceans have absorbed more than 80% of the heat [41]. Over the period of 1961–2003, the global average temperature of ocean

up to the depth of 700 m has risen by 0.10 °C [41]. In aquatic environment, many organisms thrive within their range of temperature tolerance and any increase in their surrounding temperature may have negative impact on their physiological functioning, metabolic activities, reproductive pattern, and their survival [38, 99]. Yanik and Aslan [99] reported that increase in sea temperature and ocean acidification is the primary cause of global extinction of many marine life forms (e.g., phytoplankton, zooplankton, plants, and animals) and coral bleaching. In 2016, 16 and 54% of corals were totally and partially bleached, respectively, due to rise in temperature and CO₂ emission [7].

Warming of the ocean causes expansion of water and the addition of water due to melting of ice on land contributes in sea level rise [41]. GHG emissions and climate change have led to significant rise in sea surface level from 2010 (54.5 mm) to 2020 (95 mm) [85]. Rise in sea surface level results in erosion, flooding and drowning of low-lying coastal areas, higher storm-surge flooding, and landward intrusion of seawater into estuaries and aquifers, which in turn lead to habitat destruction and biodiversity loss [3, 7].

7.5 Effects on the Terrestrial Ecosystem

Global warming and change in climatic pattern accredited to increased GHGs emissions and release of other harmful constituents such NH₃ and volatile organic compounds (VOCs) have potential impact on terrestrial ecosystems' functioning. Emission of harmful constituents such as VOCs and NH₃ from different stages of MSW management causes contamination of air, water, and soil. The GHG emissions affect the evapotranspiration, net carbon storage, biodiversity pattern, species composition, nutrient cycling, and soil dynamics [43]. Wetland and terrestrial plants are the largest carbon sinks. However, both are also vulnerable to climatic variation accredited to global warming effects. Increase in GHG concentrations in atmosphere is variably and invariably affecting the various components of a plant's carbon budget including photosynthesis, respiration, biomass accumulation as well as allocation, metabolic functioning, decomposition, growth and reproductive development [43, 63].

7.6 Socioeconomic Impacts of GHGs

The GHG emissions from intermediate processes and landfills are sources for several socioeconomic impacts like human health issues due to the exposure to noxious gases and to the ground/surface water contamination by leachates [44]. Even though advanced waste management systems in developed countries are well designed to reduce emissions but emissions from waste collection points and landfill sites are of high concern regarding the health of the rag pickers and workers near these sites

[15]. The exposure to emissions either through direct contact or inhalation and/or ingestion of contaminated food and water cause several disease such as heart-related ailments, respiratory problems, skin irritation, metabolic dysfunction, congenital malformations, nonchromosomal birth defects, reduced birth weight, premature child, improper growth of child and cancers of the lung, stomach, liver, bile ducts, cervix, and prostate [15].

Greenhouse gas emissions from waste management system are captivated with large proportion of economic implications. In high-income countries, operating costs from collection to final disposal of waste range between US\$ 100 and 170 t^{-1} , while in low to middle income countries, it varies US\$ 20 and 50 t^{-1} [78]. Global warming and climatic change due to enhanced GHGs have significant effects on agriculture, fisheries, horticulture, forestry, animal, and human health, which put enormous burden on global economy.

8 Mitigation Strategies in GHG Emissions During MSW Management

Existing practices of waste management can deliver effective mitigation of GHG emissions from waste sector. A wide range of established, sustainable, and environmentally sound technologies are available to curb GHGs emissions in conjugation with facilitation of cobenefits such as environmental protection, public health, and sustainable development. Cumulatively, these available technologies have the potentiality to directly shrink GHG emissions (through improved landfill practices, gas recovery from landfills, and tautly engineered wastewater management system) or evade significant generation of GHGs (through state-of-the-art incineration, meticulous composting of organic waste, and expanded waste collection area coverage). Furthermore, minimization of waste, reutilization, and recycling represent significant steps with huge potential toward indirect minimization of GHG emissions. This is further attributed to the conservation of raw materials, avoidance of fossil fuel and improved energy as well as resource efficiency. In many developed countries, especially Japan and the EU, waste management policies are closely related to and integrated with climate policies such as IPCC, EPA, and World Bank (Table 7).

8.1 5-R Principle

The principles of the internationally recognized 5-R hierarchy emphasize upon the resource value and future management of MSW [1, 88]. It plays a vital role in the reduction of GHG gases and lessens the burden on waste management system (Table 7). The hierarchy was set to manage the MSW at different levels:

- Reduction of wastes at source

Table 7 Management strategies to combat greenhouse gas (GHGs) emissions from municipal solid waste management and subsequent benefit to environment and socioeconomic facets

Policies and preventive measures	Minimization of GHGs	Environmental and Socio-economic benefit
Expanded sanitation coverage	NA	<ul style="list-style-type: none"> • Minimize unmanaged disposal of waste in rural and urban areas • Offers job to many people • Minimize the detrimental effects on environment and human health • Maximize material and energy recovery from wastes and economic acquisition
5Rs (Refuse, Reduce, Reuse, Repurpose, and Recycle)	CO ₂ , CH ₄ , and N ₂ O	<ul style="list-style-type: none"> • Reduction in use of raw materials, energy, and economic acquisition • Offers job creation for more people with implementation of health and safety provisions • Reduce the burden on waste management system and landfill sites
Prohibition on uncontrolled disposal and open burning of waste	CO ₂ , CH ₄ , and N ₂ O	<ul style="list-style-type: none"> • Inculcation of alternate low cost technological innovations • Minimize the detrimental effects on environment and human health • Inhibit pathogen growth and disease vectors
Use of natural gas in place of petrol or diesel-based vehicles and hand cart system	CO ₂ , CH ₄ , and N ₂ O	<ul style="list-style-type: none"> • Minimizes environmental pollution • Diminishes emission of fluorinated gases • Regulation economic incentive • Creates job opportunities

(continued)

Table 7 (continued)

Policies and preventive measures	Minimization of GHGs	Environmental and Socio-economic benefit
Efficient waste segregation	CO ₂ , CH ₄ , and N ₂ O	<ul style="list-style-type: none"> • Regulation economic incentive • Reduce the burden on waste management system and landfill sites
Reduction in biodegradable waste which is landfilled	CO ₂ , CH ₄ , and N ₂ O	<ul style="list-style-type: none"> • Prevent microbial decomposition of organic matter and subsequent emission of CH₄ and N₂O • Regulation economic incentive • Reduces foul smell
Aerobic biological treatment of wastes	CO ₂	<ul style="list-style-type: none"> • Although reduces CO₂ emissions but can emit N₂O and CH₄ under reduced aeration or anaerobic conditions • Reduces volume, stabilizes organic C, and destroys pathogens • Compost generation which can be used as fertilizer • Job creation • Foul odor reduction
Anaerobic biological treatment of wastes with energy recovery system	CH ₄ and N ₂ O	<ul style="list-style-type: none"> • Even though minimizes CO₂ generation but if not properly managed, leads to enormous CH₄ emission • CH₄ in biogas can be used as fuels for heat or electricity generation • Produce biosolid under controlled conditions • Job creation • Foul odor reduction • Job creation

(continued)

Table 7 (continued)

Policies and preventive measures	Minimization of GHGs	Environmental and Socio-economic benefit
Mandate in installation of incineration and thermal processing for waste-to-energy	CO ₂ , CH ₄ , and N ₂ O	<ul style="list-style-type: none"> • Reduce environmental pollution such as heavy metal contamination, atmospheric release of acid gases, dioxins and other noxious substituents • Potential odor reduction • Provide significant mitigation potential for the waste sector • Regulation economic incentive • Waste to energy recovery offers replacement of fossil fuels • Offers job creation for more people
Standards for combustion and landfill performance to harness gas with or without energy recovery	CH ₄ (predominant), N ₂ O, and CO ₂	<ul style="list-style-type: none"> • Regulation economic incentive • Waste to energy recovery reduce the burden of electricity generation and fuel combustion • Efficient and proper management of MSW with less adverse impact on environment and human health.

Sources Bogner et al. [5], Xin et al. [96], US EPA [92]

- Reutilization of wastes wherever possible
- Recycling of the end products toward their useful life
- Recovery of the energy or materials from the wastes
- Managing the residuals in an environmentally comprehensive way

8.2 Waste Segregation

Sorting of MSW into organic/biodegradable and nondegradable components at point source such as at domestic level are cooperative to their further segregation into biodegradable, combustible, recyclables, hazardous, infectious, and inert wastes. Segregation of wastes at waste facility center incurs energy, which in turn emits GHG gases to lesser extent but this step plays a substantial role in managing the waste at further levels and helps in minimizing CO₂, CH₄, and N₂O [5, 88]. The associated benefits of waste segregation in MSW management are stated in Table 7.

8.3 Improved Landfill Practices

In developing nations, mostly wastes are disposed of in an unscientific way after treatment, which lead to several environmental problems such as leaching, surface runoff, GHGs emissions, and ultimately affect the living beings. Developed nations such as the USA, Japan, European countries have scientifically engineered landfills for the disposal of wastes/residues. Sanitary landfill is protected with side and bottom liners where stabilized and unrecoverable waste is buried in layers following solid waste management guidelines [8]. The waste is compressed to save space and covered with an inert layer with vents for gases for recovery and a bottom drainage network to collect leachates.

From the waste sector, the major GHG emissions are landfill CH₄ and to lesser extent CO₂ and N₂O. There are primarily two key strategies to reduce CH₄ emission from landfill sites, i.e., reduction in the quantity of biodegradable waste and implementation of guidelines/standards/policies to reassure the retrieval of CH₄ from landfills. In the USA, Clean Air Act (CAA) and New Source Performance Standards (NSPS) are applied to landfill generation model to manage CH₄ emissions. Similarly, in European countries, there is a marked phase reduction in landfilled biodegradable wastes from 1995 to 2005 (by 50%) and 2016 (by 35%) following the European Union landfill directive (1999/31/EC) accompanied with collection and flaring of gases at landfill sites [5]. Recovery of gases and reduction in biodegradable components are beneficial to regulatory and economic incentives. Increased landfill taxes including landfilling cost in many countries of Europe have been implemented to combat the issue of high disposal at landfill sites [35]. Besides, an outreach program at regular time interval on landfill methane provides technical provision and resources to manage landfill gases. Being major source of GHG emissions, landfill CH₄ recovery

along with reduction in biodegradable wastes and economic as well as regulatory incentives are the most probable options to combat the issues of global warming as well as climate change (Table 7).

8.4 Controlled Composting and Anaerobic Digestion

Aerobic composting produces CO_2 and to lesser extent CH_4 and N_2O . Poorly managed composting such as wet compost in warm countries results in even higher generation of N_2O and CH_4 [35, 64]. A study conducted at the Griffith University of Queensland, Australia showed high generation of CH_4 from unmanaged household compost bins [35]. Therefore, organic wastes at home must be routinely composted in aerated chamber. Composting in controlled manner is thus essential to reduce CO_2 emission and anaerobic is better substitute to aerobic composting. This not only reduced biodegradable proportion of waste but in absence of oxygen is essential, which offers twin benefits such as generation of CH_4 , which can further be utilized as a source of energy and compost for organic farming. However, both anaerobic digestion and composting have their own advantages. Additional benefits of controlled composting are mentioned in Table 7.

8.5 Utilization of MSW Compost as Manure

Utilization of MSW compost as manure is receiving a greater attention due to less availability of land area for waste disposal, high waste management costs, and the associated environmental problems. Agricultural and horticultural utilization of MSW compost is one of the cost-operative and most promising options for MSW management [50, 83], which not only merely decreases the adverse effects of MSW on the society and environment but also supplements nutritive value to the land and plants. However, there are several studies that negate the agricultural application of MSW compost due to food chain contamination of heavy metals and faecal pathogens [79]. Gautam and Agrawal [26] exclaimed the utilization of MSW as compost for cultivation of oil yielding crops such as mustard, lemongrass, and vetiver to eliminate the food chain contamination of metals. The additional socioeconomic and environmental welfares of utilization of MSW compost at land application are illustrated in Table 7.

8.6 State-of-the-Art Incineration

Incineration is a thermal process under controlled condition of temperature and pressure to exploit the energy from postconsumer wastes. Incineration is a cost-incentive

process with emission control; therefore its application in most of the developing nations has been restricted because of less availability of resources to install the incineration facilities in MSW management system. There must be subsidies for installation of incinerators in developed countries combined with environmental standards for energy efficiencies [91]. Tax exemptions must be applied for electricity generation using incinerators and for energy recovery from wastes [35]. In many European countries, landfill taxes have been implemented to alleviate the cost of landfilling and financial allocation has been made for the installation of incinerators, combustion chambers, and mechanical biological treatment infrastructure [35].

8.7 Reclamation of Abandoned Dumpsites by Vegetation

Landfilling is the most ordinarily used technique in some developed and most developing nations to manage MSW. The disposal of MSW in landfills entails a number of environmental issues such as noxious gaseous emissions including GHGs, leachates and surface runoff carrying contaminants contaminating water and soil. These problems raise concerns about harmful impacts on human health and plants. Landfill dumpsite can interrupt the vegetation pattern of native species and create space for invasive as well as synanthropic plant species. Even though engineered techniques are available to manage waste disposal sites but reclamation by vegetation is the only long-term and sustainable approach to manage such dumpsites [27]. Reclamation of dumpsites not only improves soil properties through mycorrhizal symbiosis and improved soil enzymatic activities but also prevents leaching and surface runoff. Besides, green cover, it reduces emission of GHGs from the disposal site [76, 77].

9 Conclusions

The municipal solid waste (MSW) is mainly categorized into inorganic and organic components and its physico-chemical properties are prominently influenced by the geographical location, economic development, climatic condition, cultural norms, and energy sources. Management of MSW includes collection, transportation, segregation, material recycling, anaerobic digestion, composting, incineration, and landfill with energy-recovery system, wherein disposal at landfill sites is the most common practice of waste management in most of the developing nations. The emanation of greenhouse gases (CH_4 , CO_2 , and N_2O) associated with MSW management is the fourth largest contributor of GHGs in atmosphere accountable for global warming as well as climate change and causes adverse effects on socioeconomic and environmental facets. Life cycle assessment of MSW management reveals that landfill ($\text{CH}_4 > \text{CO}_2 > \text{N}_2\text{O}$) followed by anaerobic digestion ($\text{CH}_4 > \text{CO}_2 > \text{N}_2\text{O}$), composting ($\text{CO}_2 > \text{CH}_4 > \text{N}_2\text{O}$), incineration (CO_2), and transportation (CH_4 , CO_2 ,

and N₂O) are major contributors to GHG emissions. Since GHG emissions are an escalating problem with simultaneous increase in MSW generation; it necessitates an urgent action to combat the issue globally. Inculcation of 5R principle, expansion of waste collection area, waste segregation at source, advanced inculcation in waste management system, utilization of compost as manure, and reclamation of abandoned landfills by vegetation are the sustainable options to mitigate the global issue of GHG emissions. Besides, awareness, implementation of strict norms, regulations, and policies would be additives in regulating the problem.

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