



# Life-cycle assessment of municipal solid-waste management strategies in Tricity region of India

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## Abstract

Unscientific disposal of waste is of severe environmental concern like air, water, and soil pollution. This requires immediate attention to minimize the impact of solid waste on the existing environment and health. Generation of waste is directly influenced by economic development. Most of the municipal authorities in the developing countries are facing massive challenges in waste management in an effective and efficient manner. The present study aims to explore the life-cycle assessment methodology to determine the impact of municipal solid-waste management under different scenarios in Tricity regions of Chandigarh, Mohali, and Panchkula. The study analyzes the impacts of different potential waste management alternatives for Tricity area using life-cycle approach (LCA). Four potential scenarios of scientific solid-waste management were analyzed. The impact categories analyzed were global warming, acidification, eutrophication, and human toxicity. Among the proposed alternative scenarios, the scenario with the combination of recycling, composting, and sanitary landfill showed the least environmental impacts. The results show that the significant environmental savings are achieved through the energy recovery in the present waste management scenario. A sensitivity analysis was carried in context of recycling rate with the recycling rate varied from 90 to 10%.

**Keywords** Life-cycle assessment · Municipal solid waste · Impact categories · Life-cycle inventory

## Introduction

With the 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 Municipal Solid Waste (MSW) is one of the major challenges for Indian megacities [1–4]. The most common method for disposal of MSW in India is the practice of open dumping. These dumping sites are serious threats to environment and sustainable development. Therefore, it becomes vital to analyze the effect of MSW disposal at present and what would be the impact under integrated waste management scenarios [5–8]. In

this context, life-cycle assessment (LCA) is an important tool to identify and 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 [6, 9–11]. The initial applications of LCA analysis were for the evaluation of the limitation of raw materials and energy use with the main focus primarily on the energy and resource requirement of the waste [12–14]. LCA is a useful environmental management tool which attempts to forecast the environmental aspects and potential impacts throughout the life of the waste covering all the aspects from its generation to disposal options within a system boundary [15–18]. Different waste management systems and their various environmental impacts can be evaluated using the LCA models [19–22]. 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 along with the

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methodology in details has already been discussed in the previous studies [14, 20, 23, 24].

The LCA can be used as a tool for assessing environment by comparing and analyzing the environmental impacts of MSW management systems [18, 25]. Hence, in the last decade, a number of studies [19, 26, 27] have used LCA as a comparative tool for the selection of appropriate MSW strategies. A study [28] conducted focused on LCA of MSW management of Kathmandu city compared three different scenarios of business as usual, energy recovery with recycling and disposal system with composting and land filling. The emissions to the environment were considered and calculated as global warming potential, acidification potential, eutrophication potential, and fuel energy consumption. 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 [23], 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. Another research [29] stated that environmental assessment of MSW management scenarios would help to select the most eco-friendly scenarios. Inventory data for different scenarios were 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 [30] compared 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. A different study [3], compared five different MSW waste treatment scenarios. Scenario which was a combination of source separation with 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.

In developing countries, life-cycle assessment is also linked with the environmental sustainability which leads to the process of identification and managing environmental, health, safety, and regulatory impacts and efficient use of resources throughout their life cycle [20, 31, 32]. In the process of LCA major emphasis is being made on the dynamics to evaluate the environmental performance of a process chain which further identifies the emission hotspots [19]. The environmental impact categories like climate change, acid rains, carcinogenic impacts, etc to be considered for any particular study include internal benchmarking which helps in identifying the factors which will help to reduce the emissions [3, 6, 7, 32].

Studies have mentioned [20–22, 33] that the main objective of performing the environmental assessment by means of LCA technique is to establish sustainable and energy-efficient treatment technologies by lowering the global environmental load. While a few numbers of studies have been completed in India, a broad outreach across the country and into different regions is needed to enhance the understanding and proper application of LCA.

Technological options for water management in Amsterdam [34] were suggested through three different scenarios using the 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 [27] 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 had least environmental impacts.

A study [2] compared six scenarios in Mumbai city, India, and found that the recycling, compositing, and sanitary landfilling option were superior to the other scenarios. Different studies have shown that the impact on environment varies 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 are being made in use [35]. A successful LCA depends on the initial success of the key parameters. The key parameters include the formation of system boundaries and input data [8, 14, 20, 25, 28, 36]. 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 for LCA analysis of MSW is SimaPro. 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 commonly used software's.

Keeping in view of the above, the present study analyzes 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 analyzed for each of the three cities. The sensitivity analysis of recycling rate has also been analyzed for Tricity in the current waste management situation. The research results can help the decision-makers to evaluate strategies

for the treatment of MSW from an environmental impact point of view. The impact categories analyzed are global warming, acidification eutrophication, and human toxicity.

## Materials and methods

### Site location

Chandigarh has a population of 1.05 million as per 2011 census with a growth rate of 17% in the decade (2001–2010) covering an area of 114 km<sup>2</sup>. The entire management of solid waste is taken care by Chandigarh Municipal Corporation with a collection coverage of 70% from households under the purview of Chandigarh Municipal Corporation and about 20% from the slums.

Mohali has a population of 986,147 in 2011 with an area of 1160 km<sup>2</sup>. Mohali Municipal Corporation is responsible for management of solid waste in city. The collection coverage of the MSW generated in the Mohali is similar to collection coverage as observed in Chandigarh.

Panchkula covers an area of 816 km<sup>2</sup> having a population of 561,293 in 2011, as per the latest Indian census report [37, 38]. Panchkula Municipal Corporation is looking after the entire management of solid waste with collection coverage similar to Chandigarh and Mohali cities.

The total MSW generated from the Tricity is about 680 tons per day (TPD) (380 TPD in Chandigarh, 150 TPD

in Mohali, and 150 TPD in Panchkula) [39]. The MSW is disposed of in open dump sites located in each of the city leading to possible contamination of groundwater and thereby potential health hazards. Figure 1 shows the map of Tricity along with the location of the open dumpsites.

### MSW management scenarios

In the current study, five scenarios were analyzed reflecting different MSW management systems that could be potentially used for Chandigarh, Mohali, and Panchkula, respectively, as shown in Table 1.

#### 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 [40]. In Mohali and Panchkula, the total 150 tons per day waste generated is directly dumped in open landfills. Except for the BAU, all the scenarios assumed were the same for Chandigarh, Mohali, and Panchkula, respectively.

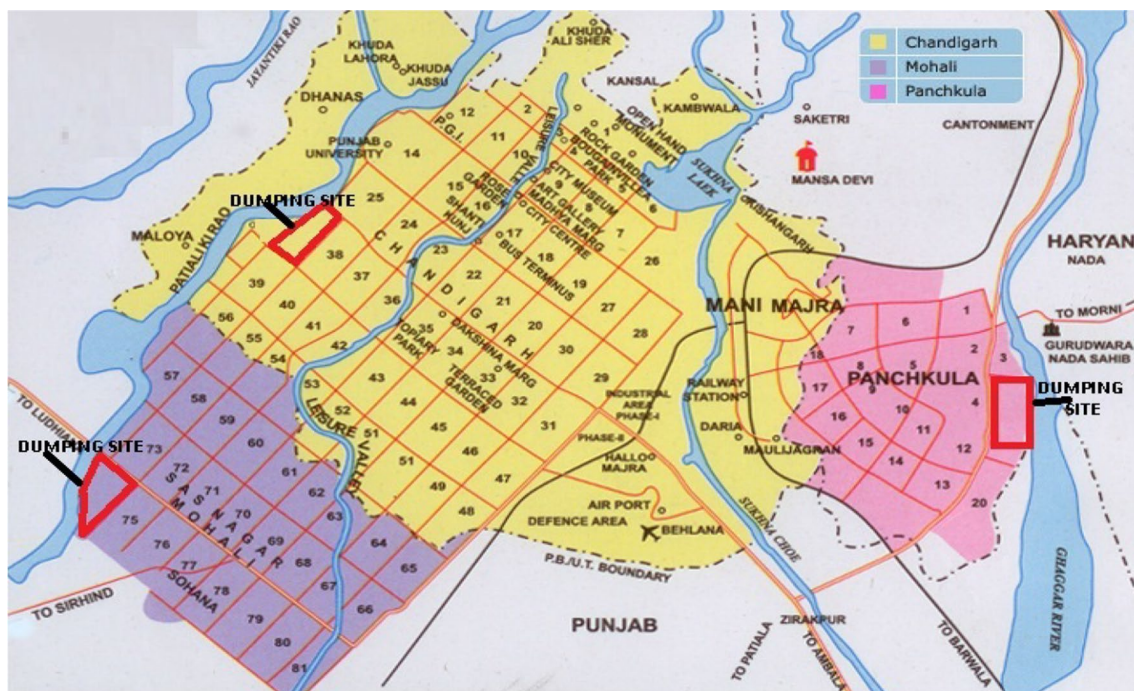


Fig. 1 Location of Tricity along with the dumping sites

**Table 1** Description of scenarios used in LCA of MSW for Tricity

Scenario	Description
Scenario 1: Baseline scenario (BAU)	Business as usual represents the present MSW management practice in Tricity
Scenario 2: Material recovery facility_Sanitary Landfilling (MRF_SLF)	20% Recycling + rest of the waste to sanitary landfilling with 50% biogas collection and electricity production
Scenario 3: Material recovery facility_composting_sanitary landfill (MRF_COM_SLF)	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
Scenario 4: Material recovery facility_composting_anaerobic digestion_sanitary landfill (MRF_COM_AD_SLF)	20% Recycling + 60% composting + 20% anaerobic digestion and rest sent to landfill with 50% biogas collection and electricity production
Scenario 5: Material recovery facility_composting_incineration (MRF_COM_INC)	20% Recycled through MRF + 40% composting and rest is sent to incineration with electricity production

### 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 wastes generated are recycled, while rest of the waste is disposed in 'sanitary landfills (SLF)'. Recycling being one of the best methods which can be implemented in all the three cities owing to the high fraction of recyclables (paper, glass and plastics) [40]. Implementation of such a scheme can significantly reduce the annual emission rates of carbon dioxide. The recycling rate is based on the recycling rates as assumed at material recovery facilities study in Pune, India [41], which is indicative of similar tier-II city comparable with our study locations. The recycling facilities also helps in providing financial benefits from recycling of certain products and thereby also helps in increasing the lifespan of the landfill sites. It was also assumed that sanitary landfill is equipped with energy recovery facility with 50% biogas released from the sanitary landfill is collected and used for generation of electricity with the remaining proportion escaping 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 are recycled through MRF and 80% of the biodegradable waste of which 40% is composted (COM), while remaining 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.

## Life-cycle assessment (LCA)

Life-cycle assessment 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, 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.

### Goal and scope definition

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 treatments, and 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.

### Functional unit

The functional unit for the comparison of MSW management systems use in the present study is 1 ton of MSW in each of the three cities of Chandigarh, Mohali, and Panchkula.

### 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 [13, 25]. All the significant processes included within the boundary of the MSW management system are as shown in Fig. 2. MSW, energy, and mass are the input to the MSW management system and all the outputs considered are air and water emission, 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.

### Life-cycle inventory analysis (LCI)

Life-cycle inventory analysis denotes the compiling of a specific set of inputs and outputs related with a product or process [35, 42, 43]. 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 [3]. The LCI data used in the present study were collected from on-site investigations, values reported in the literature similar to our study area [2, 3, 6–8, 10, 13, 18–20,

25, 28–31, 34, 36, 43, 44], and data from the municipal authorities (population, waste generation, waste processing, and transportation) in each respective city and the database Eco invent 2.2. Until now, no relevant life-cycle inventory databases are available and, in 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 the absence of any data and research studies in the study area related to LCA. The data for energy consumption, input, resource recovery, and 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, and thermal processes to final landfilling.

The input data 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 database 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 2.

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 (physical and chemical) of Chandigarh, Mohali, and Panchkula, respectively, has been considered as given in Table 3a, b 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 4.

In open dumping, the direct CO<sub>2</sub> emission is of biogenic origins which were not considered for greenhouse gas (GHG) emissions. The emissions such as particulate matter (PM), nitrous oxide (N<sub>2</sub>O), nitrogen oxides (NO<sub>x</sub>), ammonia (NH<sub>3</sub>), and sulfur oxides (SO<sub>x</sub>) have been obtained from the database of SimaPro literature [2, 45]. 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 the previous studies [7, 18, 19] and the database of the SimaPro software version 8.3.0, Eco-Indicator 99 (H), and Eco-Invent method. The inventory data of the

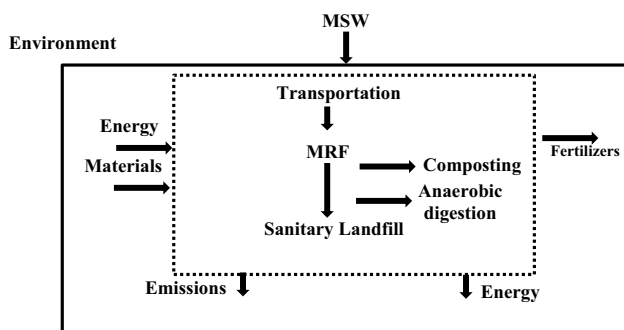


Fig. 2 System boundary of MSW management system for Tricity

**Table 2** Life-cycle inventories for Tricity

Inputs	Value	Units
<b>Landfill<sup>a</sup></b>		
Diesel	3	L <sup>-1</sup>
Net electrical efficiency	20	%
<b>Material recovery facility<sup>b</sup></b>		
Diesel	3.21	L <sup>-1</sup>
Electricity	3.2	kWh t <sup>-1</sup>
<b>Composting<sup>c</sup></b>		
Diesel	0.52	L <sup>-1</sup>
<b>By-products</b>		
Compost	130	Kgt <sup>-1</sup>
<b>Anaerobic digestion<sup>d</sup></b>		
Net electrical efficiency	20	%
<b>By-products</b>		
Digestate	100	Kgt <sup>-1</sup>
<b>Incineration<sup>e</sup></b>		
Net electrical efficiency	20	%
<b>By-products</b>		
Ash	140.8	Kgt <sup>-1</sup>

<sup>a</sup>Sharma and Chandel [2], Babu et al. [19], Chen et al. 2007

<sup>b</sup>Saheri et al. [10], Kumar et al. 2016

<sup>c</sup>Srivastava and Nema [27], Chanakya et al. [6]

<sup>d</sup>CPHEEO 2016; Kumar et al. 2016

<sup>e</sup>Chandel et al. 2012; Babu et al. [19]

environmental emissions from the production of 1 MJ of electricity and production of mineral fertilizer (SimaPro version 8.3.0, 7, 28) are as shown in Tables 5 and 6.

For sanitary landfilling, the data used for estimation of gases, transportation, and production of electricity have been obtained from various literatures [2, 7, 29, 43, 46] and the database of SimaPro version 8.3.0, Eco-Indicator 99 (H) and Eco-Invent method.

The emission processes and estimation from composting and anaerobic digestion were based on the studies as described in literature [19, 29, 36, 43, 47] and SimaPro version 8.3.0 database and Eco-Indicator 99 (H) method.

## Life-cycle impact assessment (LCIA)

Life-cycle impact assessment 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. Presently, necessary information 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

**Table 3** (a) Physical characterization of MSW from Tricity and (b) chemical characterization of MSW from Tricity

Components	CHD	MOH	PKL
<b>(a)</b>			
Density (kg/m <sup>3</sup> )	500.8	465	432
Compostable	52	46.7	42.6
Paper/cardboard	6.0	5.3	5.43
Plastics/polythene	7.3	6.6	7.06
Glass	1.6	1.4	1.44
Rubber/leather	1.7	1.2	1.186
Metals	0.8	0.6	0.68
Inert	27.0	28.6	28.46
Miscellaneous	4.1	9	13.378
Total	100	100	100
<b>(b)</b>			
Moisture content	50.18	45.78	39.6
Volatile matter	22.66	23.45	25.2
Ash content	25.94	27.51	29.9
Fixed carbon	1.39	3.4	5.4
Gross calorific value (GCV)	1929	1801	1542
Carbon	34.18	33.8	31.9
Hydrogen	4.42	4.2	4.2
Sulfur	0.2	0.004	0.001
Nitrogen	1.35	1.53	1.1
Oxygen	11.41	10.2	11.1
Mineral content	48.43	50.1	45.6
C/N ratio	25.3	22.1	27.1

Rana et al. [39]

**Table 4** Emissions from transportation of MSW in Chandigarh, Mohali, and Panchkula

Substances	Emissions (gt <sup>-1</sup> )		
	CHD	MOH	PKL
PM	115.86	112.28	114.82
CO <sub>2</sub>	156.79	191.32	142.11
NO <sub>x</sub>	103.21	141.61	98.63

**Table 5** Environmental emissions resulting from production of 1 MJ of electricity (Indian Grid and 1 L (L) of Diesel)

	Electricity grid mix (Indian grid) (MJ)	Diesel (L)
Global warming potential (GWP)	0.281	0.374
Acidification potential (AP)	0.00289	0.00176
Eutrophication potential (EP)	0.000212	0.000182
Human toxicity potential (HTP)	0.10	0.05

SimaPro software version 8.3.0 database, 2015, Rajaeifar et al. [29]

**Table 6** Environmental emissions from production of mineral fertilizers

Mineral fertilizer	Global warming potential (GWP), kgCO <sub>2</sub> eq kg <sup>-1</sup>	Acidification potential (AP), kgSO <sub>2</sub> eq kg <sup>-1</sup>	Eutrophication potential (EP), kgPO <sub>4</sub> <sup>3-</sup> kg <sup>-1</sup>	Human toxicity potential (HTP), Kg1, 4-DB eq kg <sup>-1</sup>
Nitrogen	4.7	0.0376	0.0202	0.0188
Potassium	0.2	0.0412	0.0319	0.042
Phosphorous	0.09	1.89E-3	1.1E-3	0.031

SimaPro software version 8.3.0 database, 2015; Rajaeifar et al. [29]

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 [48], the impact categories and indicators considered were global warming, acidification, eutrophication, and human toxicity potential.

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 [3] and helps in making the comparison between different MSW management scenarios.

### Life-cycle interpretation

This is the final stage of LCA that includes the reviewing of all the stages during LCA. All the data were analyzed, 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 tool, 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, Sima Pro software packages were used. SimaPro was developed by PRé Consultants with a goal of making more fact based. 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 result 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, waste treatments for products, and various impact assessment methodologies, which can be used for formation of a model for a particular study. In the data entry in the software is done in the 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.

## 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 to assess its reliability. The sensitivity analysis identifies sensitive parameters and assesses whether a small change in an input parameter would induce a large change in the impact category. For sensitivity analysis, first, 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 rate is defined as the percentage of the recycled materials or materials recovered from the waste. 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 [3, 6, 7, 19, 49] 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 analyzed.

## Results and discussion

### 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 Tables S1–S3, respectively, in the attached supplementary material. The emissions considered are GHG's ( $\text{CO}_2$ ,  $\text{CH}_4$  and  $\text{N}_2\text{O}$ ), particulate matter (PM), acidic gases ( $\text{SO}_x$ ,  $\text{NO}_x$  and  $\text{NH}_3$ ), 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. As per

the latest reports [21, 22, 33, 50], developing country like India is littering its waste without sufficient treatment. Most of the metropolitan cities are fast running out of dumping grounds or landfills. Only about 24% of the waste output is treated and the rest 76% is merely dumped in 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 coverage 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 Figs. 3, 4, 5 and 6. The results of all the environmental impacts are symbolized as (a) for Chandigarh, (b) for Mohali, and (c) for Panchkula, respectively.

### Global warming potential (GWP)

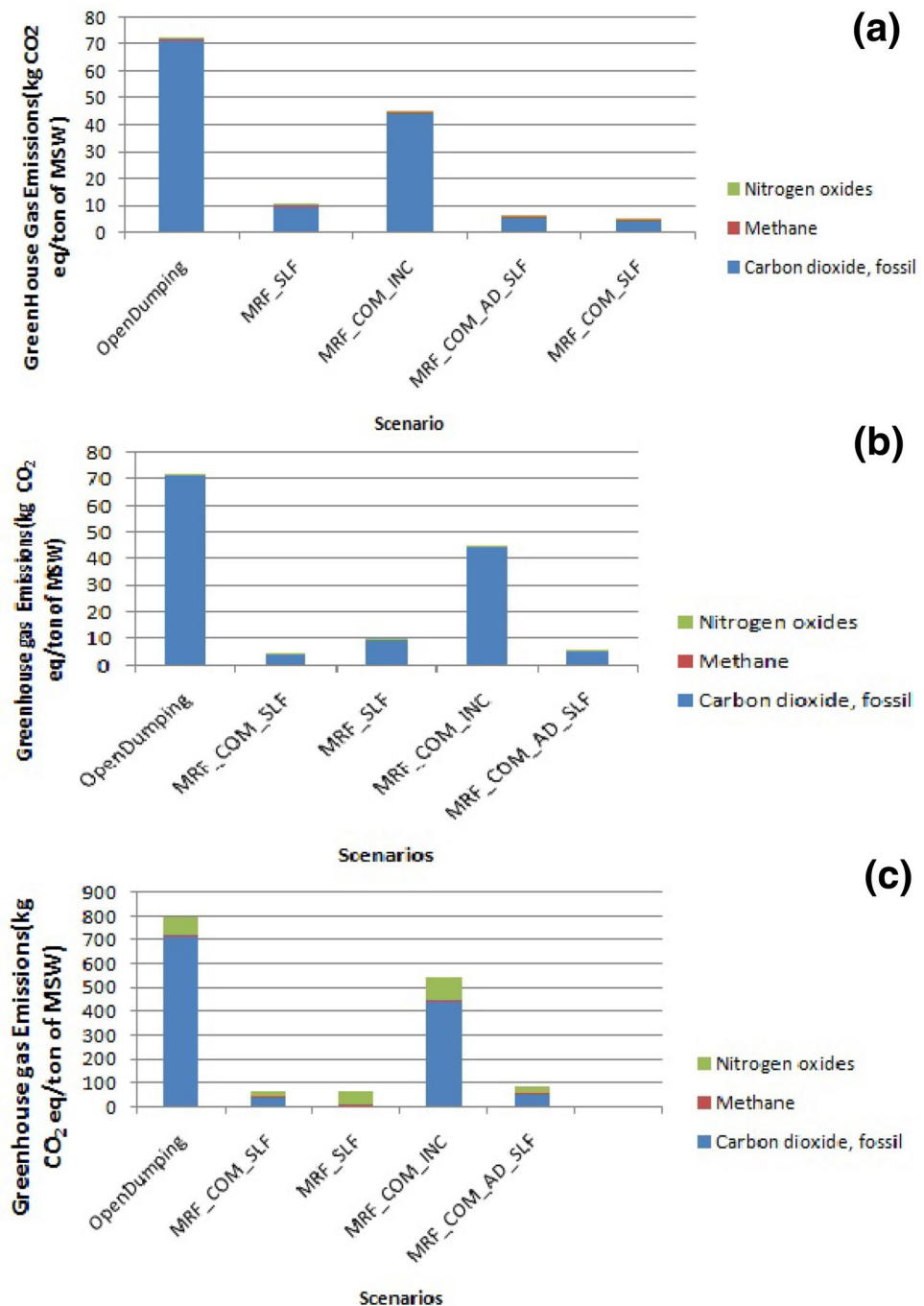
Figure 3 represents the global warming potential for different scenarios assessed for Chandigarh, Mohali, and Panchkula, respectively. The baseline (BAU) scenario for all the three cities have found to be contributing maximum greenhouse gas (GHG) emissions (CHD—75.63  $\text{kg CO}_2 \text{ eq t}^{-1}$ ; MOH—73.10  $\text{kg CO}_2 \text{ eq t}^{-1}$  and PKL—731.89  $\text{kg CO}_2 \text{ eq t}^{-1}$ ) which is owed to the high emission of methane generation along with the 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 is observed from the figures that open dumping scenario (i.e., BAU) in all the three cities produce high concentration of greenhouse gases (GHG) even more than the assumed incineration condition. This is because, in the incineration process, the GHG emitted are primarily due to the burning of fossil or anthropogenic sources like plastics, textiles, or leathers leading to higher generation of  $\text{CO}_2$  and lesser of methane. In contrast, open dumpsites have a tendency to generate more of methane gas.

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

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



**Fig. 3** Global warming potential under different scenarios for **a** Chandigarh, **b** Mohali, and **c** Panchkula



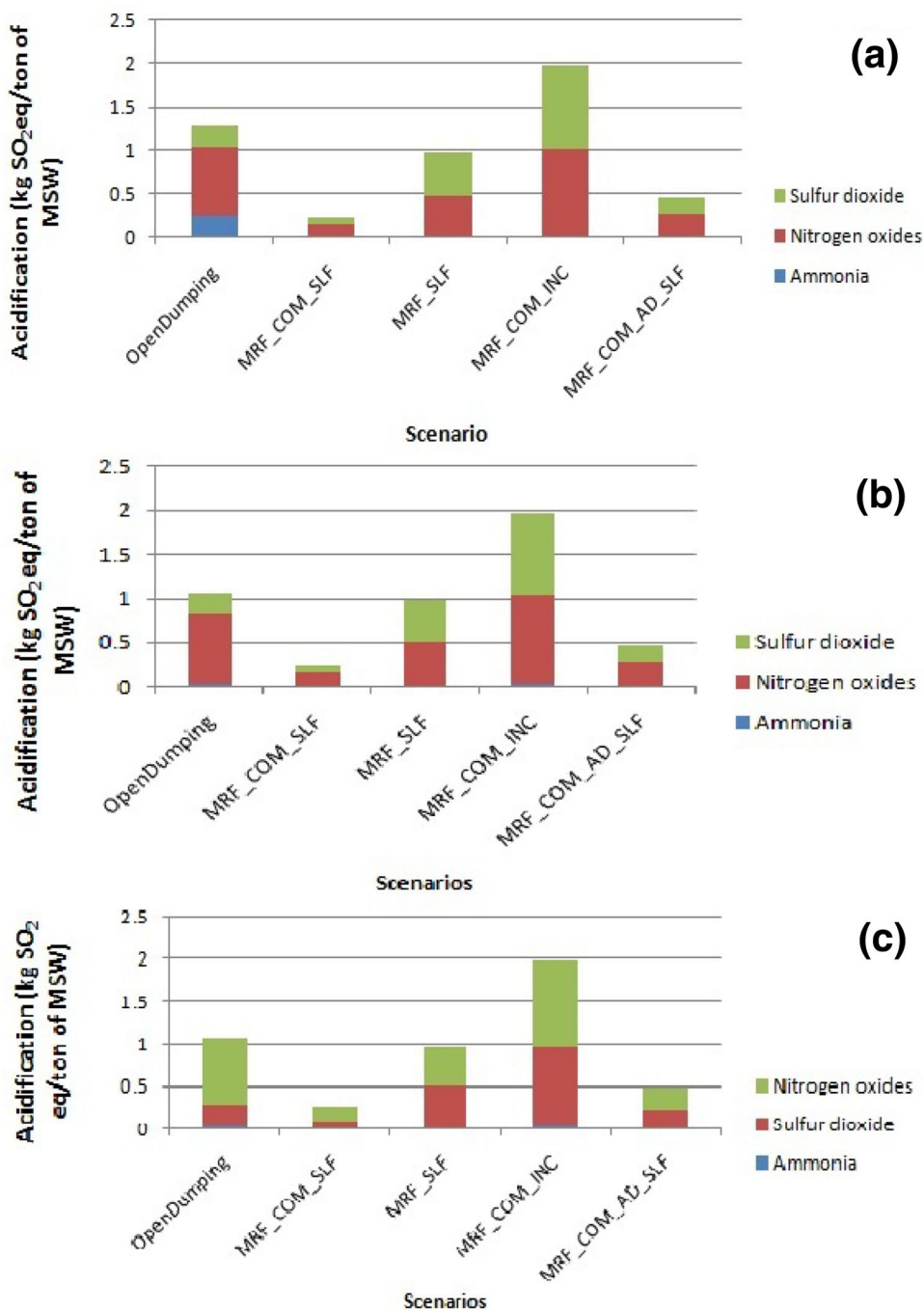
This scenario was followed by scenario 2: MRF\_SLF (CHD—10.40 kg CO<sub>2</sub> eq t<sup>-1</sup>; MOH—9.97 kg CO<sub>2</sub> eq t<sup>-1</sup> and PKL—58.77 kg CO<sub>2</sub> eq t<sup>-1</sup>) and scenario 4: MRF-COM\_AD\_SLF (CHD—5.87 kg CO<sub>2</sub> eq t<sup>-1</sup>; MOH—5.63 kg CO<sub>2</sub> eq t<sup>-1</sup> and PKL—83.43 kg CO<sub>2</sub> eq t<sup>-1</sup>).

#### Acidification potential (AP)

Figure 4 represents the acidification potential (AP) for each scenario in Chandigarh, Mohali, and Panchkula,

respectively. The maximum acidification impacts were detected in scenario 5: MRF\_COM\_INC (CHD—1.989 kg SO<sub>2</sub> eq t<sup>-1</sup>; MOH—1.98 kg SO<sub>2</sub> eq t<sup>-1</sup> and PKL—1.95 kg SO<sub>2</sub> eq t<sup>-1</sup>). As in incineration process due to the combustion of MSW, most of the sulfur and nitrogen compounds present in MSW get converted to SO<sub>x</sub> and NO<sub>x</sub> gases which in turn lead to high acidification. Major contribution is from NO<sub>x</sub> emission due to the presence of mineral fertilizers and characteristic properties of MSW.

**Fig. 4** Acidification potential under different scenarios for **a** Chandigarh, **b** Mohali, and **c** Panchkula



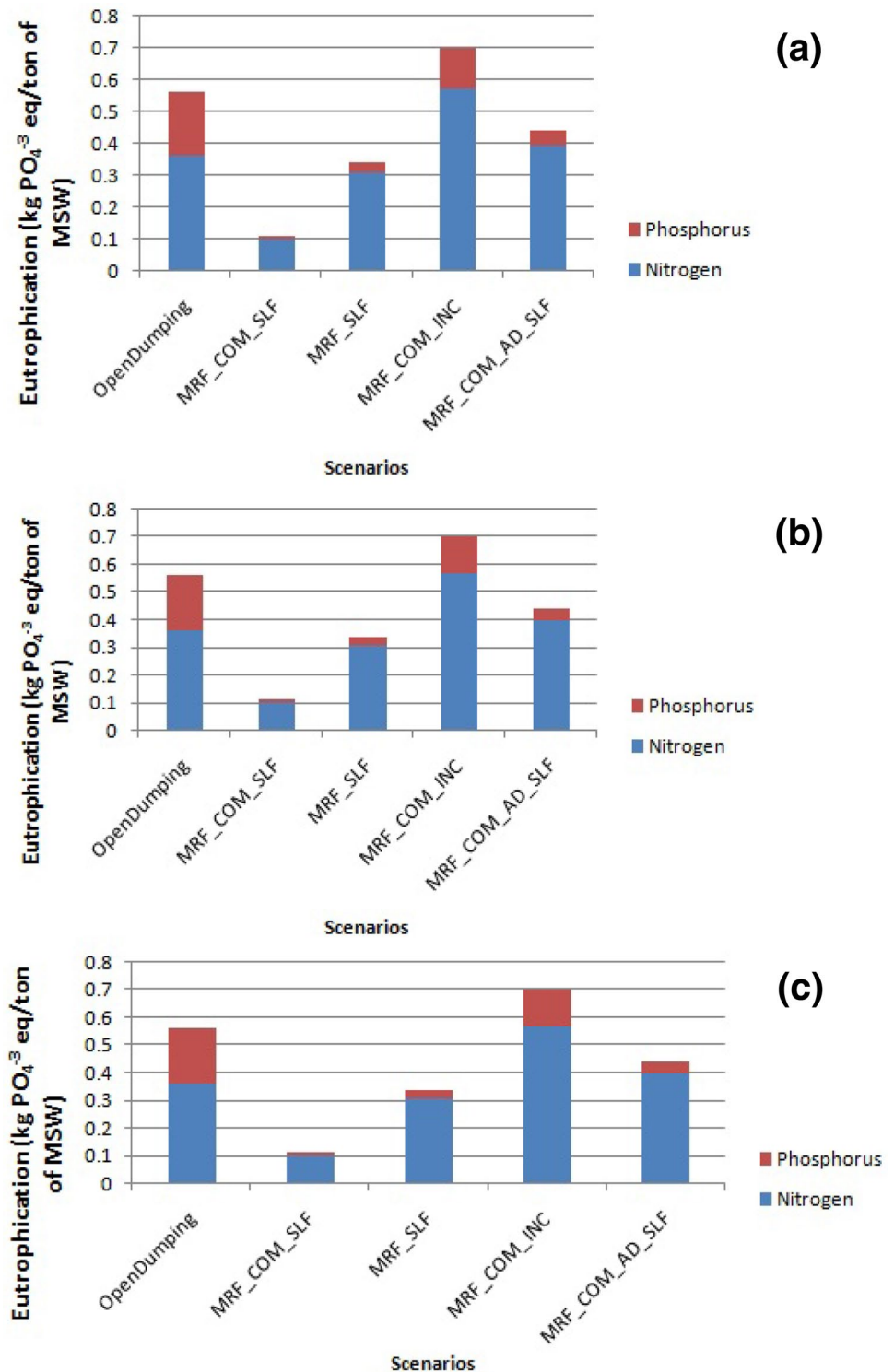
This was followed by scenario BAU (CHD—1.30 kg SO<sub>2</sub> eq t<sup>-1</sup>; MOH—1.066 kg SO<sub>2</sub> eq t<sup>-1</sup> and PKL—1.12 kg SO<sub>2</sub> eq t<sup>-1</sup>) as mixed MSW is dumped in the open dumping sites of all the three cities, moreover, due to the absence of any facilities for the resource recovery causes more environmental impacts. Leachate generated in the open dumping sites with the production of harmful gas like hydrogen sulfide (H<sub>2</sub>S) also act as a contributor to the acidification potential.

These were followed by scenario 2: MRF\_SLF (CHD—0.980 kg SO<sub>2</sub> eq t<sup>-1</sup>; MOH—0.980 kg SO<sub>2</sub> eq t<sup>-1</sup> and

PKL—0.91 kg SO<sub>2</sub> eq t<sup>-1</sup>) and scenario 4: MRF\_COM\_AD\_SLF (CHD—0.46 kg SO<sub>2</sub> eq t<sup>-1</sup>; MOH—0.46 kg SO<sub>2</sub> eq t<sup>-1</sup> and PKL—0.5 kg SO<sub>2</sub> eq t<sup>-1</sup>).

Least acidification environmental impacts were observed in scenario 3: MRF\_COM\_SLF (CHD—0.17 kg SO<sub>2</sub> eq t<sup>-1</sup>, MOH—0.28 kg SO<sub>2</sub> eq t<sup>-1</sup> and PKL—0.19 kg SO<sub>2</sub> eq t<sup>-1</sup>) 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 result in lower emissions of SO<sub>x</sub> and N<sub>Ox</sub> gases.

**Fig. 5** Eutrophication potential under different scenarios for **a** Chandigarh, **b** Mohali, and **c** Panchkula



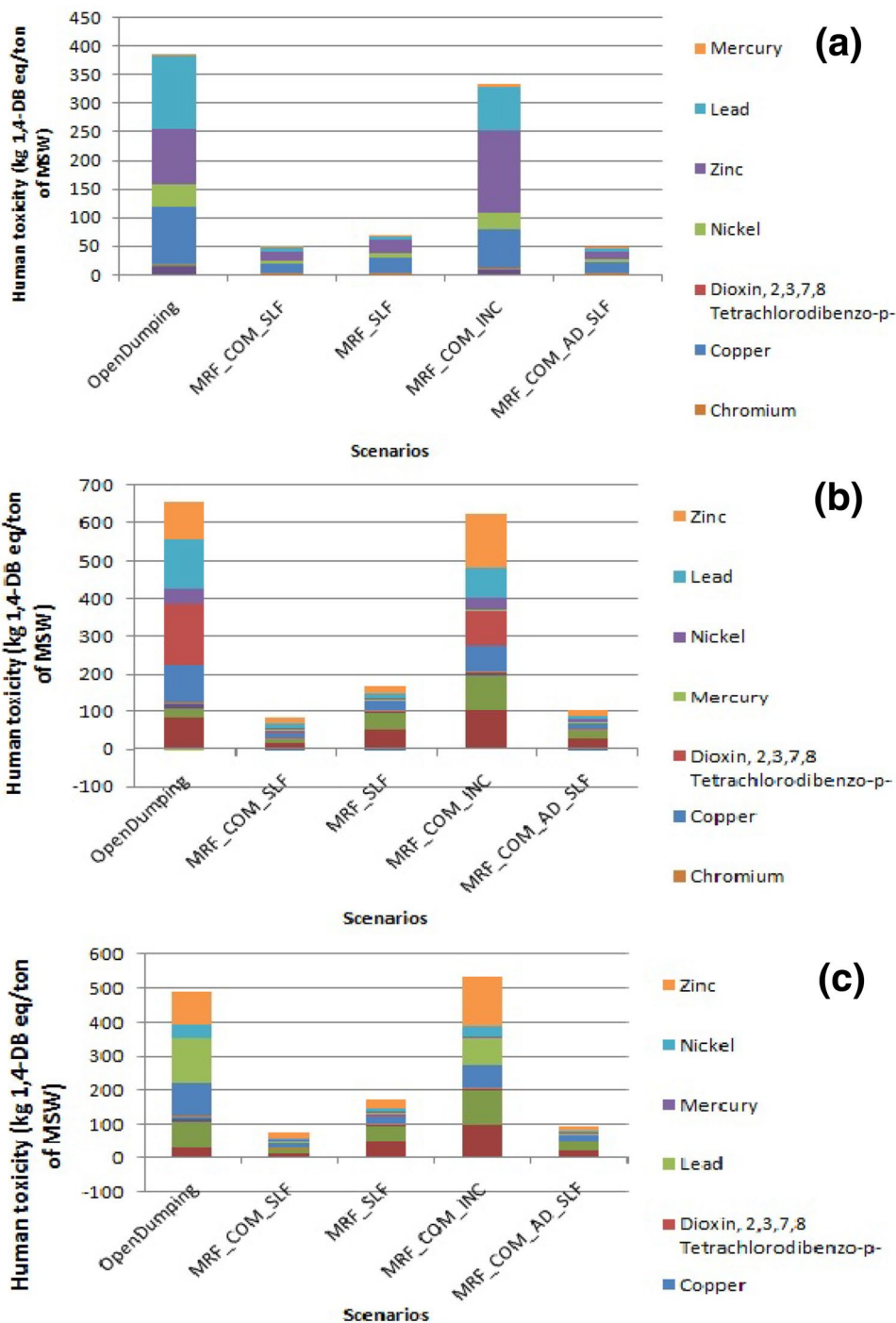
### Eutrophication potential (EP)

It is expressed as kg PO<sub>4</sub><sup>3-</sup> eq t<sup>-1</sup>. Nitrogen and phosphorous are the major substances in waste which are key contributor to eutrophication potential. Due to their increased activity, the activity of microorganism increases, causing increased

consumption of oxygen. The presence of excessive nitrogen can make ground water unfit for use.

Figure 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:

**Fig. 6** Human toxicity potential under different scenarios for **a** Chandigarh, **b** Mohali, and **c** Panchkula



MRF\_COM\_INC (CHD—0.7009 kg PO<sub>4</sub><sup>3-</sup> eq t<sup>-1</sup>; MOH—0.6995 kg PO<sub>4</sub><sup>3-</sup> eq t<sup>-1</sup> and PKL—0.7110 kg PO<sub>4</sub><sup>3-</sup> eq t<sup>-1</sup>) due to the absence of liner system harmful emissions caused by total nitrogen and phosphorous during the combustion process because of biological activities occurring in open dump sites. Phosphorous is the sum of all inorganic and organic forms present in the waste, and is generated and thereby released during the decomposition processes in the dumping sites [2, 6]. It was followed by the scenario

BAU (CHD—0.5001 kg PO<sub>4</sub><sup>3-</sup> eq t<sup>-1</sup>; MOH—0.5009 kg PO<sub>4</sub><sup>3-</sup> eq t<sup>-1</sup>; PKL—0.5010 kg PO<sub>4</sub><sup>3-</sup> eq t<sup>-1</sup>).

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 lead 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<sub>4</sub><sup>3-</sup> eq t<sup>-1</sup>; MOH—0.4365 kg PO<sub>4</sub><sup>3-</sup> eq t<sup>-1</sup> and PKL—0.4520 kg PO<sub>4</sub><sup>3-</sup> eq t<sup>-1</sup>) and scenario 2: MRF\_SLF (CHD—0.3368 kg PO<sub>4</sub><sup>3-</sup> eq t<sup>-1</sup>; MOH—0.3151 kg PO<sub>4</sub><sup>3-</sup> eq t<sup>-1</sup> and PKL—0.3471 kg PO<sub>4</sub><sup>3-</sup> eq t<sup>-1</sup>).

Scenario 3: MRF\_COM\_SLF produced least eutrophication potential impacts (CHD—0.1084 kg PO<sub>4</sub><sup>3-</sup> eq t<sup>-1</sup>; MOH—0.1182 kg PO<sub>4</sub><sup>3-</sup> eq t<sup>-1</sup> and PKL—0.1052 kg PO<sub>4</sub><sup>3-</sup> eq t<sup>-1</sup>) due to the source separation as well as the 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.

### Human toxicity potential (HTP)

The last impact category was human toxicity potential (HTP) and is expressed as kg 1, 4-DB eq t<sup>-1</sup>. It is an index which evaluates the potential of a unit chemical released in environment. Human toxicity is mainly caused by pollutants like SO<sub>x</sub>, NO<sub>x</sub>, particulate matter, lead, dioxins, copper, chromium, nickel, cadmium, mercury, and zinc. Figure 6 presents the human toxicity potential for each scenario in Chandigarh, Mohali, and Panchkula, respectively.

Maximum human toxicity impact was observed in Scenario 1 (BAU) (CHD—388.12 kg 1, 4-DB eq t<sup>-1</sup>; MOH—756.43 kg 1, 4-DB eq t<sup>-1</sup> and PKL—510 kg 1, 4-DB eq t<sup>-1</sup>) 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 large values of human toxicity potential.

LCA analysis also showed that considered scenario 5 (MRF\_COM\_INC) also generated high human toxicity potential (CHD—335 kg 1, 4-DB eq t<sup>-1</sup>; MOH—620 kg 1, 4-DB eq t<sup>-1</sup> and PKL—499.89 kg 1, 4-DB eq t<sup>-1</sup>) primarily due 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<sup>-1</sup>; MOH—170 kg 1, 4-DB eq t<sup>-1</sup> and PKL—168.1 kg 1, 4-DB eq t<sup>-1</sup>) and scenario 4: MRF\_COM\_AD\_SLF (CHD—49.9 kg 1, 4-DB eq t<sup>-1</sup>;

MOH—98.9 kg 1, 4-DB eq t<sup>-1</sup> and PKL—97.6 kg 1, 4-DB eq t<sup>-1</sup>).

Least human toxicity effects were observed in scenario 3: MRF\_COM\_SLF (CHD—50 kg 1, 4-DB eq t<sup>-1</sup>; MOH—70 kg 1, 4-DB eq t<sup>-1</sup>, and PKL—50 kg 1, 4-DB eq t<sup>-1</sup>) which reveals the environmental benefits of material recovery and composting which lead to lesser emissions of toxicity causing agents along with the sanitary landfilling.

Tricity generates 680 tons per day of MSW, with Chandigarh contributing 380 tons per day, and 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 project 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. GWP and HTP are maximum in this case. Therefore, this is the least considered option in terms of environmental consequences.

Tables 7, 8, 9 give 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, 8, 9) that the highest environmental impacts in terms of AP and EP were

**Table 7** Comparison of environmental impacts (BAU and scenario 3) for Chandigarh

Environmental impacts	Chandigarh	
	BAU	Scenario 3
Global warming potential	75.63 kg CO <sub>2</sub> eq t <sup>-1</sup>	4.5 kg CO <sub>2</sub> eq t <sup>-1</sup>
Acidification potential	1.30 kg SO <sub>2</sub> eq t <sup>-1</sup>	0.980 kg SO <sub>2</sub> eq t <sup>-1</sup>
Eutrophication potential	0.5001 kg PO <sub>4</sub> <sup>3-</sup> eq t <sup>-1</sup>	0.108 kg PO <sub>4</sub> <sup>3-</sup> eq t <sup>-1</sup>
Human toxicity potential	388.12 kg 1, 4-DB eq t <sup>-1</sup>	0.42 kg 1, 4-DB eq t <sup>-1</sup>

**Table 8** Comparison of environmental impacts (BAU and scenario 3) for Mohali

Environmental Impacts	Mohali	
	BAU	Scenario 3
Global warming potential	73.10 kg CO <sub>2</sub> eq t <sup>-1</sup>	4.4 kgCO <sub>2</sub> eq t <sup>-1</sup>
Acidification potential	1.066 kg SO <sub>2</sub> eq t <sup>-1</sup>	0.980 kgSO <sub>2</sub> eq t <sup>-1</sup>
Eutrophication potential	0.5009 kg PO <sub>4</sub> <sup>3-</sup> eq t <sup>-1</sup>	0.1182 kgPO <sub>4</sub> <sup>3-</sup> eq t <sup>-1</sup>
Human toxicity potential	756.43 kg 1, 4-DB eq t <sup>-1</sup>	0.56 kg 1, 4-DB eq t <sup>-1</sup>

**Table 9** Comparison of environmental impacts (BAU and scenario 3) for Panchkula

Environmental Impacts	Panchkula	
	BAU	Scenario 3
Global warming potential	731.89 kg CO <sub>2</sub> eq t <sup>-1</sup>	59.62 kgCO <sub>2</sub> eq t <sup>-1</sup>
Acidification potential	1.12 kg SO <sub>2</sub> eq t <sup>-1</sup>	0.910 kgSO <sub>2</sub> eq t <sup>-1</sup>
Eutrophication potential	0.5010 kg PO <sub>4</sub> <sup>3-</sup> eq t <sup>-1</sup>	0.105 kgPO <sub>4</sub> <sup>3-</sup> eq t <sup>-1</sup>
Human toxicity potential	510 kg 1, 4-DB eq t <sup>-1</sup>	0.41 kg 1, 4-DB eq t <sup>-1</sup>

being generated from Chandigarh City due to substantial emission of ammonia (AP = 1.88, EP = 0.35) compared to Mohali and Panchkula. GWP was majorly being generated from Panchkula waste as compared to the emissions from Chandigarh and Mohali as many 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.

The municipal solid waste in Panchkula dumping site is heavily mixed with dumping of the waste from the agricultural farms (comprising of 25% of agriculturally applied nitrogen that leaves the farm as food). Furthermore, the dumping site is also in the methanogenic phase, and is classified as old or matured sites, wherein the volatile fatty acids (VFA) are converted to methane, carbon dioxide, and nitrogen oxides. However, in comparison, the dumping site in Chandigarh receives the waste after processing from the Refuse Derived Fuel (RDF) plant leading to lesser generation of nitrogen oxides. Larger amount of ammonia is being generated in Chandigarh as compared to Mohali and Panchkula dumping site due to the presence of more nitrogenous matter in the MSW in Chandigarh dumping site. As the acidification effect is mainly caused by SO<sub>x</sub>, NO<sub>x</sub>, and NH<sub>3</sub> gases, where the effect of NO<sub>x</sub> is more than SO<sub>2</sub>.

## Sensitivity analysis

The impacts of different recycling rates on the life-cycle emissions were analyzed 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 Figs. 7, 8, 9, and 10. The results of all the parameters are symbolized as (a) for Chandigarh, (b) for Mohali, and (c) for Panchkula, respectively.

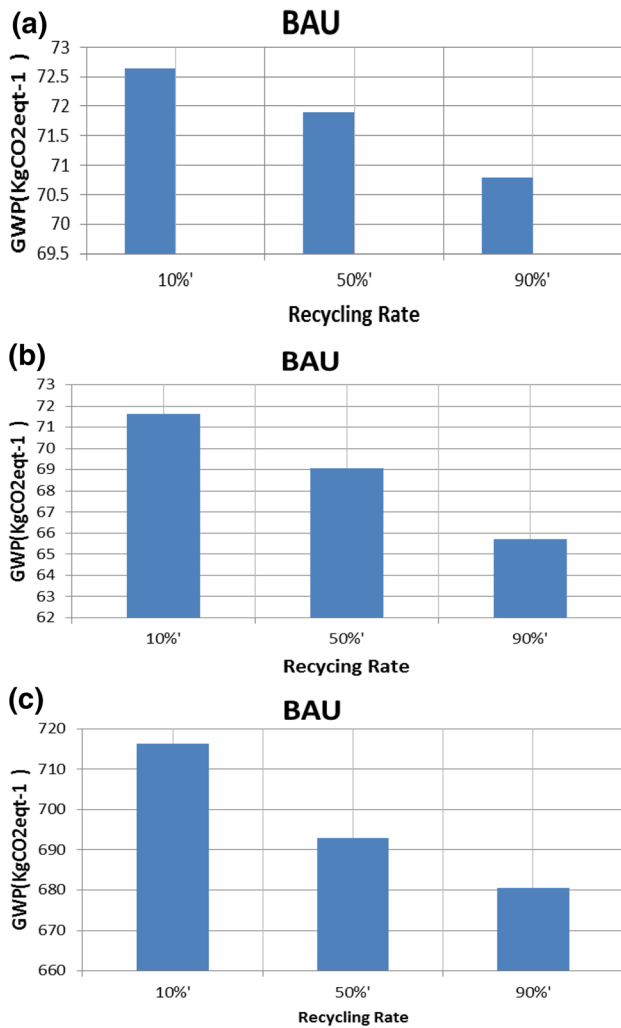
It is depicted from the results that the total environmental benefits will increase as rate of recycling increases. If the recycling rate is increased from 10 to 90%, the environmental impacts as compared with the present scenario would reduce and are summarized in Table 10.

## Policy implications

In particular, it is important to note that selection of appropriate treatment technology for an integrated waste management system or decision-making policies are difficult to create and thereby implement without performing the environmental impacts of the different proposed treatment scenarios. Furthermore, development of wrong policies based on non-optimal methods can create significant problems for the implementation of integrated and sustainable waste management policies [32]. In this context, the LCA assessment is an important tool in determining the environmental impacts of the selected or proposed waste management systems [51].

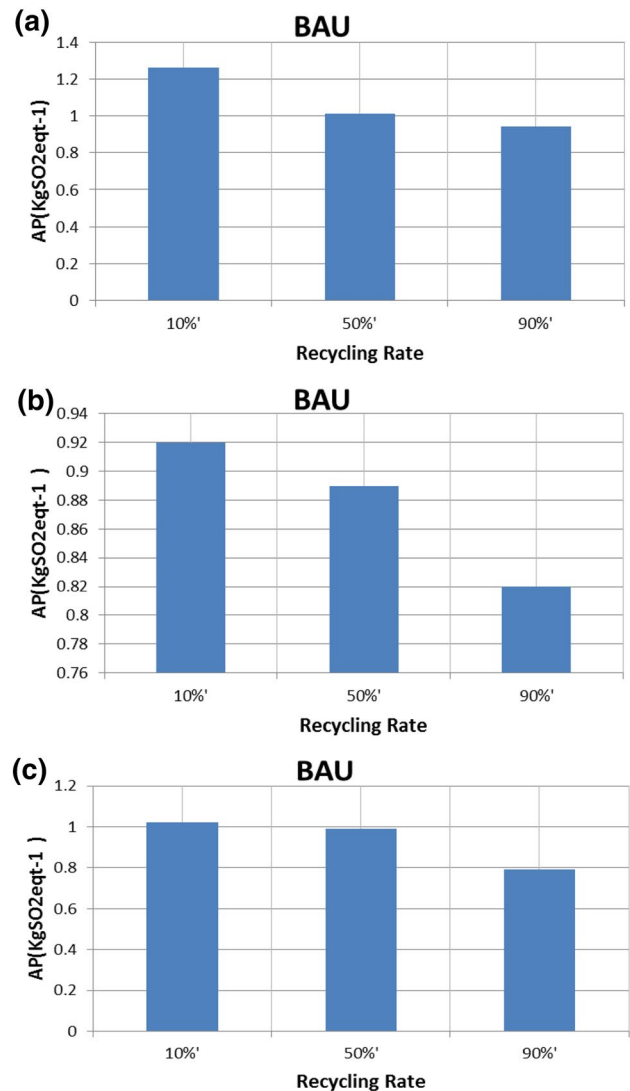
## Conclusions

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 best suitable option for the study locations will be the one which has the least



**Fig. 7** Effect of recycling rate on global warming potential under BAU scenario for **a** Chandigarh, **b** Mohali, and **c** Panchkula

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 LCA analysis showed that the present existing scenario considered (i.e., BAU) of open dumping of MSW at the three study locations had the most severe and detrimental environmental effects. This is primarily due to the fact that the existing landfill sites are non-engineered with the absence of liner systems, non-recycling, dumping of unsegregated MSW, and absence of leachate collection and treatment systems. A sensitivity analysis was carried out with a focus on the recycling rate and the impact of different recycling rates on the life-cycle emissions was analyzed for Chandigarh, Mohali, and Panchkula for the baseline scenario



**Fig. 8** Effect of recycling rate on acidification potential under BAU scenario for **a** Chandigarh, **b** Mohali, and **c** Panchkula

(BAU). In the analysis, the recycling proportions of paper, plastics, metals, textiles, and leather are 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. Recycling of valuable resources makes a significant contribution by reducing the environmental impacts. The LCA analysis carried out for Tricity of Chandigarh, Mohali, and Panchkula had certain limitations in the context of data acquisition and data availability for the study. The data utilized in the study involved combination from different databases and literature. In particular, data utilized for the LCA analysis were experimental values of site parameters (like generation rate, vehicles used for disposal, and physico-chemical parameters of groundwater) determined during the experimental phase, other data from pertinent literature

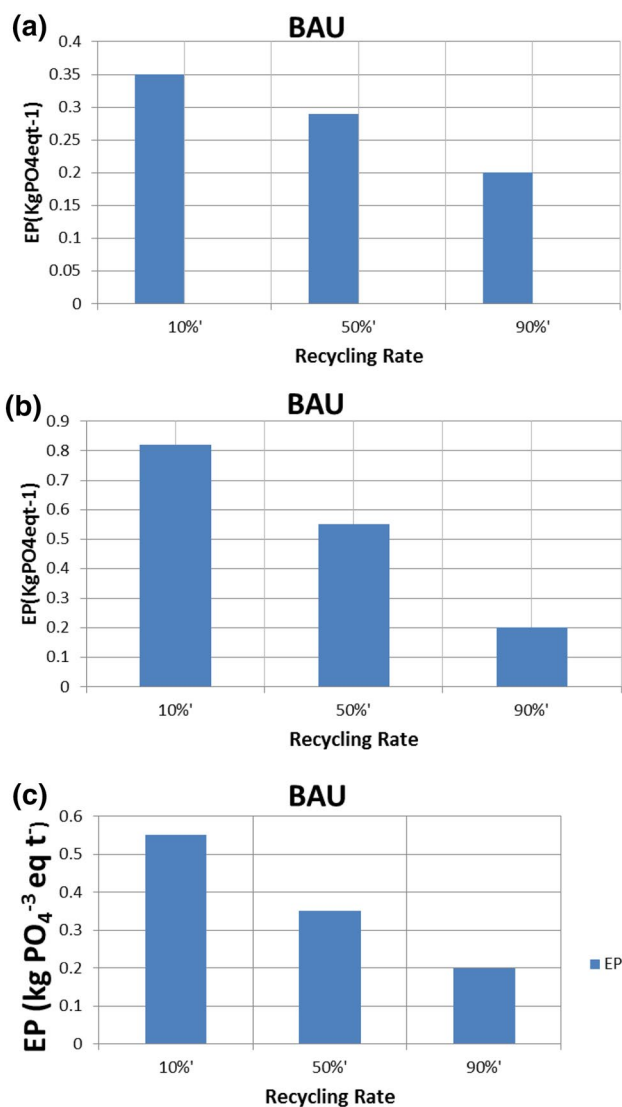


Fig. 9 Effect of recycling rate on eutrophication potential under BAU scenario for a Chandigarh, b Mohali, and c Panchkula

sources representing our study locations (like emission data), and default values of certain parameters from different inventory sources (emission inventory). It is clear from the analysis that there is no single technique that performs best for all the impact categories and, therefore, to have a comprehensive outlook of the proposed MSW management scenarios, the economic evaluation of cost and benefits of

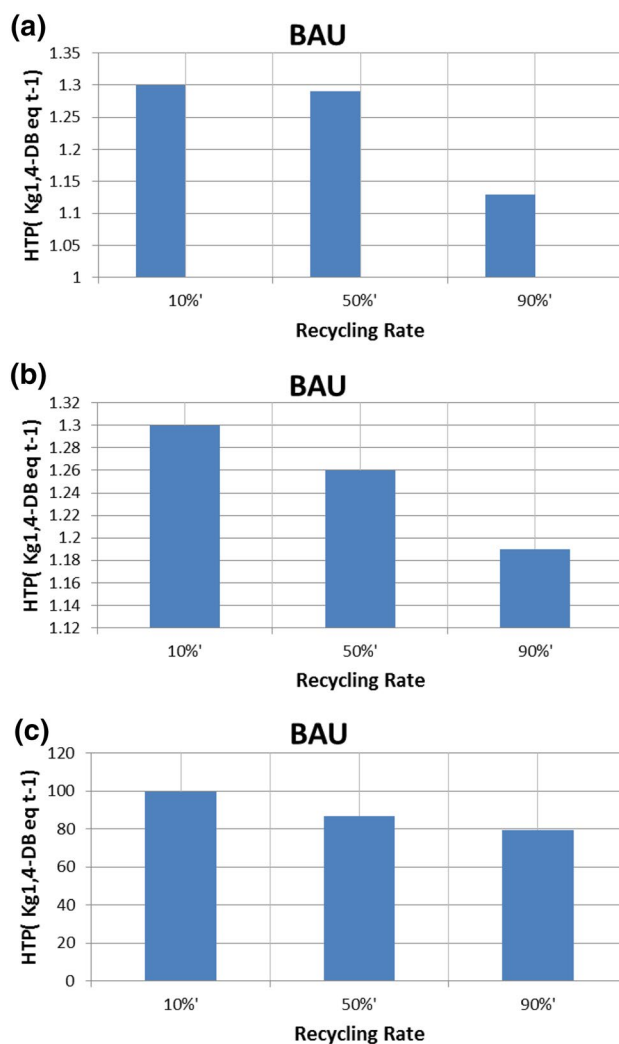


Fig. 10 Effect of recycling rate on human toxicity potential under BAU scenario for a Chandigarh, b Mohali, and c Panchkula

each proposed scenario needs to be included. Finally, as there exists no research studies and data focusing on LCA of MSW in Chandigarh, Mohali, and Panchkula, the conducted study utilizing a detailed LCA for analyzing the different MSW management systems presents the baseline conditions, thereby making it possible for the municipal authorities of the respective cities of Chandigarh, Mohali, and Panchkula to work towards improving the waste management system.



**Table 10** Environmental impacts in the BAU for sensitivity analysis at 10% and 90%

	GWP	AP	EP	HTP
Chandigarh	72.63 kg CO <sub>2</sub> eq t <sup>-1a</sup> to 70.79 kg CO <sub>2</sub> eq t <sup>-1b</sup>	1.26 kg SO <sub>2</sub> eq t <sup>-1a</sup> to 0.94 kg SO <sub>2</sub> eq t <sup>-1b</sup>	0.35 kg PO <sub>4</sub> <sup>-3</sup> eq t <sup>-1a</sup> to 0.20 kg PO <sub>4</sub> <sup>-3</sup> eq t <sup>-1b</sup>	1.30 kg 1,4-DB eq t <sup>-1a</sup> to 1.13 kg 1,4-DB eq t <sup>-1b</sup>
Mohali	71.63 kg CO <sub>2</sub> eq t <sup>-1a</sup> to 69.07 kg CO <sub>2</sub> eq t <sup>-1b</sup>	0.92 kg SO <sub>2</sub> eq t <sup>-1a</sup> to 0.82 kg SO <sub>2</sub> eq t <sup>-1b</sup>	0.82 kg PO <sub>4</sub> <sup>-3</sup> eq t <sup>-1a</sup> to 0.20 kg PO <sub>4</sub> <sup>-3</sup> eq t <sup>-1b</sup>	1.30 kg 1,4-DB eq t <sup>-1a</sup> to 1.19 kg 1,4-DB eq t <sup>-1b</sup>
Panchkula	716.3 kg CO <sub>2</sub> eq t <sup>-1a</sup> to 680.53 kg CO <sub>2</sub> eq t <sup>-1b</sup>	1.02 kg SO <sub>2</sub> eq t <sup>-1a</sup> to 0.79 kg SO <sub>2</sub> eq t <sup>-1b</sup>	0.35 kg PO <sub>4</sub> <sup>-3</sup> eq t <sup>-1a</sup> to 0.20 kg PO <sub>4</sub> <sup>-3</sup> eq t <sup>-1b</sup>	99.60 kg 1,4-DB eq t <sup>-1a</sup> to 79.45 kg 1,4-DB eq t <sup>-1b</sup>

<sup>a</sup>10%<sup>b</sup>90%

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