CHAPTER 7
LIFE CYCLE ASSESSMENT OF MSW MANAGEMENT STRATEGIES IN TRICITY

7.1 Introduction

With a rapid increase in population of urban areas, the supervision of environmental and public health sector has been a major challenging task for municipal authorities. The management of MSW is one of the major challenges for Indian megacities [163, 195, 138, 194]. Dumping of MSW into open dumping sites is the most common method used for disposal of waste in most of the cities of India. These dumping sites are serious threats to environment and sustainable development. Therefore, it becomes vital to analyse the effect of MSW disposal at present and what would be the impact under integrated waste management scenarios [5, 195, 219, 220, 130]. Life Cycle Assessment (LCA) can be an important tool to reduce environmental impacts by identifying the most significant causes of these impacts.

LCA is a compilation and evaluation of the inputs, outputs and potential environmental impacts of a product or a system throughout its life cycle [104, 219, 221, 222]. The use of LCA had started in 1960’s for evaluation of the limitation of raw materials and energy use with the main focus primarily on the energy and resource requirement of the waste [28, 29, 189, 190, 200]. LCA is a useful environmental management tool which attempts to forecast the environmental aspects and potential impacts throughout a waste life, cradle to grave options within a system boundary [99, 169, 188, 173]. Different waste management systems and their various environmental effects can be evaluated using LCA models [22, 23, 134, 192, 220, 221]. LCA process is a systematic approach and consists of the following four major components: (a) goal and definition and scoping that define and describe the product, process or activities, (b) life cycle inventory analysis, (c) life cycle impact assessment and (d) interpretation of results. An explanation of these LCA terminologies is as given in Table 7.1. The methodology of LCA with its major components is represented in figure 7.1.
Table 7.1: Life Cycle Terminology

<table>
<thead>
<tr>
<th>Goal Definition and Scope</th>
</tr>
</thead>
<tbody>
<tr>
<td>This stage defines the purpose or objective of the study, system boundaries, unit processes and scope of assessment. The functional unit is defined in this stage. The Functional unit is defined as the unit of analysis to be studied and gives a basis for comparison if more than one system or product is being studied.</td>
</tr>
<tr>
<td>Life Cycle Inventory Analysis (LCI)</td>
</tr>
<tr>
<td>It is the method which accounts for all the inputs and outputs of the system over the life cycle. It includes the raw materials, energy inputs and emissions to environment in the form of air, water and as solid waste which describes the environmental burdens.</td>
</tr>
<tr>
<td>Life Cycle Impact Assessment (LCIA)</td>
</tr>
<tr>
<td>This stage deals with all the environmental issues caused due to the system viz., ozone depletion, acidification, eutrophication etc.</td>
</tr>
<tr>
<td>Life Cycle Interpretation</td>
</tr>
<tr>
<td>It evaluates the significance of inputs and outputs of the system cycle. This is the final stage of LCA which reviews all the stages in LCA.</td>
</tr>
</tbody>
</table>

Figure 7.1: Different phases of LCA

- product development and improvement
- Strategic planning
- Public policy making
- Marketing
The LCA can be used as a tool for assessing environment by comparing and analyzing the environmental impacts of MSW management systems [188, 191]. Hence, in the last decade a number of studies [51, 159, 192, 194, 195, 223] have used LCA as a comparative tool for MSW strategies. A study [224] conducted focused on LCA of MSW management of Kathmandu city, compared three different scenarios. The study carried out, determined the best suitable and sustainable MSW management scenario and concluded that scenario comprising of composting and landfilling gave the least environmental impacts. On the similar base, a study accomplished by [43] compared five different scenarios of MSW management as alternative to the current waste management practice in Turkey concluded that the scenario with a blend of recycling and composting is the most environmentally preferred alternative. Research investigated [223] the waste management system of Karaj city and it was concluded from the study that recycling and composting lessen the load of pollutants in the environment. Another research [225] stated that environmental assessment of MSW management scenarios would help to select the most eco-friendly scenarios. An inventory data for different scenarios was presented and it was revealed that the most eco-friendly scenario to be implemented in future would be a combination of anaerobic digestion and incineration.

A study compared [194] six different MSW management scenarios in Yogyakarta, Indonesia and concluded that a combination of gasification and anaerobic digestion is the best option with regard to the environmental impacts. Another research studied [195], five different MSW waste treatment scenarios. Scenario which was a combination of source separation and incineration was found environmental favorable among the rest of the options. This methodology is much in practice in other World countries; however, it is not much used for MSW management in India.

Technological options for MSW management in Delhi [226] were suggested through three different scenarios using LCA approach. It was concluded that sanitary landfilling with energy recovery is the best option to be utilized with respect to reduction in environmental impacts. Similarly, another study [51, 52] conducted in Delhi, evaluated the environmental emissions based on LCA methodology by examining different MSW management options, considering, recycling, composting, incineration and landfilling and also predicted quantity and composition of MSW of Delhi till the year 2024. The results indicate that recycling has least environmental impacts.
Researcher compared [192] six scenarios in Mumbai city, India, and found the recycling, composting and sanitary landfilling option superior to the other scenarios. Different studies have shown that the impact on environment vary from one city to another because of the different waste composition as well as different environmental conditions. Therefore, the choice of technology may not be the same for all cities.

There are numerous tools for conducting LCA or for supporting the different applications and phases in LCA. A number of LCA softwares or models have been developed for assessment of the products and processes involved, but mainly the models targeted for the waste management area being made in use [20]. For a good LCA to be performed understanding about the key parameters is essential. The key parameters include the formation of system boundaries and input data [28, 29,158, 191, 220,224, 130]. The models based on LCA include integrated waste management (IWM)-1 and 2, WARM, ORAWARE, WASTED, WIZARD, EASWASTE, SimaPro, Gabi, WRATE, MSW-DST etc. The most commonly and widely used software in the field of MSW nowadays is SimaPro software. This software usually treats the waste as a set of separate fractions and not as a whole mass, which gives it an edge over other used softwares. Other commonly used software for MSW LCA analysis is Gabi software but it faces certain drawbacks like the database need to be downloaded over again for every process and the available data base sets are decade old in comparison to SimaPro software.

Keeping in view the above, the present study analyses the impacts of different potential MSW management scenarios in Chandigarh, Mohali and Panchkula, respectively using the LCA methodology. Five MSW management scenarios, including the current MSW management system were analysed for each of the three cities. The sensitivity analysis of recycling rate has also been analyzed for Tricity in current waste management situation. The research results can help the decision makers evaluate strategies for the treatment of MSW from an environmental impact point of view. The impact categories analysed are global warming, acidification, eutrophication and human toxicity.

7.2 Materials and Methods

7.2.1 MSW management scenarios

In the current study, five scenarios were analysed reflecting different MSW management systems that could be potentially used for Chandigarh, Mohali and Panchkula, respectively as
shown in Table 7.2. Since, the scenarios are assumed not to influence MSW generation so same amount and composition of MSW are taken in all the scenarios.

**Scenario 1 (Baseline scenario):** Business as usual (BAU) corresponds to the current MSW management practice in Chandigarh, Mohali and Panchkula.

In Chandigarh, out of the total 380 tons per day of MSW generated, approximately 70% is directed to the refuse derived fuel (RDF) plant and rest 30% is dumped in open dumping (OD’s) sites. In Mohali and Panchkula, the total 150 tons per day waste generated is directly dumped in OD’s. Except for the BAU, all the scenarios assumed were same for Chandigarh, Mohali and Panchkula respectively.

**Scenario 2 (Material recovery facility_Sanitary Landfilling-MRF_SLF):** The scenario MRF_SLF will be the simplest approach in future for converting the open dumps into sanitary landfills. This scenario assumes that 20% of the recycled materials are recycled, while rest of the waste is sanitary landfilled (SLF). The recycling rate is based on the recycling rates as assumed at material recovery facilities study in Pune, India (Annepu, 2012). It was also assumed that sanitary landfill is equipped with energy recovery facility with 50% biogas released from the sanitary landfill is collected and then used for generation of electricity and rest would escape to the atmosphere.

**Scenario 3 (Material recovery facility_composting_sanitary landfill-MRF_COM_SLF):** This scenario explores the potential to reduce the environmental impacts of MSW by assuming that 20% of the recycled materials like glass, paper and plastics is recycled through MRF and rest 80% of the biodegradable is composted (COM) and the remaining fraction is sent for disposal into sanitary landfill.

**Scenario 4 (Material recovery facility_composting_anaerobic digestion_sanitary landfill-MRF_COM_AD_SLF):** This scenario assumes that along with 20% of the recycled material being recycled, 60% of the biodegradable waste is composted and 20% of the waste is anaerobically digested (AD). The remaining fraction of waste is sent to the sanitary landfill and biogas is used for electricity generation.

**Scenario 5 (Material recovery facility_composting_incineration-MRF_COM_INC):** Due to presence of high moisture content in waste, this scenario introduced the composting along with MRF and incineration. In this scenario 20% of the recycled materials are recycled and 40% of the biodegradable waste is composted while rest of the waste incinerated.
Table 7.2: Description of scenarios used in LCA of MSW for Tricity

<table>
<thead>
<tr>
<th>Scenario</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Scenario 1: Baseline scenario (BAU)</td>
<td>Business as usual represents the present MSW management practice in Tricity</td>
</tr>
<tr>
<td>Scenario 2: Material recovery facility_Sanitary Landfill (MRF_SLF)</td>
<td>20% recycling + rest of the waste to sanitary landfilling with 50% biogas collection and electricity production</td>
</tr>
<tr>
<td>Scenario 3: Material recovery facility_composting_sanitary landfill (MRF_COM_SLF)</td>
<td>20% recycling + 80% of the biodegradable waste is composted (COM) and remaining fraction is sent to disposal into sanitary landfill with 50% biogas collection and electricity production</td>
</tr>
<tr>
<td>Scenario 4: Material recovery facility_composting_anaerobic digestion_sanitary landfill (MRF_COM_AD_SLF)</td>
<td>20% recycling+60% composting +20% anaerobic digestion and rest sent to landfill with 50% biogas collection and electricity production</td>
</tr>
<tr>
<td>Scenario 5: Material recovery facility_composting_incineration (MRF_COM_INC)</td>
<td>20% recycled through MRF +40% composting and rest is sent to incineration with electricity production</td>
</tr>
</tbody>
</table>

7.2.2 Life Cycle Assessment (LCA)

LCA has been extensively used tool to evaluate solid waste management systems. In the present study, the methodological framework used the International Organization for Standardization (ISO) 14040:2006 methodology for LCA. As per ISO14040:2006 [226] , LCA consists of four phases: Goal and scope definition which defines the purpose of the study, Life cycle inventory which focuses on quantification of energy and mass, Life cycle impact assessment which aims at evaluating the significance of potential environmental impacts of a system, and interpretation of results which helps to reach the conclusion.

7.2.2.1 Goal and Scope Definition

In order to achieve environmental stability the MSW management scenarios were compared in an LCA context. The goal of the study is to assess the environmental impacts of the MSW management system in Chandigarh, Mohali and Panchkula, respectively using LCA methodology. Five scenarios of MSW management that include various treatment, processing and disposal methods were developed in the study and then compared with respect to the environmental burdens like global warming potential (GWP), eutrophication potential (EP),
acidification potential (AP) and human toxicity potential (HTP) for each of the three cities of Chandigarh, Mohali and Panchkula. The comparison among the scenarios was done using the MSW composition characteristics as described in Chapter 4.

7.2.2.2 Functional Unit

The functional unit for the comparison of MSW managements systems used in the present study is one ton of MSW in each of the three cities of Chandigarh, Mohali and Panchkula.

7.2.2.3 System Boundary

The system boundary of study starts with the collection of MSW, transportation of the waste to its treatment and final disposal. The system boundary makes the study easier, helps in comparing options and making decision easier [27, 28, 29, 191]. All the significant processes included within the boundary of the MSW management system are as shown in figure 7.2. MSW, energy and mass are the input to the MSW management system and all the outputs considered are air and water emissions, generation of compost, digestate and electricity from the processes. The system boundaries selected for the study include direct emissions viz., emissions associated with different MSW treatment facilities like recycling, sanitary landfilling, composting, anaerobic digestion, incineration and the indirect emissions like fuel requirement and supply of electricity.

![Figure 7.2: System boundary of MSW management system for Tricity](MRF: material recovery facility, MSW: municipal solid waste)
7.2.3 Life Cycle Inventory Analysis (LCI)

LCI denotes the compiling of a specific set of inputs and outputs related with a product or process [20,73,227]. It helps to predict the environmental performance. LCI is a phase of data collection related to all the inputs and outputs of the study. LCI aims at classifying and measuring the environmental interventions related to the study [194, 195]. The LCI data used in the present study was collected from on-site investigations, different references [20, 28, 29, 73, 226, 194, 195, 68,189, 190, 192, 121,219, 220, 222, 225, 228], data from the municipal authorities (population, waste generation, waste processing and transportation) in each respective city and the database Ecoinvent 2.2. Until now, no relevant life cycle inventory data bases are available and with addition to this a very little public data in regard with MSW management system are available. The attainment of adequate LCI data in the present study turned out to be very difficult due to absence of any data and research studies in the study area related to LCA. The data for energy consumption, input, resource recovery, emissions of pollutants to water and air were computed for all the scenarios. The major components of LCI are identified at each stage starting from MRF, composting, landfilling, thermal processes to final landfilling.

The input data’s are those that are derived from the non-renewable sources like fuel, which is required in transportation and management of waste. The direct and indirect emissions considered in the study were taken from various literatures, references and data base of SimaPro version 8.3.0, Eco-Indicator 99 (H) and Eco-Invent method and included the inputs from the recycling facilities, composting, sanitary landfilling, anaerobic digestion, incineration and supply of electricity and fuel requirement respectively. The inventories of resource use and by-products for various processes are as represented in Table 7.3.
Table 7.3: Life Cycle Inventories for Tricity

<table>
<thead>
<tr>
<th>Inputs</th>
<th>Value</th>
<th>Units</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Landfill</strong>a</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Diesel</td>
<td>3</td>
<td>Lt⁻¹</td>
</tr>
<tr>
<td>Net electrical efficiency</td>
<td>20</td>
<td>%</td>
</tr>
<tr>
<td><strong>Material Recovery Facility</strong>b</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Diesel</td>
<td>3.21</td>
<td>Lt⁻¹</td>
</tr>
<tr>
<td>Electricity</td>
<td>3.2</td>
<td>kWh t⁻¹</td>
</tr>
<tr>
<td><strong>Composting</strong>c</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Diesel</td>
<td>0.52</td>
<td>Lt⁻¹</td>
</tr>
<tr>
<td><strong>By-products</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Compost</td>
<td>130</td>
<td>Kgt⁻¹</td>
</tr>
<tr>
<td><strong>Anaerobic Digestion</strong>d</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Net Electrical Efficiency</td>
<td>20</td>
<td>%</td>
</tr>
<tr>
<td><strong>By-products</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Digestate</td>
<td>100</td>
<td>Kgt⁻¹</td>
</tr>
<tr>
<td><strong>Incineration</strong>e</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Net Electrical Efficiency</td>
<td>20</td>
<td>%</td>
</tr>
<tr>
<td><strong>By-products</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Ash</td>
<td>140.8</td>
<td>Kgt⁻¹</td>
</tr>
</tbody>
</table>

[a195, 192, 121; b222, 195; c51, 219; d73, 195; e194, 195, 194, 192]

The data used for the current study were population of the Tricity, waste characteristics, and rate of waste collection and data of dumping site. The MSW composition of Chandigarh, Mohali and Panchkula, respectively has been considered as given in Chapter 4 to check the influence of MSW composition on total environment profile of each scenario in each case for each city. Transportation of MSW to the disposal site is also included in the system boundary. Three different types of vehicles (tractor trolleys, dumpers and compactors) are used for transportation of MSW to the final disposal site in Tricity. The emissions from the transportation of waste from Chandigarh, Mohali and Panchkula, respectively were obtained from the database of SimaPro software version 8.3.0, Eco-Indicator 99 (H) and Eco-Invent method and literature and have been described in Table 7.4.
Table 7.4: Emissions from transportation of MSW in Chandigarh, Mohali and Panchkula

<table>
<thead>
<tr>
<th>Substances</th>
<th>Emissions (gt(^{-1}))</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>CHD</td>
</tr>
<tr>
<td>PM</td>
<td>115.86</td>
</tr>
<tr>
<td>CO(_2)</td>
<td>156.79</td>
</tr>
<tr>
<td>NO(_x)</td>
<td>103.21</td>
</tr>
</tbody>
</table>

In open dumping, the direct CO\(_2\) emission is of biogenic origins which were not considered for greenhouse gas (GHG) emissions. The emissions such as particulate matter (PM), nitrous oxide (N\(_2\)O), nitrogen oxides (NO\(_x\)), ammonia (NH\(_3\)), and sulphur oxides (SO\(_x\)) have been obtained from the database of SimaPro, literature [195, 228]. The emissions to water in the form of total nitrogen (N) and phosphorous (P), chromium (Cr), cadmium (Cd), arsenic (As), copper (Cu), lead (Pb), zinc (Zn), mercury (Hg) and nickel (Ni) were attained from previous studies [188, 192, 195] and the data base of the SimaPro software version 8.3.0, Eco-Indicator 99 (H) and Eco-Invent method. The inventory data of the environmental emissions from the production of 1MJ of electricity and production of mineral fertilizer (SimaPro version 8.3.0, 222, 225) are as shown in Table 7.5 and 7.6.

Table 7.5: Environmental emissions resulting from production of 1MJ of electricity (Indian Grid and 1 Liter (L) of Diesel)

<table>
<thead>
<tr>
<th></th>
<th>Electricity grid mix (Indian grid) (MJ)</th>
<th>Diesel (L)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Global warming potential (GWP)</td>
<td>0.281</td>
<td>0.374</td>
</tr>
<tr>
<td>Acidification potential (AP)</td>
<td>0.00289</td>
<td>0.00176</td>
</tr>
<tr>
<td>Eutrophication potential (EP)</td>
<td>0.000212</td>
<td>0.000182</td>
</tr>
<tr>
<td>Human toxicity potential (HTP)</td>
<td>0.10</td>
<td>0.05</td>
</tr>
</tbody>
</table>

[SimaPro software version 8.3.0 database, 2015, 225]

Table 7.6: Environmental Emissions from production of mineral fertilizers

<table>
<thead>
<tr>
<th>Mineral Fertilizer</th>
<th>Global warming potential (GWP) kgCO(_2) eq kg(^{-1})</th>
<th>Acidification potential (AP) kgSO(_2) eq kg(^{-1})</th>
<th>Eutrophication potential (EP) kgPO(_4^{3-}) kg(^{-1})</th>
<th>Human toxicity potential (HTP) Kg1, 4-DB eq kg(^{-1})</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nitrogen</td>
<td>4.7</td>
<td>0.0376</td>
<td>0.0202</td>
<td>0.0188</td>
</tr>
<tr>
<td>Potassium</td>
<td>0.2</td>
<td>0.0412</td>
<td>0.0319</td>
<td>0.042</td>
</tr>
<tr>
<td>Phosphorous</td>
<td>0.09</td>
<td>1.89E-3</td>
<td>1.1E-3</td>
<td>0.031</td>
</tr>
</tbody>
</table>

[SimaPro software version 8.3.0 database, 2015; 225]
For sanitary landfilling, the data used for estimation of gases, transportation and production of electricity has been obtained from various literatures [129, 158, 222, 225, 194, 192, 195, 73] and the data base of SimaPro version 8.3.0, Eco-Indicator 99 (H) and Eco-Invent method.

The emissions processes and estimation from composting and anaerobic digestion were based on the studies as described in literature [3, 6, 104, 121, 158, 227, 192, 225] and SimaPro version 8.3.0 database and Eco-Indicator 99 (H) method.

7.2.4 Life Cycle Impact Assessment (LCIA)

LCIA is the phase of LCA which intends at understanding and associating the inputs and outputs with particular environmental issues. It is composed of several mandatory elements that convert the LCI result to indicator result. So far at present, necessary information in order to perform LCIA and scientific methods for long term assessment does not exist. The important elements of LCIA are: classification and selection of impact categories (selected on the basis of goal and scope of study), characterization (assigning of impact indicators), normalization and weighting (converting indicator results to impact categories).

In the present study, the emissions accounted for inventory stages have been allocated into four impact categories: global warming, acidification, eutrophication and human toxicity. As per the basic model for LCA (ISO 14040:2006) [226], the impact categories and indicators considered are as follows:

- **Global warming potential (kg CO₂ eq t⁻¹)** - In LCA methodologies, the greenhouse effect is quantified by using global warming potential for substances having the same effect as CO₂ in reflection of heat radiations. It is generally expressed as CO₂ equivalents. The global warming potential of a product or process can be estimated by calculating the amount of greenhouse gases emitted per functional unit.

- **Acidification potential (kg SO₂eq t⁻¹)** - The primary contributors to acidification are oxides of nitrogen, sulfur and ammonia. Acidification potential is quantified by using the acidification of substances having same effect as SO₂ in reflection of acidification. It is expressed as SO₂ equivalents i.e., potentials relative to SO₂.

- **Eutrophication potential (kg PO₄³⁻ eq t⁻¹)** – Eutrophication or nutrient enrichment leads to oxygen depletion. Major contribution to the impact category is from nitrogen and phosphorous. Mostly the loading of nitrogen and phosphorous is due to the discharge from the municipal or sewage and agriculture. The total eutrophication potential expresses the emissions from a substance as an equivalent emission of the reference substance PO₄³⁻.
- **Human toxicity potential (kg 1,4-DB eq t⁻¹)**—In context of LCA, the human toxicity covers many effects like acute toxicity, corrosive effects, allergenic effects, irritation effects, carcinogenic effects, genotoxic effects, irreversible damage, organ damage, toxicity to reproductive system and neurological disorders in a single parameter. The equivalence factors are quantified for emissions to different sections as: air emissions, water emissions and soil emissions and exposure via various mediums like air, water and soil.

The LCIA was constructed for the study using SimaPro software version 8.3.0 and expressed with the Eco-indicator 99 (H) method. Eco-indicator 99 method is a multi-step aggregating method which helps in leading result of a single number [194] and helps in making the comparison between different MSW management scenarios.

### 7.2.5 Life Cycle Interpretation

This is the final stage of LCA that includes the reviewing of all the stages during LCA. All the data was analysed and the findings were combined with the defined goal and scope of the study.

**Review of LCA software used for MSW management in Tricity**

There are many examples of the software tools used to support LCA assessments. The programs like SimaPro, Gabi, Integrated waste management models (IWM-1, 2), environmental assessment of solid waste systems and technologies (EASEWASTE), waste resources assessment too, for environment (WRATE), waste-integrated systems for assessment of recovery and disposal (WISARD) and organic waste research (ORWARE) to name a few have been used to evaluate existing as well as model new waste management systems.

In the present study, SimaPro software packages were used. SimaPro was developed by PRé Consultants with a goal of making more fact based studies. SimaPro software version 8.3.0 (PRé Consultants 2015) is a professional tool which helps in monitoring the sustainability performance of a product or process. It was developed for an integrated waste management, life cycle analysis, carbon and water foot printing, product design, generating environmental product declarations, determining key performance indicators and sustainability reporting. The MSW stream in its life cycle is followed in this software. SimaPro database is structured in three main parts: project data, library data and general data. It develops the complex life cycles hence saving lot of time. Each of the stages in the life cycle of MSW management
scenarios is represented and stored in the software: goal and scope definition, data quality profile, process data, product storage data, impact assessment methods and data on results interpretation. SimaPro software is fully compliant with ISO 14040/14044 providing complete LCI and LCIA capabilities. A life cycle of a product or process is modeled as a collection of assemblies (collection of waste, substances, chemicals, processes and materials), processes, and waste, treatment and disposal scenarios. Multiple libraries of databases are available in the software containing predefined materials, substances, processes, wastetreatments for products and various impact assessment methodologies which can be used for formation of a model for a particular study. The data entry in the software is done in following steps:

1) Inspect goal and scope
2) Inspect the processes in database
3) Analyze the environmental profile of a product or process
4) Generation of process network
5) Analyzing full life cycle
6) Comparing products or processes in production stage
7) Compare life cycles
8) Perform sensitivity analysis
9) Inspect of select the method
10) Inspect the interpretation section

The input information related to the composition of MSW from Tricity was entered in the SimaPro software version 8.3.0. On the basis of the data entered, the software calculated emissions based on various scenarios making use of Eco-indicator 99 method and Ecoinvent database and various literatures.

7.2.6 Sensitivity Analysis to Recycling Rates

The sensitivity analysis is used to check the strength of LCI stage with the main aim to identify how the final results are influenced by uncertainties in the data and to calculate the results of LCA in order to assess its reliability [194, 192]. The sensitivity analysis identifies sensitive parameters and assess whether a small change in an input parameter would induce a large change in the impact category. For sensitivity analysis, firstly the identification of the main assumptions are made and then calculation of the results along with confirmation of whether the conclusion changes is performed.
In the present study, input parameters for sensitivity analysis focus on the recycling rate. Recycling is the important parameter in MSW management as resource recovery and reduction of waste can be obtained efficiently through recycling. In regard with the resource recovery, the recycling represents the opportunities for increasing the utilization of materials and thus reducing the need for production of virgin materials. Studies [71, 75, 219, 194, 195, 192] have shown that the economic impact of recycling includes an evaluation of current recyclable market value of materials and market trends. The results concluded that most economic and environmental friendly recycling rate is 50%. The environmental implications of recycling depend upon the substance being recycled and for what purpose. For the present study, the materials considered for the recycling are paper, plastics, glass, metals, leather and textiles and the total amount of these recyclable materials for MSW composition for Chandigarh, Mohali and Panchkula are 15%, 13% and 14% respectively. The impact of the different recycling rates of 10%, 50% and 90% on each scenario was analysed.

7.3 Results and Discussion

7.3.1 Quantification of Environmental Impacts

SimaPro software version 8.3.0 was run for each of the scenario for Chandigarh, Mohali and Panchkula based on the data collected at the inventory analysis stage. The environmental emissions under different scenarios for Chandigarh, Mohali and Panchkula are presented in Table 7.7, 7.8 and 7.9 respectively. The emissions considered are GHG’s (CO$_2$, CH$_4$ and N$_2$O), particulate matter (PM), acidic gases (SO$_x$, NO$_x$ and NH$_3$), total nitrogen (N) and phosphorous (P), dioxins, cadmium, copper, lead, nickel, chromium, arsenic, zinc and mercury in both water and air emissions.

One of the main goals of the waste disposal system is to minimize the stream of waste entering the landfills. When the MSW is directly sent to the landfill, without giving any prior treatment, it undergoes anaerobic decomposition leading to release of high amount of gases like methane, nitrous oxides, nitrogen oxides, carbon monoxide and carbon dioxide. The biodegradable fraction in MSW also releases large amount of nitrogenous and phosphorous compounds. They all contribute towards the global warming, acidification, eutrophication and human toxicity. The ratio of the landfilled waste to the waste generated act as an indicator of the efficiency of the waste disposal system. The results of global warming potential (GWP), acidification potential (AP), eutrophication potential (EP) and human toxicity potential (HTP) for Chandigarh, Mohali and Panchkula, respectively are displayed in
The results of all the environmental impacts are symbolized as (a) for Chandigarh, (b) for Mohali and (c) for Panchkula respectively.

Table 7.7: Emissions under each scenario for Chandigarh

<table>
<thead>
<tr>
<th>Scenario</th>
<th>OD(BAU)</th>
<th>MRF_COM_SLF</th>
<th>MRF_SLF</th>
<th>MRF_COM_INC</th>
<th>MRF_COM_AD_SLF</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Emissions to air</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Carbon dioxide, fossil (kg)</td>
<td>71.63</td>
<td>4.40</td>
<td>9.90</td>
<td>44.22</td>
<td>5.58</td>
</tr>
<tr>
<td>Methane (kg)</td>
<td>0.19</td>
<td>0.03</td>
<td>0.01</td>
<td>0.10</td>
<td>0.02</td>
</tr>
<tr>
<td>Nitrogen oxides (kg)</td>
<td>0.79</td>
<td>0.15</td>
<td>0.48</td>
<td>1.01</td>
<td>0.27</td>
</tr>
<tr>
<td>Ammonia (g)</td>
<td>0.26</td>
<td>0</td>
<td>0</td>
<td>0.01</td>
<td>0</td>
</tr>
<tr>
<td>Sulfur dioxide (kg)</td>
<td>0.24</td>
<td>0.08</td>
<td>0.48</td>
<td>0.95</td>
<td>0.19</td>
</tr>
<tr>
<td>Arsenic (µg)</td>
<td>13.69</td>
<td>2.07</td>
<td>1.65</td>
<td>7.52</td>
<td>1.53</td>
</tr>
<tr>
<td>Cadmium (µg)</td>
<td>1.89</td>
<td>0.66</td>
<td>0.73</td>
<td>1.36</td>
<td>0.55</td>
</tr>
<tr>
<td>Chromium (µg)</td>
<td>1.19</td>
<td>0.04</td>
<td>0.01</td>
<td>0.48</td>
<td>0.02</td>
</tr>
<tr>
<td>Copper (mg)</td>
<td>99.42</td>
<td>15.83</td>
<td>25.77</td>
<td>66.90</td>
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<td>Dioxins (µg)</td>
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<td>5.62</td>
<td>8.63</td>
<td>30.14</td>
<td>5.78</td>
</tr>
<tr>
<td>Zinc (mg)</td>
<td>97.45</td>
<td>15.72</td>
<td>22.43</td>
<td>142.95</td>
<td>14.66</td>
</tr>
<tr>
<td>Lead (mg)</td>
<td>130.13</td>
<td>10.41</td>
<td>9.18</td>
<td>77.74</td>
<td>8.05</td>
</tr>
<tr>
<td>Mercury (mg)</td>
<td>3.63</td>
<td>0.30</td>
<td>0.20</td>
<td>5.81</td>
<td>0.28</td>
</tr>
<tr>
<td>Particulate Matter, &lt; 2.5µm (µg)</td>
<td>90.18</td>
<td>7.11</td>
<td>16.96</td>
<td>41.33</td>
<td>6.36</td>
</tr>
<tr>
<td>Carbon dioxide, biogenic (kg)</td>
<td>1.76</td>
<td>1.47</td>
<td>1.84</td>
<td>1.32</td>
<td>0.96</td>
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<tr>
<td><strong>Emissions to water</strong></td>
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<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total Nitrogen (kg)</td>
<td>0.35768</td>
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<td>0.30547</td>
<td>0.57081</td>
<td>0.39441</td>
</tr>
<tr>
<td>Total Phosphorous (kg)</td>
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<td>0.03141</td>
<td>0.13011</td>
<td>0.04727</td>
</tr>
<tr>
<td>Arsenic (µg)</td>
<td>73.58</td>
<td>15.82</td>
<td>22.30</td>
<td>165.23</td>
<td>12.68</td>
</tr>
<tr>
<td>Cadmium (µg)</td>
<td>20.24</td>
<td>7.36</td>
<td>7.45</td>
<td>78.24</td>
<td>5.68</td>
</tr>
<tr>
<td>Chromium (µg)</td>
<td>10.28</td>
<td>0.56</td>
<td>1.79</td>
<td>7.71</td>
<td>0.93</td>
</tr>
<tr>
<td>Copper (µg)</td>
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<td>0.03</td>
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<td>0.21</td>
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<tr>
<td>Lead (µg)</td>
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<td>23.80</td>
<td>8.38</td>
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<tr>
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<tr>
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<td>0.21</td>
</tr>
<tr>
<td>Zinc (µg)</td>
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<td>0.75</td>
<td>4.83</td>
<td>0.48</td>
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<tr>
<td>Scenario</td>
<td>OD(BAU)</td>
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<td>MRF_SLF</td>
<td>MRF_COM_INC</td>
<td>MRF_COM_AD_SLF</td>
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<td><strong>Emissions to air</strong></td>
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<tr>
<td>Carbon dioxide, fossil (kg)</td>
<td>71.63</td>
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<tr>
<td>Nitrogen oxides (g)</td>
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<td>26.04</td>
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<td>3.02</td>
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<tr>
<td>Ammonia (g)</td>
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<td>50.37</td>
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<td>63.31</td>
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<tr>
<td>Sulfur dioxide (g)</td>
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<td>48.05</td>
<td>46.76</td>
<td>137.40</td>
<td>61.29</td>
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<tr>
<td>Arsenic (µg)</td>
<td>126.89</td>
<td>43.66</td>
<td>45.73</td>
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<td>59.55</td>
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<tr>
<td>Cadmium (µg)</td>
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<td>45.01</td>
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<td>58.02</td>
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<tr>
<td>Chromium (µg)</td>
<td>124.42</td>
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<td>44.77</td>
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<td>Nickel (mg)</td>
<td>120.13</td>
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<td>42.18</td>
<td>129.74</td>
<td>54.05</td>
</tr>
<tr>
<td>Zinc (mg)</td>
<td>119.45</td>
<td>22.72</td>
<td>40.43</td>
<td>127.95</td>
<td>52.66</td>
</tr>
<tr>
<td>Lead (mg)</td>
<td>119.45</td>
<td>22.72</td>
<td>40.43</td>
<td>127.95</td>
<td>52.66</td>
</tr>
<tr>
<td>Mercury (mg)</td>
<td>121.39</td>
<td>30.62</td>
<td>42.63</td>
<td>130.14</td>
<td>55.78</td>
</tr>
<tr>
<td>Particulate Matter, &lt; 2.5µm (µg)</td>
<td>90.18</td>
<td>7.11</td>
<td>16.96</td>
<td>41.33</td>
<td>6.36</td>
</tr>
<tr>
<td>Carbon dioxide, biogenic (g)</td>
<td>1.76</td>
<td>1.47</td>
<td>1.84</td>
<td>1.32</td>
<td>0.96</td>
</tr>
<tr>
<td><strong>Emissions to water</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total Nitrogen (kg)</td>
<td>0.35768</td>
<td>0.09527</td>
<td>0.30547</td>
<td>0.57081</td>
<td>0.39441</td>
</tr>
<tr>
<td>Total Phosphorous (kg)</td>
<td>0.20548</td>
<td>0.01314</td>
<td>0.03141</td>
<td>0.13011</td>
<td>0.04727</td>
</tr>
<tr>
<td>Arsenic (µg)</td>
<td>73.58</td>
<td>15.82</td>
<td>22.30</td>
<td>165.23</td>
<td>12.68</td>
</tr>
<tr>
<td>Cadmium (µg)</td>
<td>20.24</td>
<td>7.36</td>
<td>7.45</td>
<td>78.24</td>
<td>5.68</td>
</tr>
<tr>
<td>Chromium (µg)</td>
<td>10.28</td>
<td>0.56</td>
<td>1.79</td>
<td>7.71</td>
<td>0.93</td>
</tr>
<tr>
<td>Copper (µg)</td>
<td>1.40</td>
<td>0.31</td>
<td>0.03</td>
<td>2.21</td>
<td>0.21</td>
</tr>
<tr>
<td>Lead (µg)</td>
<td>8.21</td>
<td>23.80</td>
<td>8.38</td>
<td>123.71</td>
<td>15.73</td>
</tr>
<tr>
<td>Mercury (µg)</td>
<td>7.06</td>
<td>0.40</td>
<td>1.28</td>
<td>4.91</td>
<td>0.35</td>
</tr>
<tr>
<td>Nickel (µg)</td>
<td>7.35</td>
<td>0.30</td>
<td>0.49</td>
<td>3.88</td>
<td>0.21</td>
</tr>
<tr>
<td>Zinc (µg)</td>
<td>1.40</td>
<td>0.55</td>
<td>0.75</td>
<td>4.83</td>
<td>0.48</td>
</tr>
</tbody>
</table>
Table 7.9: Emissions under each scenario for Panchkula

<table>
<thead>
<tr>
<th>Scenario</th>
<th>OD(BAU)</th>
<th>MRF_COM_SLF</th>
<th>MRF_SLF</th>
<th>MRF_COM_INC</th>
<th>MRF_COM_AD_SLF</th>
</tr>
</thead>
<tbody>
<tr>
<td>Emissions to air</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Carbon dioxide, fossil (kg)</td>
<td>716.37</td>
<td>440.01</td>
<td>390.90</td>
<td>442.28</td>
<td>550.81</td>
</tr>
<tr>
<td>Methane (g)</td>
<td>710.98</td>
<td>410.35</td>
<td>350.12</td>
<td>432.08</td>
<td>535.22</td>
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<tr>
<td>Nitrogen oxides (g)</td>
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<td>390.25</td>
<td>300.74</td>
<td>411.60</td>
<td>505.38</td>
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<tr>
<td>Ammonia (kg)</td>
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<td>0.50</td>
<td>1.91</td>
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<tr>
<td>Sulfur dioxide (g)</td>
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<td>0.08</td>
<td>0.48</td>
<td>1.55</td>
<td>0.39</td>
</tr>
<tr>
<td>Arsenic (µg)</td>
<td>98.69</td>
<td>14.07</td>
<td>47.65</td>
<td>139.52</td>
<td>17.53</td>
</tr>
<tr>
<td>Cadmium (µg)</td>
<td>93.89</td>
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<td>47.73</td>
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<td>16.55</td>
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<td>Chromium (µg)</td>
<td>91.19</td>
<td>13.04</td>
<td>47.01</td>
<td>135.48</td>
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<td>Copper (mg)</td>
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<td>12.83</td>
<td>46.77</td>
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<tr>
<td>Zinc (mg)</td>
<td>79.45</td>
<td>9.72</td>
<td>43.43</td>
<td>123.95</td>
<td>13.66</td>
</tr>
<tr>
<td>Lead (mg)</td>
<td>85.13</td>
<td>11.41</td>
<td>45.18</td>
<td>131.74</td>
<td>15.05</td>
</tr>
<tr>
<td>Mercury (mg)</td>
<td>83.63</td>
<td>11.30</td>
<td>44.20</td>
<td>128.81</td>
<td>14.28</td>
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<tr>
<td>Particulate Matter, &lt; 2.5µm (µg)</td>
<td>7.11</td>
<td>90.18</td>
<td>16.96</td>
<td>41.33</td>
<td>6.36</td>
</tr>
<tr>
<td>Carbon dioxide, biogenic (kg)</td>
<td>5.79</td>
<td>0.40</td>
<td>0.85</td>
<td>1.01</td>
<td>0.32</td>
</tr>
<tr>
<td>Emissions to water</td>
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<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total Nitrogen (kg)</td>
<td>0.35768</td>
<td>0.09527</td>
<td>0.30547</td>
<td>0.57081</td>
<td>0.39441</td>
</tr>
<tr>
<td>Total Phosphorous (kg)</td>
<td>0.20548</td>
<td>0.0131</td>
<td>0.03141</td>
<td>0.13011</td>
<td>0.04727</td>
</tr>
<tr>
<td>Arsenic (µg)</td>
<td>73.58</td>
<td>15.82</td>
<td>22.30</td>
<td>165.23</td>
<td>12.68</td>
</tr>
<tr>
<td>Cadmium (µg)</td>
<td>20.24</td>
<td>7.36</td>
<td>7.45</td>
<td>78.24</td>
<td>5.68</td>
</tr>
<tr>
<td>Chromium (µg)</td>
<td>10.28</td>
<td>0.56</td>
<td>1.79</td>
<td>7.71</td>
<td>0.93</td>
</tr>
<tr>
<td>Copper (µg)</td>
<td>1.40</td>
<td>0.31</td>
<td>0.03</td>
<td>2.21</td>
<td>0.21</td>
</tr>
<tr>
<td>Lead (µg)</td>
<td>8.21</td>
<td>23.80</td>
<td>8.38</td>
<td>123.71</td>
<td>15.73</td>
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<tr>
<td>Mercury (µg)</td>
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<tr>
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<td>0.30</td>
<td>0.49</td>
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<td>0.21</td>
</tr>
<tr>
<td>Zinc (µg)</td>
<td>1.40</td>
<td>0.55</td>
<td>0.75</td>
<td>4.83</td>
<td>0.48</td>
</tr>
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</table>
Global Warming Potential (GWP)

*Figure 7.3* represents the global warming potential for different scenarios assessed for Chandigarh, Mohali and Panchkula, respectively. The baseline (BAU) scenario for all the three cities have found to be contributing maximum green-house gas (GHG) emissions (CHD-75.63 kg CO$_2$ eq t$^{-1}$; MOH- 73.10 kg CO$_2$ eq t$^{-1}$ and PKL- 731.89 kg CO$_2$ eq t$^{-1}$) which is owed to the high emission of methane generation along with other anthropogenic gases and biogenic and fossil carbon dioxide. The biogenic carbon dioxide contributes lesser to greenhouse gas emissions as they are a part of carbon cycle. It can be comprehended from the figures that open dumping scenario (BAU) in all the three cities is producing greenhouse gases seven more than the assumed incineration scenario as in incineration the greenhouse gases emerge due to burning of fossil or anthropogenic carbon dioxide from plastics, textiles or leather which tends to generate lesser methane as compared to the ones generating from open dumping sites.

BAU was followed by scenario 5: MRF_COM_INC having GHG emissions (CHD- 46.32 kg CO$_2$ eq t$^{-1}$; MOH- 45.12 kg CO$_2$ eq t$^{-1}$ and PKL- 451.35 kg CO$_2$ eq t$^{-1}$).

Scenario 3: MRF_COM_SLF produces the least GHG emissions (CHD- 5.03 kg CO$_2$ eq t$^{-1}$; MOH- 4.45 kg CO$_2$ eq t$^{-1}$ and PKL- 59.62 kg CO$_2$ eq t$^{-1}$) as due to the benefits generated from the process of composting the biological processes leads to removal of methane from the global warming potential.

This Scenario was followed by scenario 2: MRF_SLF (CHD- 10.40 kg CO$_2$ eq t$^{-1}$; MOH- 9.97 kg CO$_2$ eq t$^{-1}$ and PKL- 58.77 kg CO$_2$ eq t$^{-1}$) and scenario 4: MRF-COM AD_SLF (CHD- 5.87 kg CO$_2$ eq t$^{-1}$; MOH- 5.63 kg CO$_2$ eq t$^{-1}$ and PKL- 83.43 kg CO$_2$ eq t$^{-1}$).
Figure 7.3: Global warming potential under different scenarios for (a) Chandigarh, (b) Mohali and (c) Panchkula.
Acidification Potential (AP)

Figure 7.4 represents the acidification potential (AP) for each scenario in Chandigarh, Mohali and Panchkula, respectively. Acidification is an environmental problem mainly caused due to SO$_x$, NO$_x$ and NH$_3$ gases and is expressed as kg SO$_2$ eq t$^{-1}$. Acidification increases the leaching and mobilization of metals and causes adverse impacts on environment.

The maximum acidification impacts were detected in scenario 5: MRF_COM_INC (CHD- 1.989 kg SO$_2$ eq t$^{-1}$; MOH- 1.98 kg SO$_2$ eq t$^{-1}$ and PKL- 1.95 kg SO$_2$ eq t$^{-1}$). As in incineration process due to the combustion of MSW, most of the sulfur and nitrogen compounds present in MSW get converted to SO$_x$ and NO$_x$ gases which in turn lead to high acidification. Major contribution is from NO$_x$ emission due to the presence of mineral fertilizers and characteristic properties of MSW.

This was followed by scenario BAU (CHD- 1.30 kg SO$_2$ eq t$^{-1}$; MOH- 1.066 kg SO$_2$ eq t$^{-1}$ and PKL- 1.12 kg SO$_2$ eq t$^{-1}$) as mixed MSW is dumped in the open dumping sites of all the three cities, moreover due to absence of any facilities for the resource recovery causes more environmental impacts. Leachate generated in the open dumping sites with the production of harmful gas like hydrogen sulfide(H$_2$S) also act as a contributor to the acidification potential.

These were followed by Scenario 2: MRF_SLF (CHD-0.980 kg SO$_2$ eq t$^{-1}$; MOH- 0.980 kg SO$_2$ eq t$^{-1}$ and PKL- 0.91 kg SO$_2$ eq t$^{-1}$) and scenario 4: MRF_COM_AD_SLF (CHD- 0.46 kg SO$_2$ eq t$^{-1}$; MOH-0.46 kg SO$_2$ eq t$^{-1}$ and PKL- 0.5 kg SO$_2$ eq t$^{-1}$).

Least acidification environmental impacts were observed in scenario 3:MRF_COM_SLF (CHD- 0.17 kg SO$_2$ eq t$^{-1}$, MOH- 0.28 kg SO$_2$ eq t$^{-1}$ and PKL- 0.19 kg SO$_2$ eq t$^{-1}$) due to the environmental benefits by a combination of composting and material recovery. The compounds of sulfur and nitrogen get oxidized in the lesser amount resulting in lower emissions of SO$_x$ and NO$_x$ gases.
Figure 7.4: Acidification potential under different scenarios for (a) Chandigarh, (b) Mohali and (c) Panchkula
Eutrophication Potential (EP)

Eutrophication is the phenomenon of excess loading of nutrients due to waste, chemical fertilizers, discharged waste water, which triggers the algal growth. It is expressed as kg PO$_4^{3-}$ eq t$^{-1}$. Nitrogen and phosphorous are the major substances in waste which are key contributors to eutrophication potential. Due to their increased activity, the action of microorganism increases, causing increased consumption of oxygen. Presence of excessive nitrogen can make ground water unfit for use.

*Figure 7.5* represents the nutrition enrichment potential or eutrophication potential for each scenario in Chandigarh, Mohali and Panchkula, respectively. It was observed that maximum eutrophication potential was shown in scenario 5: MRF_COM_INC (CHD-0.7009 kg PO$_4^{3-}$ eq t$^{-1}$; MOH- 0.6995 kg PO$_4^{3-}$ eq t$^{-1}$ and PKL-0.7110 kg PO$_4^{3-}$ eq t$^{-1}$) due to harmful emissions during the combustion process. It was followed by the scenario BAU (CHD- 0.5001 kg PO$_4^{3-}$ eq t$^{-1}$; MOH- 0.5009 kg PO$_4^{3-}$ eq t$^{-1}$ and PKL-0.5010 kg PO$_4^{3-}$ eq t$^{-1}$).

The presence of maximum eutrophication in BAU is attributed to the dumping of MSW in open dumping sites with no provision of liner systems or treatment or collection facility. The biological processes occurring inside the dumping sites leads to the emission of nitrogen and phosphorous compounds. These compounds dissolve along with the leachate and cause more environmental impacts. It was followed by scenario 4: MRF_COM_AD_INC (CHD-0.4416 kg PO$_4^{3-}$ eq t$^{-1}$; MOH-0.4365 kg PO$_4^{3-}$ eq t$^{-1}$ and PKL-0.4520 kg PO$_4^{3-}$ eq t$^{-1}$) and scenario 2: MRF_SLF (CHD-0.3368 kg PO$_4^{3-}$ eq t$^{-1}$; MOH-0.3151 kg PO$_4^{3-}$ eq t$^{-1}$ and PKL-0.3471 kg PO$_4^{3-}$ eq t$^{-1}$).

Scenario 3: MRF_COM_SLF produced least eutrophication potential impacts (CHD-0.1084 kg PO$_4^{3-}$ eq t$^{-1}$; MOH-0.1182 kg PO$_4^{3-}$ eq t$^{-1}$ and PKL-0.1052 kg PO$_4^{3-}$ eq t$^{-1}$) due to the source separation as well as presence of impermeable synthetic bottom liners in sanitary landfills. Sanitary landfills also help in isolating the waste, thus, minimizing the amount of water entering and gases escaping from the waste.
Figure 7.5: Eutrophication potential under different scenarios for (a) Chandigarh, (b) Mohali and (c) Panchkula
Human Toxicity Potential (HTP)

The last impact category was human toxicity potential (HTP) and is expressed as kg 1, 4-DB eq t⁻¹. Figure 7.6 presents the human toxicity potential for each scenario in Chandigarh, Mohali and Panchkula, respectively. It is an index which evaluates the potential of a unit chemical released in environment. Human toxicity is mainly caused by pollutants like SOₓ, NOₓ, particulate matter, lead, dioxins, copper, chromium, nickel, cadmium, mercury and zinc.

Maximum human toxicity impact was observed in BAU (CHD- 388.12 kg 1, 4-DB eq t⁻¹; MOH-756.43 kg 1, 4-DB eq t⁻¹ and PKL- 510 kg 1, 4-DB eq t⁻¹) owing to the absence of any recovered resources and separation facilities in any of the three cities. Unsegregated MSW is sent to these open dumping sites which have no provision of collection and treatment facility for leachate and absence of proper synthetic liner systems. The leachate generated from these sites tends to percolate into ground water thus leading to emission of high toxicity potential.

Scenario 5: MRF_COM_INC also generated high human toxicity potential (CHD- 335 kg 1, 4-DB eq t⁻¹; MOH-620 kg 1, 4-DB eq t⁻¹ and PKL- 499.89 kg 1, 4-DB eq t⁻¹) owed to the emissions from heavy metals during the combustion process. It was followed by scenario 2: MRF_SLF (CHD- 53.7 kg 1, 4-DB eq t⁻¹; MOH-170 kg 1, 4-DB eq t⁻¹ and PKL-168.1 kg 1, 4-DB eq t⁻¹) and scenario 4: MRF_COM_AD_SLF (CHD-49.9 kg 1, 4-DB eq t⁻¹; MOH-98.9 kg 1, 4-DB eq t⁻¹ and PKL-97.6 kg 1, 4-DB eq t⁻¹).

Least human toxicity effects were observed in scenario 3: MRF_C0M_SLF (CHD-50 kg 1, 4-DB eq t⁻¹; MOH-70 kg 1, 4-DB eq t⁻¹ and PKL-50 kg 1, 4-DB eq t⁻¹) which reveals the environmental benefits of material recovery and composting which lead to lesser emissions of toxicity causing agents along with the sanitary landfilling.
Figure 7.6: Human Toxicity potential under different scenarios for (a) Chandigarh, (b) Mohali and (c) Panchkula
Tricity generates 680 tons per day of MSW, with Chandigarh contributing 380 tons per day, Mohali and Panchkula 150 tons per day respectively. The final disposal method of MSW in all the cities is open dumping which makes the effective waste management a highly challenging task. The results of the environmental LCA under the five scenarios have shown that the least environmental impacts were generated in scenario 3: MRF_COM_SLF. The scenario revealed that with effective use of source separation and resource recovery, composting and sanitary landfilling method, maximum benefits could be generated along with lesser environmental impacts. The global warming potential (GWP), human toxicity potential (HTP), eutrophication potential (EP) and acidification potential (AP), all the environmental impacts studied have shown least values in this scenario. Under scenario 3: MRF_COM_SLF, minimum global warming potential was generated in Chandigarh while low emissions from acidification potential, eutrophication and human toxicity potential were observed in Panchkula.

The present, BAU, MSW disposal scenarios for Chandigarh, Mohali and Panchkula, projects maximum environmental consequences. The reason for this is the absence of liner systems, material recovery systems, dumping of unsegregated MSW and absence of leachate collection and treatment systems. The GWP and HTP are extreme in this case. Therefore, this is the least considered option in terms of environmental consequences.

Table 7.10, 7.11 and 7.12 gives the summary of the environmental impacts for scenario: BAU and scenario 3: MRF_COM_SLF for Chandigarh, Mohali and Panchkula, respectively showing the reduction in level of environmental impacts if the current open dumping is replaced with the combination of material recycling, composting and sanitary landfilling. It can be observed from the tables (7.10, 7.11 and 7.12), that highest environmental impacts in terms of AP and EP were being generated from Chandigarh city due to more generation of MSW as compared to Mohali and Panchkula. GWP was majorly being generated from Panchkula waste as compared to the emissions from Chandigarh and Mohali as many a times the incidents of illegally burning of waste are being reported in Panchkula city. Scenario 3 shows that Panchkula city generates lowest emissions in terms of acidification potential; eutrophication potential and human toxicity potential while in terms of global warming potential lowest emissions were generated in Mohali city. As Chandigarh is generating more quantity of waste in comparison to the other two cities, so it produces more emissions to environment as compared to Mohali and Panchkula in scenario 3.
Table 7.10: Comparison of environmental impacts (BAU and Scenario 3) for Chandigarh

<table>
<thead>
<tr>
<th>Environmental Impacts</th>
<th>Chandigarh</th>
<th>Scenario 3</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>BAU</td>
<td></td>
</tr>
<tr>
<td>Global Warming Potential</td>
<td>75.63 kg CO₂ eq t⁻¹</td>
<td>4.5 kgCO₂ eq t⁻¹</td>
</tr>
<tr>
<td>Acidification Potential</td>
<td>1.30 kg SO₂ eq t⁻¹</td>
<td>0.980 kgSO₂ eq t⁻¹</td>
</tr>
<tr>
<td>Eutrophication Potential</td>
<td>0.5001 kg PO₄³⁻ eq t⁻¹</td>
<td>0.108 kgPO₄³⁻ eq t⁻¹</td>
</tr>
<tr>
<td>Human Toxicity Potential</td>
<td>388.12 kg 1, 4-DB eq t⁻¹</td>
<td>0.42 kg 1, 4-DB eq t⁻¹</td>
</tr>
</tbody>
</table>

Table 7.11: Comparison of environmental impacts (BAU and Scenario 3) for Mohali

<table>
<thead>
<tr>
<th>Environmental Impacts</th>
<th>Mohali</th>
<th>Scenario 3</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>BAU</td>
<td></td>
</tr>
<tr>
<td>Global Warming Potential</td>
<td>73.10 kg CO₂ eq t⁻¹</td>
<td>4.4 kgCO₂ eq t⁻¹</td>
</tr>
<tr>
<td>Acidification Potential</td>
<td>1.066 kg SO₂ eq t⁻¹</td>
<td>0.980 kgSO₂ eq t⁻¹</td>
</tr>
<tr>
<td>Eutrophication Potential</td>
<td>0.5009 kg PO₄³⁻ eq t⁻¹</td>
<td>0.1182 kgPO₄³⁻ eq t⁻¹</td>
</tr>
<tr>
<td>Human Toxicity Potential</td>
<td>756.43 kg 1, 4-DB eq t⁻¹</td>
<td>0.56 kg 1, 4-DB eq t⁻¹</td>
</tr>
</tbody>
</table>

Table 7.12: Comparison of environmental impacts (BAU and Scenario 3) for Panchkula

<table>
<thead>
<tr>
<th>Environmental Impacts</th>
<th>Panchkula</th>
<th>Scenario 3</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>BAU</td>
<td></td>
</tr>
<tr>
<td>Global Warming Potential</td>
<td>731.89 kg CO₂ eq t⁻¹</td>
<td>59.62 kgCO₂ eq t⁻¹</td>
</tr>
<tr>
<td>Acidification Potential</td>
<td>1.12 kg SO₂ eq t⁻¹</td>
<td>0.910 kgSO₂ eq t⁻¹</td>
</tr>
<tr>
<td>Eutrophication Potential</td>
<td>0.5010 kg PO₄³⁻ eq t⁻¹</td>
<td>0.105 kgPO₄³⁻ eq t⁻¹</td>
</tr>
<tr>
<td>Human Toxicity Potential</td>
<td>510 kg 1, 4-DB eq t⁻¹</td>
<td>0.41 kg 1, 4-DB eq t⁻¹</td>
</tr>
</tbody>
</table>

7.3.2 Sensitivity Analysis

The impact of different recycling rates on the life cycle emissions were analysed for Chandigarh, Mohali and Panchkula for the baseline scenario (BAU). In the analysis the recycling proportions of paper, plastics, metals, textiles and leather were assumed to be recycled from 10%, 50% and 90%. The results showed that recycling rate will considerably lower the life cycle emissions from the MSW management systems in all the three cities. The results of global warming potential (GWP), acidification potential (AP), eutrophication
potential (EP) and human toxicity potential (HTP) for Chandigarh, Mohali and Panchkula, respectively are displayed in figure 7.7 to 7.10. The results of all the parameters are symbolized as (a) for Chandigarh, (b) for Mohali and (c) for Panchkula respectively.

**Figure 7.7:** Effect of recycling rate on global warming potential under BAU scenario for (a) Chandigarh, (b) Mohali and (c) Panchkula
Figure 7.8: Effect of recycling rate on acidification potential under BAU scenario for (a) Chandigarh, (b) Mohali and (c) Panchkula
Figure 7.9: Effect of recycling rate on eutrophication potential under BAU scenario for (a) Chandigarh, (b) Mohali and (c) Panchkula
Figure 7.10: Effect of recycling rate on human toxicity potential under BAU scenario for (a) Chandigarh, (b) Mohali and (c) Panchkula
It is depicted from the results that the total environmental benefits will increase as rate of recycling increases. If the recycling rate is increased from 10% to 90%, the environmental impacts as compared with present scenario would reduce and are shown in Table 7.13.

Table 7.13: Environmental Impacts in the BAU for sensitivity analysis at 10% (a) and 90% (b)

<table>
<thead>
<tr>
<th></th>
<th>GWP</th>
<th>AP</th>
<th>EP</th>
<th>HTP</th>
</tr>
</thead>
<tbody>
<tr>
<td>Chandigarh</td>
<td>72.63 kg CO₂ eq t⁻¹a</td>
<td>1.26 kg SO₂ eq t⁻¹a</td>
<td>0.35 kg PO₄⁻³ eq t⁻¹a</td>
<td>1.30 kg 1,4-DB eq t⁻¹a</td>
</tr>
<tr>
<td></td>
<td>70.79 kg CO₂ eq t⁻¹b</td>
<td>0.94 kg SO₂ eq t⁻¹b</td>
<td>0.20 kg PO₄⁻³ eq t⁻¹b</td>
<td>1.13 kg 1,4-DB eq t⁻¹b</td>
</tr>
<tr>
<td>Mohali</td>
<td>71.63 kg CO₂ eq t⁻¹a</td>
<td>0.92 kg SO₂ eq t⁻¹a</td>
<td>0.82 kg PO₄⁻³ eq t⁻¹a</td>
<td>1.30 kg 1,4-DB eq t⁻¹a</td>
</tr>
<tr>
<td></td>
<td>69.07 kg CO₂ eq t⁻¹b</td>
<td>0.82 kg SO₂ eq t⁻¹b</td>
<td>0.20 kg PO₄⁻³ eq t⁻¹b</td>
<td>1.19 kg 1,4-DB eq t⁻¹b</td>
</tr>
<tr>
<td>Panchkula</td>
<td>716.3 kg CO₂ eq t⁻¹a</td>
<td>1.02 kg SO₂ eq t⁻¹a</td>
<td>0.35 kg PO₄⁻³ eq t⁻¹a</td>
<td>99.60 kg 1,4-DB eq t⁻¹a</td>
</tr>
<tr>
<td></td>
<td>680.53 kg CO₂ eq t⁻¹b</td>
<td>0.79 kg SO₂ eq t⁻¹b</td>
<td>0.20 kg PO₄⁻³ eq t⁻¹b</td>
<td>79.45 kg 1,4-DB eq t⁻¹b</td>
</tr>
</tbody>
</table>

(First values depict at 10%; Second value depicts 90%)

7.4 Summary and Discussion

The life cycle assessment (LCA) is used as a tool to compare the different MSW management system options and to determine the best possible and feasible system for Chandigarh, Mohali and Panchkula. The most feasible system considered is the one which produces least environmental impacts. In the study, five scenarios were considered for different impact categories viz., global warming potential, acidification potential, eutrophication potential and human toxicity potential to evaluate the potential for reducing the environmental impacts in Chandigarh, Mohali and Panchkula, respectively. Under the present conditions of MSW management system in Tricity are producing - global warming (CHD-75.63 kg CO₂ eq t⁻¹; MOH-73.10 kg CO₂ eq t⁻¹; PKL-731.89 kg CO₂ eq t⁻¹), acidification (CHD-1.30 kg SO₂ eq t⁻¹; MOH-1.066 kg SO₂ eq t⁻¹; PKL-1.12 kg SO₂ eq t⁻¹), eutrophication (CHD-0.5001 kg PO₄⁻³ eq t⁻¹; MOH-0.5009 kg PO₄⁻³ eq t⁻¹; PKL-0.5010 kg PO₄⁻³ eq t⁻¹) and human toxicity (CHD-388.12 kg 1,4-DB eq t⁻¹; MOH-756.43 kg 1,4-DB eq t⁻¹; PKL-510 kg 1,4-DB eq t⁻¹) environmental impacts. Among the proposed scenarios, the scenario 3; with the combination of material recovery recycling, composting and sanitary landfilling has the least environmental impacts. Results have shown that integrated MSW management with environmental benefits can be achieved with the introduction of recycling the valuable recovered resources (paper, plastics, metals etc.), composting and with energy recovery. The sensitivity analysis for the recycling rate reveals that there is reduction in environmental impacts if the recycling rate is increased from 10% to 90%. Recycling of valuable resources makes a significant contribution by reducing the environmental impacts. Since there
are no research studies and data focusing on LCA of MSW in Chandigarh, Mohali and Panchkula, the use of detailed LCA for analyzing the different MSW management systems makes it possible for the municipal authorities of the respective cities of Chandigarh, Mohali and Panchkula to work towards improving the present management system.