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Life cycle assessment of municipal solid waste generated from hilly cities in India – A case study

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ABSTRACT

Improper disposal of waste poses a grave environmental threat, contributing to pollution of air, water, and soil. It is necessary to address this issue in order to mitigate the adverse effects of solid waste on both the environment and public health. In many developing nations, municipal authorities of bigger cities are enduring significant challenges in proper management of waste. The present study evaluates the impacts of various waste management alternative scenarios for environmental impacts for the selected study locations using Life Cycle Assessment (LCA) methodology. The methodology comprised of five different scenarios of waste management including an existing baseline scenario. In this context, the environmental impact categories analyzed were Global Warming potential (GWP), Acidification potential (AP), Eutrophication potential (EP) and Human Toxicity potential (HTP). The results indicated that amongst all the proposed scenarios, Scenario 1 and 4 exhibited the maximum and minimum environmental impacts respectively. The study revealed that least greenhouse gas emissions, acidification potential, eutrophication potential and human toxicity potential were comparatively lesser for scenario 4 varying from 5.65 to 11.36 kg CO_2eq t^{-1}; 1.24–3.345 kg SO_2eq t^{-1}, EP 0.19–0.68 kg PO_4eq t^{-1}, and 0.35–4.22 kg 1,4-DBeq t^{-1} respectively. Further, a sensitivity analysis was also performed to evaluate the influence of recycling rate of valuable resources in all the considered scenarios. The sensitivity analysis indicated an inversely proportional relation between change in recycling rate and total environmental burdens.

1. Introduction

An increased population and urbanization have brought about new challenges for waste management systems in terms of generation, collection, treatment, disposal, recycling, and possible energy recovery [1,2]. It has been reported that the rate of MSW generation is faster than the rate of urbanization, with about 0.64 kg of MSW generated per person per day a few decades ago, reaching 1.2 kg per person per day in the year 2012 [3]. It has been anticipated that by the year 2025, 4.3 billion urban residents in the world will generate about 1.42 kg of MSW per person per day, totaling 2.2 billion tons per year [4]. Rapid urbanization in India has resulted in a significant generation of MSW and has led to one of the significant environmental challenges. Similar impacts have been observed in the Indian context, with per capita waste generation varying between 0.25 and 0.90 kg per person per day, with higher per capita generation in urban areas compared to rural ones [2,5].

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It is an established fact that open dumping is the most preferred method of waste disposal in developing countries like India because it is highly economical. However, such inappropriate methods of handling MSW, including open dumping, open burning, and unsanitary landfilling, create problems for public health and the environment. In principle, these open dumpsites pose severe threats to the ambient environment as they cause groundwater pollution (due to leaching effects), emit harmful gases into the air (due to the degradation of methane and the release of carbon dioxide), and lead to soil pollution (due to the impact of leachate on soil), thereby affecting its geotechnical properties [6,7]. Since most waste generated in India is of organic nature, the application of anaerobic treatment processes (under supervision) can lead to the generation of methane for use by industries and households. Similarly, the provision of generating Refuse-Derived Fuel (RDF) can also be studied and implemented. This entire coordinated process, from waste generation to production, can be achieved using an Integrated Waste Management (IWM) technique. Hence, it is imperative to study the effects of MSW disposal in current conditions and the expected impact using integrated waste management techniques.

In this context, Life Cycle Assessment (LCA) analysis is often used to identify and minimize environmental effects by analyzing the most significant issues generated due to the selection of different treatment alternatives for the waste generated. When applied to waste management, Life Cycle Assessment (LCA) becomes an important tool for reducing environmental impacts by identifying the substantial effects of ineffective waste management systems [8]. LCA involves the collection and evaluation of inputs and outputs, as well as the assessment of the environmental effects of a product system throughout its entire life cycle [9,10]. However, LCA can also serve as an essential environmental organizational tool (computer-based, using appropriate software) that helps in identifying environmental issues and their potential influences throughout the entire lifespan of waste within a defined system boundary [11–13].

Life Cycle Assessment (LCA) models can be used to assess different waste management systems and their associated environmental impacts [14–16]. The LCA method generally follows a four-step process, which includes (a) setting the boundary conditions of the assessment, including the goal, scope, and description of process or management activities; (b) detailed life cycle inventory analysis; (c) impact assessment of the life-cycle process; and (d) drawing inferences and explanations from the results [17]. Detailed descriptions, including various terminologies, have already been presented in earlier scientific literature [18–20]. The popularity of utilizing this method for analyzing different MSW management systems is exemplified in numerous published articles [21–30].

The Life Cycle Assessment (LCA) tool is utilized to assess the life cycle of products and waste management systems for disposal and recycling of waste [27]. In this context, LCA assessment is an important step before making any decisions regarding the selection of technology, policies, and approaches for implementation. Various software tools are available for computing LCA performances, such as SimaPro, GaBi, IWM-2 (integrated waste management II), WRATE (waste resources assessment tool for the environment), EASE-WASTE (environmental assessment of solid waste systems and technologies), ORWARE (organic waste research), and WISARD (waste – integrated systems for assessment of recovery and disposal).

In principle, different LCA models are available for product assessment, but in the context of waste management, they are primarily used to assess potential environmental impacts from different alternative treatment scenarios [31]. Differences between studies using different software tools are often associated with input data, algorithms used, inventories containing updated values, and the required output data [27,32]. Furthermore, differences between the applications of different LCA software tools lie in the scope of the environmental impacts required for the assessment.

A detailed examination and comparison of different LCA methodologies have been performed to ascertain the best LCA software tool [33]. Consequently, the study utilized more than 20 LCA software tools, considering various aspects, including graphic interfaces, databases, uncertainty analysis, and many other associated parameters [33]. In this context, the study concluded that SimaPro and GaBi were the most popular and frequently used software tools for LCA assessment [33]. A similar conclusion was observed in a review of LCA studies conducted to assess the performance of LCA software for the same product system [33]. Another comparative study summarized the use of more than one LCA software tool. The comparison generally considered characterization factors, normalization, as well as weighting factors for various environmental impact categories, including GWP, HTP, EP, OD, AP [34]. Another study adopted and performed [35] revealed a comparative analysis between SimaPro and Gabi software tool LC impact methodology. In this study, ten impact categories were included, and it was concluded that both software tools showed almost similar results, with very minute differences observed in the terrestrial eco-toxicity category. In principle, the outcome of LCA assessment depends on various factors, such as databases, assumptions, system boundaries, and the algorithms of the software used.

In this context, a study conducted concluded that differences in LCA results between SimaPro and GaBi (two of the most popular LCA software tools) could be attributed to the inventories, with substance characterization factors included in SimaPro and omitted in GaBi [36]. To summarize, most common LCA comparative studies of software tools focus on SimaPro and GaBi [35,36]. However, in a study conducted by Ref. [37], a comparison of LCA was made using SimaPro, GaBi, Umberto, and open LCA software. Nevertheless, the study was limited to a gate-to-gate approach and did not use a 'cradle-to-grave' life cycle assessment, which is the primary focus of a conducted LCA assessment study and was not considered in the study [35].

The application of LCA methodology in developing countries like India is primarily associated with the management of environmental health and safety, regulatory impacts, and the productive use of resource allocation over their lifespan [38]. LCA is used to assess environmental impact assessments related to climate change, toxicity potential, carcinogenic behaviour, and helps recognize associated systems and parameters that can reduce their effects [30,38–40]. However, this approach of life cycle analysis should be encouraged in low to middle-income countries, where the implementation of appropriate solid waste management activities is usually required to reduce global environmental influences [30]. It is imperative to incorporate different waste management technologies in a strategic way to achieve the objectives of sustainable waste management [41]. In a research study conducted in Kathmandu [42], a Life Cycle Assessment (LCA) was carried out concerning the management of Municipal Solid Waste (MSW) within Kathmandu city. This study undertook a comparative analysis involving three distinct scenarios: the conventional approach, energy recovery combined with recycling, and a disposal system integrating composting and landfilling. The assessment encompassed the evaluation and quantification of emissions released into the environment, including factors like global warming potential, acidification potential, eutrophication potential, and fuel energy consumption. Through this comprehensive study, the objective was to identify the most suitable and sustainable management scenario for MSW. The findings and subsequent analysis led to the conclusion that the scenario incorporating composting and landfilling presented the least significant environmental impacts among the alternatives considered. In a similar study conducted in Turkey [43], an LCA assessment was carried out on five scenarios. These scenarios were explored as alternatives to the existing waste management practices. The study concluded that the most environmentally favourable option among the selected scenarios involved a combination of recycling and composting. A study conducted in Yogyakarta, Indonesia [44], utilized LCA assessment for comparing six varied scenarios for managing Municipal Solid Waste (MSW). The study concluded that the optimal choice, considering environmental impacts, involves the integration of gasification and anaerobic digestion.

Finally, to highlight, very few LCA studies have been conducted in the Indian context [45]. In the Indian context, a study conducted for Delhi city [1] adopted an LCA methodology to assess environmental emissions. This assessment involved the examination of various Municipal Solid Waste (MSW) management possibilities, encompassing recycling, composting, incineration, and landfilling. Furthermore, the study forecasted the projected quantity and composition of Delhi's MSW up to 2024. The outcomes of the study revealed that recycling exhibited the minimal environmental impacts among the considered options. The investigation unveiled that the recycling, composting, and sanitary landfilling approach outperformed the other considered scenarios. A similar study conducted for Mumbai city [2] compared six different scenarios and found that the best options compositing and sanitary landfilling option were superior to the other scenarios.

Life-cycle assessment (LCA) is a methodology for evaluating the environmental aspects and practical effects associated with waste by compiling an inventory of relevant inputs and outputs over the entire life cycle [41]. The LCA technique helps to identify the roots of changeable vulnerabilities and hence allows decision-makers to mend the environmental performance of the waste management practices [46]. In this context, the study presents an LCA assessment of MSW generated in four different locations in the state of Himachal Pradesh in India.

2. Methods

2.1. Study locations and waste composition

The state of Himachal Pradesh is currently experiencing an alarming trend in the rise of MSW generated, with an open disposal system creating additional environmental and public health issues. Furthermore, since the state is a popular tourist destination, and the study locations are 'en-route' to other popular tourist destinations, it is often not possible to manage the entire waste scenario effectively. The waste disposed of in open landfills often leads to the generation of methane gas, which pollutes the surrounding ambient air and has the tendency to catch fire, leading to adverse effects on human health and the environment. Hence, there is an urgent need to incorporate an effective waste management strategy that addresses environmental sustainability concerns. It is in this context that the application of LCA methodology can contribute by computing the environmental impacts of the implementation of integrated municipal solid waste management systems.

The current study was conducted in four study locations (namely Solan, Mandi, Sundernagar, and Baddi) in the state of Himachal Pradesh, located in the northern part of India. Details of these study locations, including their population, per capita waste generation, characterization of waste generated, and all other associated information, have already been reported in earlier scientific literature [2, 47]. To summarize, all the study locations share almost similar characteristics, with a total estimated waste generation varying between 18 and 22 tons per day (TPD) and per capita generation ranging from 0.42 to 0.44 kg per day. The locations of the four distinct study regions have been shown in Fig. S1 in the supplementary material.

2.2. Life cycle analysis

In the present study, the proposed LCA assessment has been carried out following the framework designed by the International Organization for Standardization (ISO) 14,040:2006 methodology. As mentioned earlier, LCA includes four steps comprising the goal of the study, a life cycle inventory that highlights the inputs and outcomes, a life cycle impact assessment that consists of environmental impacts, and finally, the interpretation of the results obtained. The goal of the study is to evaluate the environmental impacts of the municipal solid waste management strategy in Solan, Mandi, Sundernagar, and Baddi regions using an LCA approach. In this context, four scenarios of municipal solid waste management have been designed (to be presented in the next section) to select an optimum waste management system that comprises waste treatment, processing, and disposal facilities. These scenarios will then be compared with respect to potential environmental impacts, including Global Warming potential (GWP), Acidification potential (AP), Eutrophication potential (EP), and Human Toxicity potential (HTP), for each of the four study regions in Himachal Pradesh.

2.2.1. Functional unit

Functional unit is described for the given quantity of municipal solid waste that will be managed under a specific waste management strategy. The functional unit is taken as 1 ton of MSW in each of the four study regions of Himachal Pradesh for the comparison of municipal solid waste management system.

2.2.2. System boundary

The system boundary consists of a collection of unit processes that perform distinct functions. The general description of the system boundary is shown in Fig. 1, and the systematic approaches of LCA have been summarized in Fig. S2 of the supplementary material. The description of the system boundary for the study regions in Himachal Pradesh is demonstrated in Fig. 2. The input data utilized in the system boundary include municipal solid waste composition, energy, and mass, whereas the outputs considered are air emissions, water emissions, and emissions to soil from all the processes. The second step in conducting the LCA assessment includes the preparation of the inventory analysis, which primarily involves data collection related to the inputs and outputs of the study system. LCI involves collating specific information on inputs and outputs associated with the process, helping determine the environmental impacts [31,48]. The LCI data for the present assessment was derived from 'in-situ' analysis with appropriate data collected from relevant municipalities (waste generation, waste processing, transportation, and population) and utilization of the database Ecoinvent 2.2.

The emissions utilized for the study were determined after a thorough review of scientific literature, the database of SimaPro version 8.3.2, and the Eco-Inventory characterization method. Furthermore, the database of the software was adjusted to simulate the conditions prevalent in Himachal Pradesh. The description of scenarios and the summary details of the inventories have been presented in Tables 1 and 2, respectively. Other current data utilized in the present assessment were the population details of the study locations, waste characteristics, waste collection information, and data from open landfills. The physico-chemical characterization of waste for the study locations, as reported by the authors in another scientific literature [49], was used to determine the environmental profile of different considered scenarios for each of the study locations. Similarly, the processes involved in the transportation of MSW were also included in the system boundary, the details of which were reported and utilized by the authors in another scientific publication [2]. In summary, the data needed for the life cycle inventory were gathered from earlier reported scientific literature, the database of the software, and other relevant information collected from municipal authorities. In this respect, the outcomes can assist decision-makers in formulating efficient municipal solid waste management strategies.

Life-Cycle Impact Assessment (LCIA) is the third stage of the process that associates all the inputs and outputs with environmental impact categories [5,34]. The present study uses four impact categories, namely Global Warming, Acidification, Eutrophication, and Human Toxicity, using the Eco-indicator 99 (H) method. The last stage of the LCA assessment process is the interpretation of results, which reviews all the different stages during the LCA analysis. This stage summarizes all the data analyzed and checks the outcomes against the defined goals and scopes of the study. The review of LCA software is presented in the next paragraph.

The present study utilized the SimaPro software package for conducting the LCA analysis of the waste generated in the study areas. SimaPro software version 8.3.2 was used in the study and is commercial software licensed by PRe consultants, assessing the sustainable performance of a product or system. The software is also fully compliant with ISO 14040/14,044 and has complete functional abilities for computing LCI and LCIA analyses. The software has the capability to incorporate the entire MSW generation stream into its operating system and is highly specific in its input requirements. In principle, it uses data from three component sources, namely project data, library data, and general information. Thereafter, it builds the entire life cycle using the associated input data. It models the life cycle using the incorporated assemblies and input information provided. Its library functions within the software incorporate voluminous amounts of pre-defined information, including substances, materials, treatment systems, and associated impact assessment procedures used for formulating the model for a required study. The different input details are discussed separately in earlier reported literature by the authors [5]. Relevant input information regarding waste characteristics and other associated parameters from the four study locations in Himachal Pradesh were recorded in the SimaPro software. It utilized this input data to calculate possible emissions from various scenarios using the Eco-indicator 99 method and Ecoinvent database.

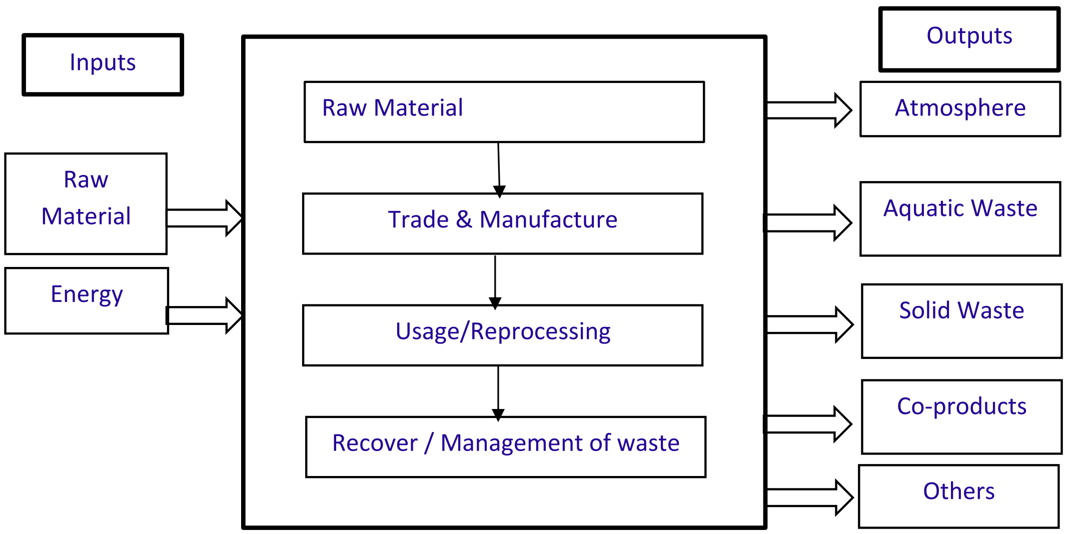


Fig. 1. The general description of system boundary.

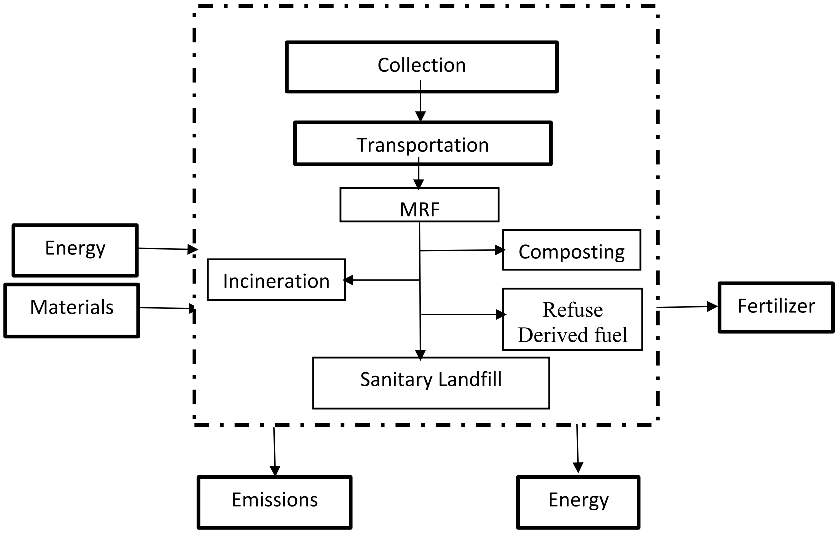


Fig. 2. System boundary for study regions in Himachal Pradesh.

Table 1
Depiction of scenarios used in present study.

Sr. No.	Scenarios	Description
S (1)	Baseline scenario (BAU)	Business as usual signifies the current MSW management practice in study regions of Himachal Pradesh.
S (2)	Material recovery facility _Composting, Incineration (MRF_COM_INC)	20 % recycling+40 % composting+30%incineration
S (3)	Reduced derived fuel Material recovery facility Composting, Sanitary landfilling (RDF_MRF_COM_SLF)	30 % reduced derived fuel + 20 % material recovery facility + 30 % composted + 20 % sanitary landfilling.
S (4)	Composting Material recovery facility Sanitary landfilling (COM_MRF_SLF)	50 % composting + 30 % material recovery facility + 20 % landfilling
S (5)	Reduced derived fuel Sanitary landfilling (RDF_SLF)	60 % reduced derived fuel + 40 % sanitary landfilling.

Table 2
Life-cycle inventories for Himachal Pradesh [19,20,29].

Inputs	Values	Units
1. Landfill		
(a) Diesel	2	L^{-1}
(b) Net electrical Efficiency	10	%
2. Material recovery facility		
(a) Diesel	3.20	
(b) Electricity	3.1	L^{-1}
		kWh t^{-1}
3. Composting		
(a) Diesel	0.53	
By-product		L^{-1}
(a) Compost	140	
		kg t^{-1}
4. Incineration (a) Net electrical efficiency	20	%
By- product Ash	140.8	Kgt^{-1}
5. Refuse derived fuel (a) Net electrical efficiency		%
By-product Ash	15	
		Kgt^{-1}
	90.76	

2.3. Different MSW scenarios considered for the LCA study

The following scenarios were considered for the LCA analysis for the management of MSW generated at the study locations.

2.3.1. Scenario 1: (baseline or BAU scenario)

The Baseline or Business as Usual (BAU) scenario corresponds to the current status of solid waste management strategies in various selected study locations, including Solan, Mandi, Sundernagar, and Baddi in Himachal Pradesh. To summarize, the study locations of Baddi and Sundernagar, which generate an average of 18–20 TPD of MSW, dispose of their entire waste in open landfill conditions. Similarly, in the study locations of Solan and Mandi city, which generate about 21–22 TPD, a proportion of the waste is being dumped in an open landfill, with some portions being used for composting. However, the quality of the compost is not good enough to be directly used for agricultural purposes. Furthermore, no recycling activities were taking place during these times. This has already been described by the authors in earlier reported scientific literature [2,49]. However, with the passage of time and during the conduct of our study, there was some improvement in recycling rates, with about 10 % of the waste material being informally recycled. Considering this, the different options considered for the study in the BAU scenario for Sundernagar and Baddi were that 90 % of the waste was being open dumped, and 10 % of the waste was being recycled (as per discussions with local municipal authorities). However, for the study locations of Solan and Mandi, it was assumed that 50 % of the waste was open dumped, 10 % of the waste was being recycled, and the remaining waste was used in composting plants. However, with only a small fraction of recycling taking place and many unwanted materials being present during the composting process, the quality of the compost obtained was not of good quality, as previously reported by the authors in earlier scientific literature [49].

2.3.2. Scenario 2: (MRF_COM_INC)

This scenario describes the combination of a Material Recovery Facility (MRF), composting (COM) due to the high fraction of moisture content in the waste, and incineration (INC) for the management of MSW generated in the study locations. It is one of the most simplistic approaches for an integrated waste management system in the future. In this scenario, 20 % of the materials are recycled, 40 % of the biodegradable waste is composted, while the rest of the waste is incinerated.

2.3.3. Scenario 3: (RDF_COM_MRF_SLF)

This scenario depicts the potential to diminish the environmental impacts of municipal solid waste by presuming that 30 % of the material is directed to an RDF plant, 30 % of the biodegradable waste is composted (COM), 20 % of the waste is recycled (MRF), and the remaining 20 % is disposed of in a sanitary landfill (SLF).

2.3.4. Scenario 4: (MRF_COM_SLF)

Due to the presence of high moisture content in the total waste, this scenario includes composting along with MRF, and the rest of the waste is directly disposed of in an engineered sanitary landfill site. In this scenario, 30 % of the waste materials are recycled, 50 % of the biodegradable waste is processed through composting, with the remaining quantity of the waste being disposed in sanitary landfills.

2.3.5. Scenario 5: (RDF_SLF)

This scenario introduces the waste processing technique, including refuse-derived fuel (RDF), while the rest of the waste is directly transported to the properly engineered sanitary landfill site (SLF). In this scenario, 60 % of the waste is utilized in the RDF plant, and the remaining portion is disposed of in sanitary engineered landfills. It is important to mention that the five case scenarios considered in the study, along with the different proportions involved in each of these scenarios, were discussed in detail with municipal authorities of these study locations, senior scientists from the State and Central Pollution Control Board of India, and other senior personnel involved in the management of MSW in the hilly state of Himachal Pradesh. Once a consensus on the different scenarios was achieved, the detailed LCA assessment was conducted. The summary of the different scenarios considered for the study has been presented in Table 1, and the inventories used for the assessment of these cases are listed in Table 2.

2.4. Sensitivity analysis

The sensitivity analysis was carried out to determine the assumptions used in the LCA assessment and how the final outcomes were affected by uncertainties in the input data. In other words, it also assesses the reliability of the LCA assessment results. The main aim of a sensitivity analysis is the identification of a parameter in which inducing a small change in its value leads to a significant influence on the outcome. In the present study, the sensitivity analysis was carried out on recycling rates. Typical examples of recycling materials obtained from waste are paper, glass, and metals. In principle, recycling is one of the most important components in the management of MSW. With proper implementation of this component, it can lead to resource recovery and significantly reduce the waste burden entering the landfill. The benefits associated with resource recovery of products like paper, glass, and metals are that they can be recycled with ease in industries, thereby reducing the requirement for raw materials in their manufacture. Further, the implementation of a formal system of recycling will lead to the generation of income for these recycling workers, which enters the main economic cycle. Currently, the entire recycling activities in the Indian context are dominated by the informal sector. Additional benefits of recycling include significant environmental implications depending on the material recycled and its purpose. The materials considered for recycling in the present study include paper, plastics, glass, metals, leather, and textile goods from all the study locations. The entire recyclable fraction of the total waste generated for the study locations was greater than 30 % for all the study locations [2]. The literature review revealed that the economically and environmentally friendly recycling rate is 50 %. The sensitivity analysis was conducted for three percentages: 10 %, 40 %, and 90 % recycling rate, indicating the least, intermediate, and maximum proportions of recycling.

3. Results and discussion

3.1. Assessment of environmental effects

The results of the LCA analysis for each of the study locations and the different scenarios considered are presented in this section. The LCA analysis tool, SimaPro version 8.3.2, was run for five different scenarios, including the baseline (BAU) condition for the respective study regions of Himachal Pradesh. The different study locations exhibited different environmental problems due to differences in the nature of waste. The study is new in Himachal Pradesh, and the maximum data were obtained from the municipal authorities of various study regions. The different environmental emissions (air, water, emissions to soil) under different scenarios for Solan, Mandi, Sundernagar, and Baddi have been summarized in Tables S1–S4 of the supplementary material, respectively.

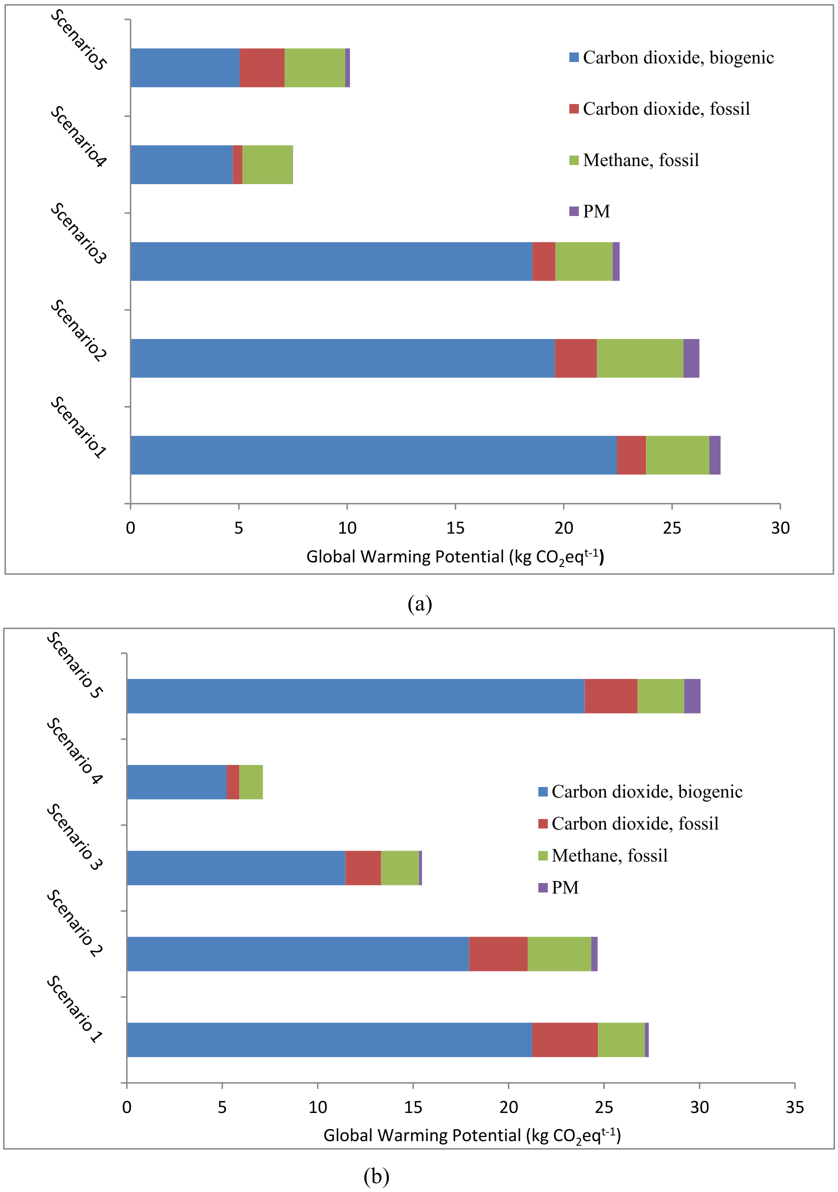
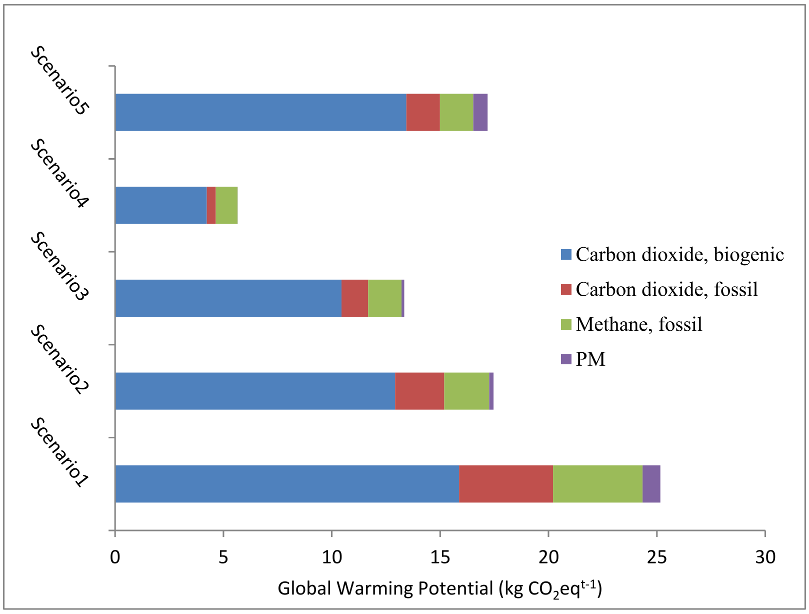
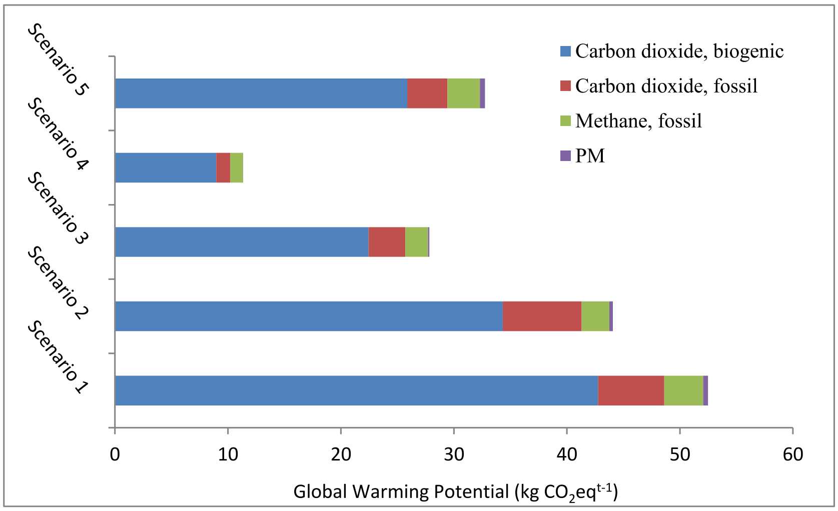


Fig. 3. Global warming potential under different scenarios for (a) Solan, (b) Mandi (c) Sundernagar (d) Baddi.



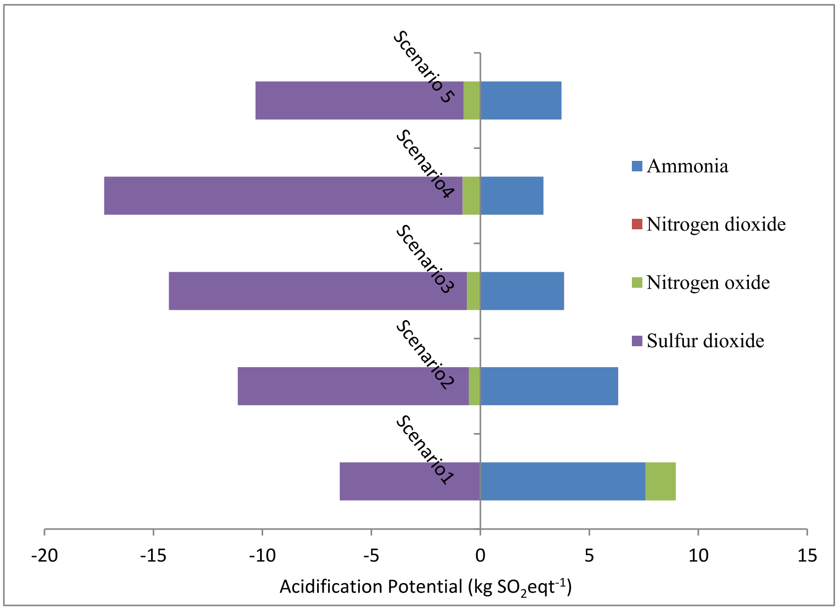
(c)



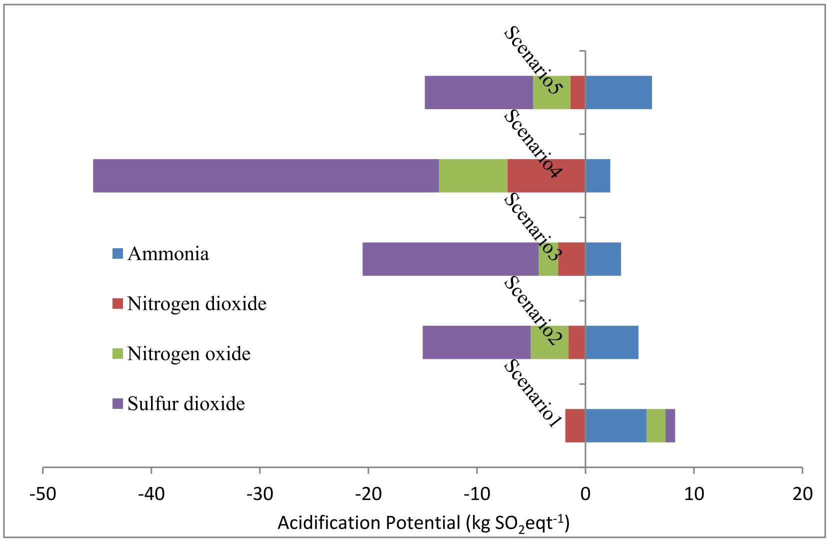
(d)

Fig. 3. (*continued*).

To summarize, the airborne emissions are categorized into four categories (Global Warming Potential, Human Toxicity Potential, Acidification Potential, and Eutrophication Potential). The second type is waterborne emissions, and the categories covered under such conditions are Eutrophication and Human Toxicity Potential. The third type is soil emissions, and it is categorized by Eutrophication and Human Toxicity Potential. A major objective of MSW management is to minimize the quantity of waste disposed of in a landfill site. It has been reported that only about 20 % of the waste generated in developing countries like India is treated, with the remaining being dumped in open landfills. This is primarily because wastes dumped in open landfills undergo anaerobic degradation, leading to the generation of potential greenhouse gases (GHG) like carbon dioxide and methane. Along with this, the biodegradable portion of the waste generates large volumes of nitrogen and phosphorus compounds, which contribute heavily to Acidification, Eutrophication, and Human Toxicity Potential. The results have been summarized in Figs. 5–8. The environmental impacts are denoted as (a) Solan, (b) Mandi, (c) Sundernagar, and (d) Baddi, respectively. The following sections present the details of the environmental impact assessments obtained from the different scenarios.



(a)

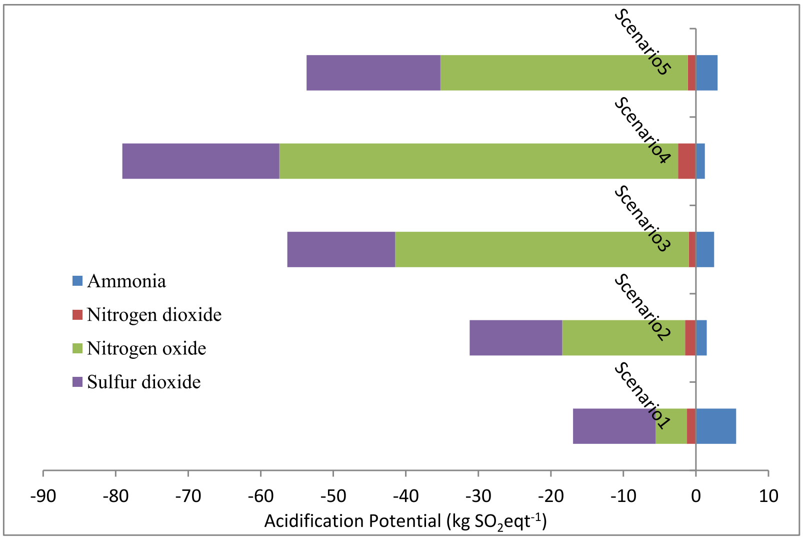


(b)

Fig. 4. Acidification potential under different scenarios for (a) Solan, (b) Mandi (c) Sundernagar (d) Baddi.

3.2. Global warming potential

Global Warming is the consequence of temperature increments owing to emissions of greenhouse gases, including carbon dioxide, methane, CFCs, and other heat-trapping compounds [15]. Fig. 3 summarizes the GHG emissions under the four scenarios along with the baseline scenario. Scenario 1 (BAU) depicted the maximum emissions of GHGs at 27.24 kg CO_2eq t^{-1} (Solan), 27.34 kg CO_2eq t^{-1} (Mandi), 25.16 kg CO_2eq t^{-1} (Sundernagar), 52.51 kg CO_2eq t^{-1} (Baddi) due to the emissions of methane, carbon dioxide (fossil), carbon dioxide (biogenic), and particulate matter. In particular, the burning of MSW leads to the generation of both biogenic and fossil carbon dioxide. The positive values depict a load on the environment, whereas negative values depict reduced emissions [28]. However, emissions from fossil CO_2 and CH_4 are comparatively lower in the case of the incineration process rather than in open dumps. However, if the waste is not burned, it is likely to be disposed of in an open dumpsite, which is the least environmentally friendly option. In contrast, the burning of waste can also cause severe environmental pollution and can affect public health as it emits dioxins,



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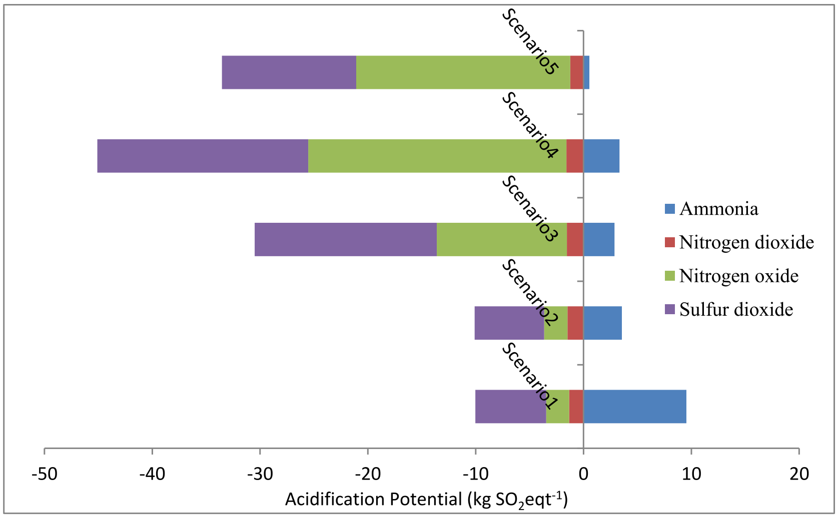


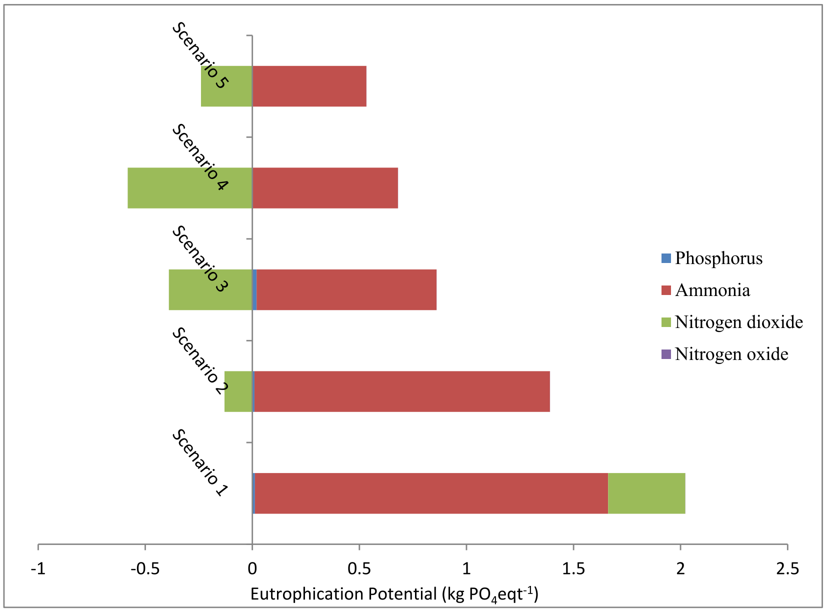
(d)

Fig. 4. (*continued*).

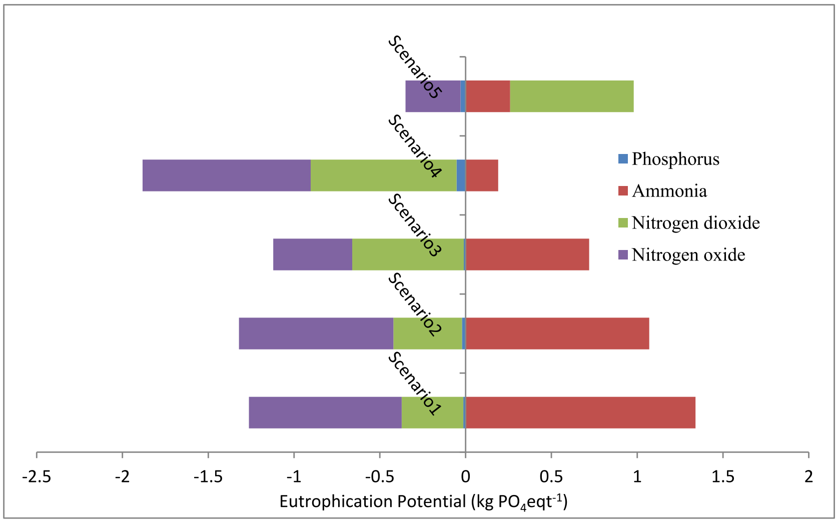
mercury, carbon dioxide, and many more pollutants but is safer than the open dumping process (i.e., the lesser of the two evils).

It is also interesting to note that emissions of GHG from Baddi are almost double the emission rates from the other study locations. This can be attributed to the possible fact that this study location is an industrial hub of the state and is also a border region with a neighbouring state. Characterization studies have earlier shown that this study location has almost three times the proportions of plastic in comparison to the other three study locations, which in turn leads to more GHG production, as observed from the LCA analysis results. However, it has been observed that the least greenhouse gas emissions occur for scenario 4 (MRF_COM_SLF), i.e., 7.51 kg CO_2eq t^{-1} (Solan), 7.13 kg CO_2eq t^{-1} (Mandi), 5.65 kg CO_2eq t^{-1} (Sundernagar), 11.36 kg CO_2eq t^{-1} (Baddi), which is the combination of material recovery facility, composting process, and sanitary landfilling processes. This can be attributed to the reason that all the remaining considered scenarios had the option of burning waste (Scenario 2) and using refuse-derived fuel (scenarios 3 & 5), which would lead to the emission of GHGs.

A comparative analysis of the above results was carried out with findings from previous scientific literature, as presented in Table 5. Notably, the observed GWP values in our study locations were significantly lower in comparison to earlier literature for both the best- and worst-case scenarios. For instance, a study in La Paz, Bolivia, found the least GWP value (772.8 kg CO_2eq t^{-1}) for a scenario involving sanitary landfill and small-scale composting [30]. In a landfill study in Sakarya, Turkey, without biogas recovery, GWP was determined to be 1840 kg CO_2eq t^{-1} [43]. Another study in Mauritius, which incorporated energy recovery in landfilling, yielded a GWP of 767 kg CO_2eq t^{-1} [37]. A study conducted in Astana; Kazakhstan reported the GWP as 1910.8 kg CO_2eq t^{-1} for waste disposal in landfill without landfill gas being captured [50]. In a similar study conducted in Hangzhou, China, for a landfill site being used for



(a)



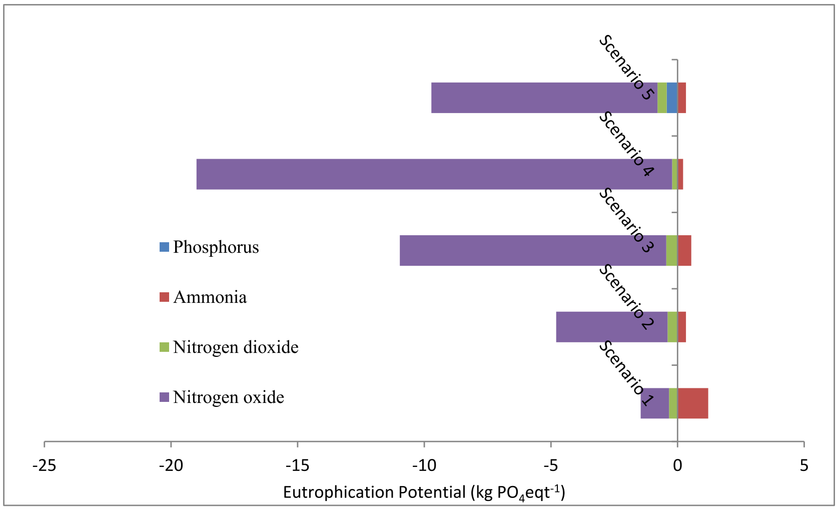
(b)

Fig. 5. Eutrophication potential under different scenarios for (a) Solan, (b) Mandi (c) Sundernagar (d) Baddi.

dumping mixed MSW and incineration, revealed a GWP value of 502 kg CO_2eq t^{-1} using Gabiv8.0 [51]. In the Indian context, GWP values were diverse: 998.4 and 731.9 kg CO2eq t^{-1} for assessments in Mumbai [28] and Panchkula [19], respectively. GWP values for the present study locations were determined to be (Solan – 27.24 kg CO_2eq t^{-1}; Mandi – 27.34 kg CO_2eq t^{-1}; Sundernagar – 25.16 kg CO_2eq t^{-1}; Baddi – 52.51 kg CO_2eq t^{-1}) in the worst-case scenario and (Solan – 7.51 kg CO_2eq t^{-1}; Mandi – 7.13 kg CO_2eq t^{-1}; Sundernagar – 5.65 kg CO_2eq t^{-1}; Baddi – 11.36 kg CO2eq t^{-1}) in the best-case scenario. These values were notably lower compared to prior literature, primarily due to the lesser amount of waste being disposed of in the landfills at our study sites.

3.3. *Acidification potential*

Acidification is generally defined as the release of acidifying substances into the environment. In principle, Acidification Potential (AP) denotes the impact of gases, including SO_2, SO_3, NO_x, HCl, and hydrogen fluoride, released into the air that can combine with atmospheric moisture and consequently fall on the Earth's surface as 'acid rain.' In this context, the pH of the precipitation decreases (becomes more acidic) due to the reacted acid gases. When such rainwater is absorbed by plants, soil, and surface waters, it leads to the



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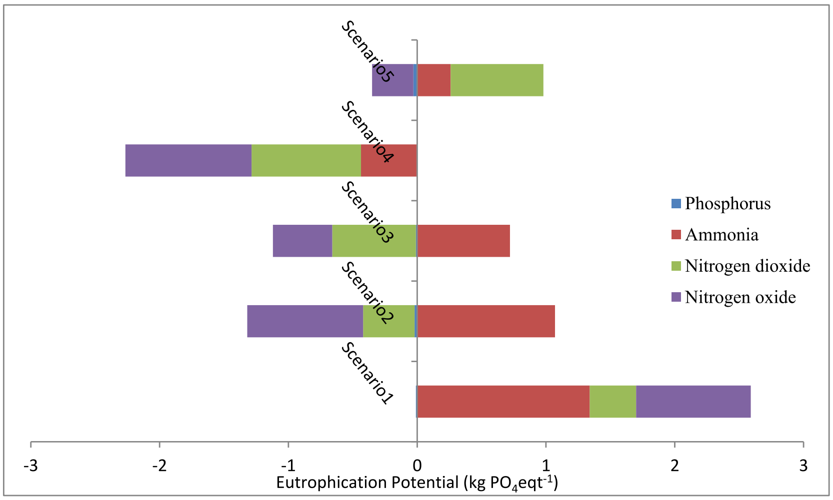


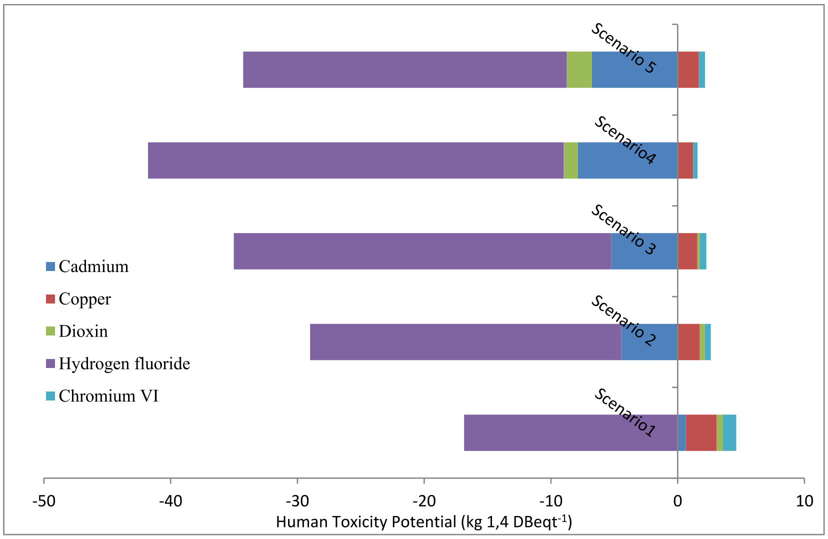
(d)

Fig. 5. (*continued*).

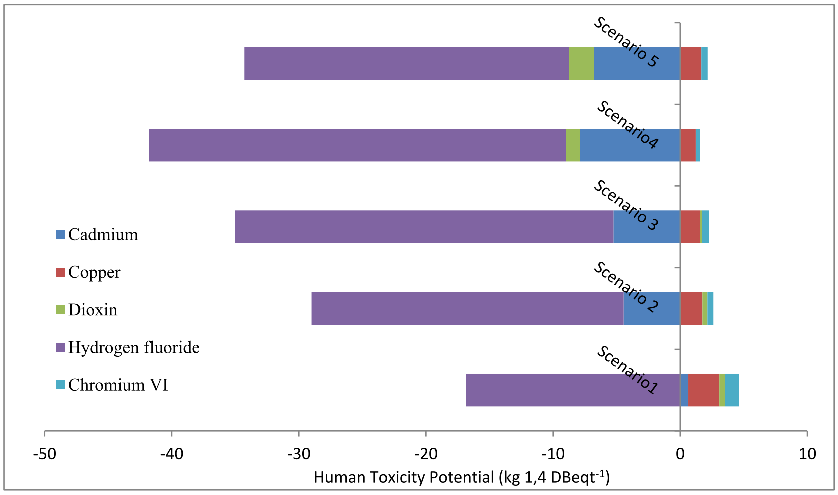
degradation of soil, air, and water quality. Furthermore, acidification is a severe health concern for humans as it directly affects the respiratory system. Earlier scientific literature has shown that the incineration process has a higher impact on AP than landfilling [20]. In this context, the adoption of practices that do not include incineration or burning of waste can significantly reduce the acidification potential of the waste generated [20].

Fig. 4 summarizes the acidification potential under the four scenarios along with the baseline scenario. The maximum AP was observed in the baseline scenario, with determined values of 8.98 kg $SO_2eq\ t^{-1}$ (Solan), 8.26 kg $SO_2eq\ t^{-1}$ (Mandi), 5.56 kg $SO_2eq\ t^{-1}$ (Sundernagar), 9.55 kg $SO_2eq\ t^{-1}$ (Baddi). Further, BAU consists of open and uncontrolled dumping of municipal solid waste with very little material recovery facility, which leads to increased Acidification Potential. The least acidification potential has been noticed in Scenario 4 due to environmental benefits by a combination of composting and material recovery. Hence, the overall impacts of Scenario 4 have the least AP amongst all the other considered alternative scenarios, with determined values of 2.89 kg $SO_2eq\ t^{-1}$ (Solan), 2.28 kg $SO_2eq\ t^{-1}$ (Mandi), 1.24 kg $SO_2eq\ t^{-1}$ (Sundernagar), 3.35 kg $SO_2eq\ t^{-1}$ (Baddi).

A comparative analysis of Acidification Potential (AP) was conducted, juxtaposing it with earlier scientific literature findings summarized in Table 5. The results obtained from this study demonstrated significantly higher values for the study locations in comparison to previously reported data considering both worst- and best-case scenarios. For instance, in a study carried out in La Paz, Bolivia, the scenario involving sanitary landfill usage and small-scale composting exhibited the lowest AP value at 0.10 kg $SO_2eq\ t^{-1}$ [30]. Another investigation conducted in a landfill site in Sakarya, Turkey, without considering biogas recovery, yielded an AP of 0.169 kg $SO_2eq\ t^{-1}$ [55]. Similarly, a study in Mauritius, involving landfill disposal with energy recovery provisions, resulted in an AP of 1.20 kg $SO_2eq\ t^{-1}$ [37]. A similar study carried out in Astana; Kazakhstan yielded an AP of 0.12 kg $SO_2eq\ t^{-1}$ when waste was disposed of in a landfill setting without capturing landfill gas emissions [50]. Similarly, a comparative investigation conducted in



(a)



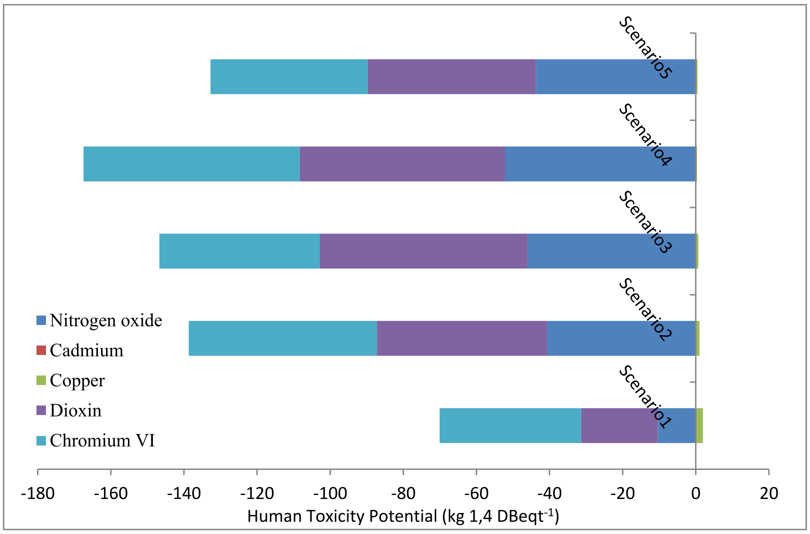
(b)

Fig. 6. Human toxicity potential under different scenarios for (a) Solan, (b) Mandi (c) Sundernagar (d) Baddi.

Hangzhou, China, focused on a landfill site utilized for mixed municipal solid waste (MSW) dumping and incineration. This study yielded AP value of −0.30 kg SO_2eq t^{-1}, employing the Gabiv8.0 methodology [51]. Very high AP of 5.20 kg SO_2eq t^{-1} were observed for a study conducted in Alytus region in Lithuania [53] In the context of India, specific assessments in Mumbai [28] and Panchkula [19] showcased AP values of 0.10 and 1.12 kg SO_2eq t^{-1}, respectively. Notably, the AP values generated for the present study locations were as follows: for the worst-case scenario - Solan: 8.98 kg SO_2eq t^{-1}, Mandi: 8.26 kg SO_2eq t^{-1}, Sundernagar: 5.56 kg SO_2eq t^{-1}, and Baddi: 9.56 kg SO_2eq t^{-1}; and for the best-case scenario - Solan: 2.89 kg SO_2eq t^{-1}, Mandi: 2.28 kg SO_2eq t^{-1}, Sundernagar: kg SO_2eq t^{-1}, and Baddi: kg SO_2eq t^{-1}. The results signify that acidification plays a crucial role in exerting a substantial influence on soil, water, and air quality. Notably impactful pollutants such as nitrogen oxides, sulphur dioxide, hydrochloric acid, and ammonia are encompassed within the system boundary, underscoring the considerable potential for acidification, as has been reported in earlier literature [45].

3.4. Eutrophication potential

Eutrophication is activated by the discharge of nitrogen-based compounds like ammonia and phosphates [16]. Water bodies are enriched with additional minerals and nutrients, leading to the excessive growth of algae. In such ecosystems, this increased algae



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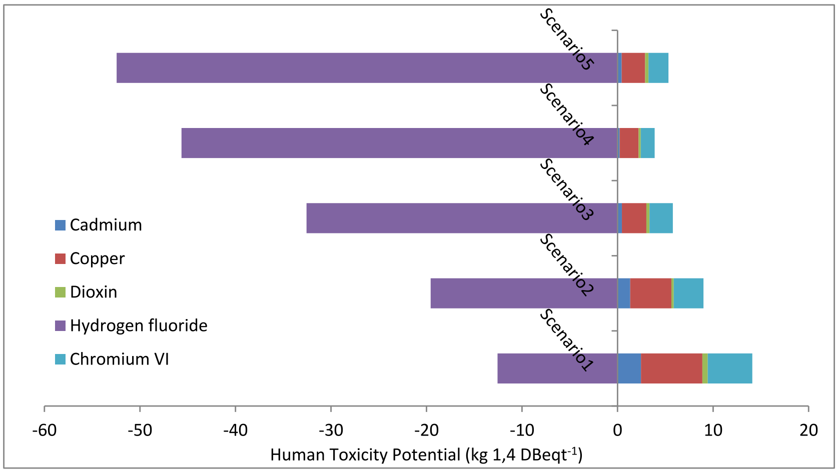

(d)

Fig. 6. (*continued*).

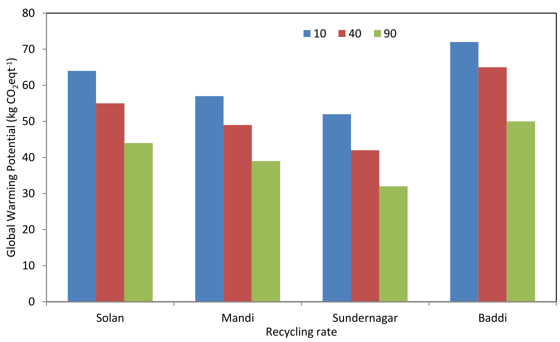

Fig. 7. Effect of recycling rate on GWP under BAU scenario.

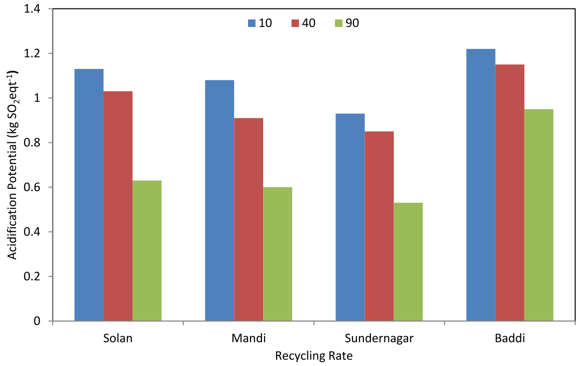

Fig. 8. Effect of recycling rate on AP under BAU scenario.

Table 3
Physical characterization of MSW for study regions.

Sr. No.	Parameters	Solan	Mandi	Sundernagar	Baddi
1.	Density (kg/m^3)	552 ± 1.35	540 ± 2.82	512 ± 1.27	487 ± 0.98
2.	Organic waste (%)	57.67 ± 0.52	56.00 ± 0.63	52.83 ± 0.98	50.83 ± 0.75
3.	Paper (%)	17.17 ± 0.75	18.17 ± 0.75	20.83 ± 0.75	11.50 ± 0.55
4.	Plastic (%)	6.33 ± 0.55	6.33 ± 0.82	6.67 ± 0.52	13.67 ± 0.82
5.	Glass (%)	3.33 ± 0.52	3.17 ± 0.55	3.17 ± 0.41	3.17 ± 0.41
6.	Metal (%)	1.67 ± 0.53	2.17 ± 0.55	2.17 ± 0.75	2.00 ± 0.63
7.	Inert (%)	5.67 ± 1.68	6.00 ± 0.52	6.00 ± 0.63	9.00 ± 0.89
8.	Rubber (%)	2.67 ± 0.52	3.17 ± 0.41	3.17 ± 0.75	1.83 ± 0.41
9.	Textile (%)	5.33 ± 2.67	5.67 ± 0.52	5.17 ± 0.75	8.00 ± 0.63

growth reduces the amount of sunlight reaching the deeper layers, thereby decreasing photosynthesis and oxygen concentration. This low oxygen concentration is inadequate for the survival of aquatic animals. The main substances in municipal solid waste that contribute to eutrophication potential (EP) are phosphorus and ammonium, expressed in kg PO_4eq t^{-1}. Furthermore, the presence of excess nitrogen may render groundwater unfit for drinking. Fig. 5 summarizes the eutrophication potential under four scenarios along with the baseline scenario. It was observed that the maximum eutrophication potential was in scenario 1 due to the absence of a liner system, with determined values of Solan - 2.03 kg PO_4eq t^{-1}; Mandi - 1.34 kg PO_4eq t^{-1}, Sundernagar – 2.15 kg PO_4eq t^{-1}, and Baddi - kg PO_4eq t^{-1} respectively. The primary cause of eutrophication potential is the large voluminous quantities of waste being open-dumped. These compounds dissolve along with the leachate and cause severe environmental impacts. However, the least eutrophication potential was observed in scenario 4 (MRF_COM_SLF), i.e., Solan 0.68 kg PO_4eq t^{-1}; Mandi - 0.19 kg PO_4eq t^{-1}, Sundernagar - 0.23 kg PO_4eq t^{-1}, and Baddi - 0.98 kg PO_4eq t^{-1}respectively.

A comparative assessment of Eutrophication Potential (EP) was carried out, comparing the results obtained at our selected study locations with earlier reported scientific literature as mentioned in Table 5. The study's outcomes revealed notably higher values for the examined locations compared to previously reported data for worst-case scenarios but significantly lower values when considering the best treatment alternative. For example, in a study conducted in La Paz, Bolivia, the scenario involving sanitary landfill utilization and small-scale composting displayed the lowest EP value at 0.14 kg PO_4eq t^{-1} [30]. Another investigation in a landfill site in Sakarya, Turkey, excluding biogas recovery, yielded an EP of 0.10 kg PO_4eq t^{-1}; [43]. Similarly, a study in Mauritius, involving landfill disposal with energy recovery provisions, resulted in an EP of 2.10 kg PO_4eq t^{-1} [37]. A similar inquiry carried out in Astana, Kazakhstan, showed an EP of 14.0 kg PO_4eq t^{-1} when waste was landfilled without capturing gas emissions [50]. Notably high EP of 50.6 kg PO_4eq t^{-1} were observed in a study in the Alytus region in Lithuania [53]. In the Indian context, specific assessments in Mumbai [28] and Panchkula [19] demonstrated EP of 0.5 kg PO_4eq t^{-1}, for both locations. Importantly, the EP values obtained for the current study locations were as follows: for the worst-case scenario - Solan: 2.03 kg PO_4eq t^{-1}, Mandi: 1.34 kg PO_4eq t^{-1}, Sundernagar: 2.15 kg PO_4eq t^{-1}, and Baddi: kg PO_4eq t^{-1}; and for the best-case scenario - Solan: 0.68 kg PO_4eq t^{-1}, Mandi: 0.19 kg PO_4eq t^{-1}, Sundernagar: 0.23 kg PO_4eq t^{-1}, and Baddi: 0.98 kg PO_4eq t^{-1}. It may be mentioned that while the EP conditions for the BAU scenario reveal slightly higher values, comparative values with literature are observed for the best-selected treatment alternative at the study sites.

3.5. Human toxicity potential

The main contributor to human toxicity potential is heavy metals released into the soil, water, and air. Human toxicity is expressed as kg 1,4-DBeq t^{-1}. Generally, human toxicity is an index value that assesses the potential of a unit chemical released into the environment. Fig. 6 reveals the human toxicity potential under four scenarios along with the baseline scenario. The maximum human toxicity impact was observed in Scenario 1 (BAU): Solan – 4.62 kg 1,4-DBeq t^{-1}; Mandi – 5.51 kg 1,4-DBeq t^{-1}, Sundernagar - 1.96 kg

Table 4
Summary of Environmental impacts for all the considered Scenarios at the study locations.

	Solan				Mandi				Sundernagar				Baddi			
	GWP	AP	EP	HTP	GWP	AP	EP	HTP	GWP	AP	EP	HTP	GWP	AP	EP	HTP
Scenario 1	27.24	8.97	2.02	4.62	27.34	8.26	1.34	5.51	25.16	5.55	1.21	1.96	52.49	9.54	2.59	14.11
Scenario 2	26.26	6.32	1.39	2.61	24.66	4.89	1.07	3.96	17.46	1.50	0.54	1.00	44.07	3.56	1.07	8.99
Scenario 3	22.58	3.84	0.86	2.26	15.46	3.28	0.72	3.57	13.34	2.51	0.33	0.71	27.83	2.87	0.72	5.79
Scenario 4	7.50	2.89	0.53	1.56	7.13	2.28	0.19	1.37	5.65	1.23	0.22	0.35	11.35	3.34	0.98	3.88
Scenario 5	10.13	3.72	0.68	2.16	30.05	6.13	0.98	3.04	17.19	2.99	0.33	0.47	32.75	0.54	0.99	5.33

Note: GWP is in kg CO2-eq t-1; AP is in kg SO2-eq t-1; EP is in kg PO43−eq t-1; HTP is in kg 1,4-DCB eq t-1.

Table 5
Comparison of Environmental impacts with other scientific reported literature.

Reference	City/Country	LCA software	GWP kg CO_2 $^-$eqt^{-1}	AP $SO_2$$^{-eq}$ t^{-1}	EP PO_4^{3-eq} t^{-1}	HTP kg 1,4-DCB-eq t^{-1}	Notes
[28]	Mumbai, India	GaBi v6.0	998.4	0.10	0.50	0.4	31 % in bioreactor landfill and 69 % in open dumping.
[20]	Ahvaz, Iran	–	3.0 E+03	1.1 E+03	–	–	Municipal waste is collected and sent to the waste processing plant. 40 % of the total wastes are separated and processed into compost and 3 % of the total wastes are recycled. Rest of wastes which are about 57 % are landfilled without any recovery of biogas and energy.
[16]	Nagpur, India	Gabi 8.5.0.79	1259.69	6.86E-01	7.9E-02	8.56E-01	All the MSW generated in Nagpur city is sent to the landfill site, where 17 % is allocated to composting, and the rest is directly deposited off at the landfill site.
[18]	Bangalore/India	–	3335.0	0.0142	0.0026	–	Waste is sent to the landfill
[19]	Panchkula /India	SimaPro V8.3	731.9	1.12	0.5	510.0	Landfill, open dumping, open burning and production of RDF
[37]	Mauritius	SimaPro v8.0.4.30	767.0	1.20	2.1	9.4	MSW sent to landfill with energy recovery
[52]	Nepal	–	1.35	0.24	0.088	–	MSW is sent to MRF and open dumps.
[51]	Hangzhou/Chin a	Gabi v8.0	502.0	−0.30	–	–	Mixed MSW sent for landfill or incineration
[50]	Astana/Kazakhs tan	SimaPro v.8.2	1910.8	0.12	14.0	–	Sanitary landfill without landfill gases valorization
[53]	Alytus region/ Lithuania	WAWPS	1135.0	5.20	50.6	–	Most of MSW is sent to the landfill
[43]	Sakarya/Turkey	SimaPro v8.0.2	1840.0	0.169	0.10	47.9	Waste is sent to landfill without any biogas recovery

Note: GWP- Global warming potential, AP- Acidification potential, EP- Eutrophication Potential, HTP- Human toxicity potential, 650 WRATE- Waste and Resource Assessment Tool for the Environment, WAMPS- Waste Management Planning System, RDF- Refuse 651 derived fuel, MSW- Municipal solid management, LCA- Life cycle assessment.

1,4-DBeq t^{-1}, and Baddi – 14.11 kg 1,4-DBeq t^{-1}. However, scenario 4: MRF_COM_SLF had the least impact: Solan – 1.56 kg 1,4-DBeq t^{-1}, Mandi – 1.37 kg 1,4-DBeq t^{-1}, Sundernagar – 0.35 kg 1,4-DBeq t^{-1}, and Baddi – 4.22 kg 1,4-DBeq t^{-1} among the alternative scenarios. Furthermore, emissions under other alternative scenarios have values that range between the Baseline scenario and scenario 4, i.e., COM_MRF_SLF. Apart from this, it has been observed that Baddi region has the maximum pollution potential of all the emissions, including global warming potential, acidification potential, eutrophication potential, and human toxicity potential because Baddi town is the hub of industries and various pharmaceutical companies. Further, pollution results from unsegregated waste, the lack of provision for collection and treatment of leachate, and the absence of a proper liner system. In this aspect, the leachate generated from non-engineered landfill sites tends to permeate into groundwater and hence leads to greater human toxicity potential.

A comparative assessment of Human Toxicity Potential with other earlier reported scientific literature (Table 5) showed that the values observed for the study locations were significantly lower. For example, in a study conducted in Bolivia, the HTP was determined to be the least for a scenario which included the use of sanitary landfill and small-scale composting. The HTP value was determined to be 21.035 kg 1,4-DBeq t^{-1} [30]. In a study conducted in a landfill site in Sakarya, Turkey, wherein no biogas recovery option was considered, using SimaPro version 8.0.2, the HTP was determined to be 47.9 kg 1,4-DBeq t^{-1} [43]. A similar study conducted in Mauritius, wherein the waste was disposed of in a landfill with provisions for energy recovery, using SimaPro version 8.0.4.30, the HTP was determined to be 9.4 kg 1,4-DBeq t^{-1} [37]. For studies conducted in the Indian context, it was observed that the HTP values were found to be 0.4 and 510 kg 1,4-DBeq t^{-1}, respectively, for assessments carried out in Mumbai [28] and Panchkula [19]. It was observed that the HTP generated for the present study locations yielded values of (Solan – 4.62 kg 1,4-DBeq t^{-1}; Mandi – 5.51 kg 1,4-DBeq t^{-1}, Sundernagar - 1.96 kg 1,4-DBeq t^{-1}, and Baddi – 14.11 kg 1,4-DBeq t^{-1}) for the worst and (Solan – 1.56 kg 1,4-DBeq t^{-1}, Mandi – 1.37 kg 1,4-DBeq t^{-1}, Sundernagar – 0.35 kg 1,4-DBeq t^{-1}, and Baddi – 4.22 kg 1,4-DBeq t^{-1}) for the best-case scenarios, respectively. These values were lower compared to most of the earlier reported literature, primarily due to the lower quantity of waste being disposed at the landfill sites.

3.6. Critical discussion of LCA analysis of different scenarios for the different study locations and comparison with other reported literature

The physical characterization of MSW for four study regions has been mentioned in Table 3. From Table 4, it was observed that in Scenario 1 (BAU), fossil CO_2 and CH_4 are produced to a higher extent due to the open dumping of municipal solid waste, whereas

Scenario 4 (Scenario: MRF_COM_SLF) has the least greenhouse emissions due to lower emissions of fossil CO_2 and CH_4. Furthermore, the combustion of MSW generates both biogenic CO_2 and fossil CO_2. Biogenic CO_2 is generated due to the burning of biodegradable waste, while fossil CO_2 is generated owing to the burning of non-biodegradable materials such as plastic, and from some amount of textile and leather. It was observed that Scenario 4 has no option for incineration or RDF associated with it, hence yielding the best environmental impact. Similarly, the maximum acidification impact for all the study regions was observed under Scenario 1. Thereafter, Scenario 2 showed the second-highest AP for Solan and Baddi regions, which was observed in Scenario 5 for Sundernagar and Mandi study areas, as seen in Table 4. This may be attributed to the fact that both Scenarios 2 and 5 involve the burning of waste, either through incineration or RDF techniques, which, in turn, leads to higher emissions of pollutants. This is because during the combustion process, most of the sulphur and nitrogen compounds are converted into the oxides of sulphur and nitrogen, leading to increased air emissions. The lowest AP was observed in Scenario 4, as it did not involve any burning. Scenario 1 (BAU) reported the maximum eutrophication impact due to the absence of a liner system in open dumpsites, and since the entire waste is open-dumped, it leads to very high emissions of Total Nitrogen and Phosphorous due to the biological decomposition of waste occurring in open dumpsites.

Finally, human toxicity is primarily caused by pollutants such as PM, SO_2, NO_x, arsenic, cadmium, chromium, copper, nickel, zinc, mercury, lead, and dioxins. Scenario 1 has the highest HTP values among all the scenarios. Furthermore, it has been observed that Scenario 2 (including the incineration process) had the second-highest human toxicity impact for all the study regions due to the emission of air pollutants during the incineration process. Scenario 4 had the lowest human toxicity potential, as observed from Table 4. In summary, out of the four study regions, Baddi experiences the maximum environmental impacts, with the highest values being reported for all the categories of assessment (GHG, AP, EP, HTP). This is because Baddi region has the maximum number of industries and pharmaceutical companies, which account for maximum production of harmful gases and contribute to various impact categories due to mixed nature of waste, including MSW and hazardous wastes [47]. Among the five scenarios considered, Scenario 4, which combines composting, a material recovery facility, and a sanitary landfill facility, proves to be the most beneficial. This is because it includes proper waste treatment strategies and the scientific disposal of municipal solid waste in an engineered sanitary landfill. It also does not include any provisions for burning the waste, as in Scenario 2 and 5, making it more effective than other integrated waste management systems considered.

Similar assessments carried out and reported in earlier scientific literature have been summarized in Table 5. In summary, the GWP values observed in our study were notably lower than those reported in previous literature [19,28,30,37]. This difference is mainly because there was a reduced quantity of waste being deposited in the landfills at our research locations compared to the earlier studies. Furthermore, the decrease in GWP for the best and worst-case conditions was approximately 72 %, 74 %, 77 %, and 78 % for the Solan, Mandi, Sundernagar, and Baddi study locations, respectively. Therefore, it can be inferred that the average decrease in potential GWP at these locations, considering the worst case (Scenario 1) and the best-case scenario (Scenario 4), is 75 %. This implies a high potential for reducing environmental impacts with the proper implementation of Scenario 4. Regarding the impacts of AP, the reduction for the study locations was determined to be 68 %, 72 %, 78 %, and 65 % for Solan, Mandi, Sundernagar, and Baddi, respectively, with an average reduction rate of 71 %. Previous comparisons with earlier literature indicated slightly higher values of AP [19,28] for Indian conditions, implying high concentrations of acidic materials in the waste. The findings also indicate that acidification significantly contributes to affecting the ambient environment due to emissions of NO_2, SO_2, CH_4, and HCl considered within the defined system boundary. This emphasizes the substantial potential for acidification, as previously reported in the literature [45]. Furthermore, considering the environmental impact of EP, a comparison with existing literature revealed that (Scenario 1) had values greater than those reported, while the best-case scenario (Scenario 4) reported values comparable to the literature. The potential reduction of EP with the implementation of Scenario 4 yielded a 67 %, 86 %, 89 %, and 62 % decrease for the locations Solan, Mandi, Sundernagar, and Baddi, respectively, with an average decrease of 76 %. Although the HTP values were significantly less than those reported in the literature, the possible reduction in HTP values with the implementation of Scenario 4 compared to the existing condition (Scenario 1 – BAU) was determined to be 66 %, 75 %, 82 %, and 70 % for the Solan, Mandi, Sundernagar, and Baddi regions, respectively, with an average decrease of 73 %."

3.7. Sensitivity analysis

This section presents the results of a sensitivity analysis due to an increase in the recycling rate in the material recovery process,

Table 6
Environmental Impacts in the BAU for sensitivity analysis at 10 % (a) and 90 % (b).

	GWP	AP	EP	HTP
Solan	63.98 kg CO_2eq To 44.80 kg CO_2eq	1.13 kg SO_2eq To 0.63 kg SO_2eq	0.28 kg PO_4eq To 0.16 kg PO_4eq	1.2 kg 1,4-DBeq To 1.09 kg 1,4-DBeq
Mandi	57.32 kg CO_2eq To 39.44 kg CO_2eq	1.08 kg SO_2eq To 0.6 kg SO_2eq	0.24 kg PO_4eq To 0.12 kg PO_4eq	1.18 kg 1,4-DBeq To 1.02 kg 1,4-DBeq
Sundernagar	52.38 kg CO_2eq To 32.11 kg CO_2eq	0.93 kg SO_2eq To 0.53 kg SO_2eq	0.16 kg PO_4eq To 0.08 kg PO_4eq	1.02 kg 1,4-DBeq To 0.66 kg 1,4-DBeq
Baddi	72.00 kg CO_2eq To 49.81 kg CO_2eq	1.22 kg SO_2eq To 0.95 kg SO_2eq	0.43 kg PO_4eq To 0.26 kg PO_4eq	1.42 kg 1,4-DBeq To 1.18 kg 1,4-DBeq

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

varied from 10 %, 40 %, and 90 %. In this context, the influence of varying recycling rates on the life cycle emissions was examined for the present waste management scenario, i.e., BAU or Scenario 1 condition. In the current study, the sensitivity analysis involves recycling materials such as paper, plastic, textiles, etc. The impact of various recycling rates, ranging from 10 % to 90 %, has been analyzed in the study. These percentages were selected as they are assumed to represent the worst and best-case scenarios for recycling. The analysis results reveal that the recycling rate significantly decreases the emissions released from the MSW management systems in the selected study regions. It is demonstrated from the analysis that environmental benefits intensify as the recycling rate increases. If the recycling and material recovery facility increase from 10 % to 90 %, the environmental impacts will surely decrease compared to the prevalent condition.

The environmental impacts in the baseline scenario for sensitivity analysis have been presented in Table 6. However, the effect of the recycling rate on GWP, AP, EP, and HTP for Solan, Mandi, Sundernagar, and Baddi has been summarized in Figs. 7–10. The baseline scenario for the four study regions exhibited the highest environmental impacts with the highest reported values for GHG, AP, EP, and HTP. This can be attributed to the absence of waste segregation and a material recovery (recycling) facility in the baseline scenario. Furthermore, the baseline scenario represents the absence of a proper landfill control system to mitigate environmental impacts. A review of the literature suggests that there exists an inverse relationship between the change in recycling rate and environmental benefits [34]. The same has been observed in our study, where an increase in the recycling proportion led to a significant deterioration in environmental impacts, as demonstrated in Figs. S3–S6 of the supplementary material. In summary, it may be mentioned that the recycling rate is a good parameter to consider in sensitivity analysis, and it has been shown that an increase in recycling or MRF will significantly reduce the environmental impact even in the baseline scenario (Scenario 1). This implies that recycling facilities, which are almost non-existent in the study areas, should be implemented immediately to reduce the potential environmental impacts.

3.8. *Limitations and future perspectives*

The present study only considers the various waste management alternatives from an environmental standpoint, based on the waste fractions generated at different study locations. Furthermore, a comprehensive socio-economic analysis of MSW management, including impacts at site locations, infrastructural details, and noise and odor assessments, should be carried out to reveal the overall impacts.

4. Conclusion

The LCA assessment was carried out considering different scenarios for the proper management of MSW generated at four study locations in Himachal Pradesh, India. The study considered a total of five scenarios, including the existing scenario (Scenario 1). The conducted LCA study found that Scenario 4 (material recovery facility + composting + sanitary landfill facility) has the minimum impact on the environment. However, an increase in recycling and waste segregation practices could lead to an improvement in environmental impacts. Furthermore, in the existing scenarios, i.e., the baseline scenario (BAU) of our study regions in Himachal Pradesh, including Solan, Mandi, Sundernagar, and Baddi, the greatest environmental impacts were observed due to the process of open dumping and lack of waste treatment. This is primarily because the prevailing dumping sites are unscientific, non-engineered, and lack provisions for a liner system, leachate collection facility, and other protective measures. A sensitivity analysis was performed, considering recycling rate as the parameter, to observe its effects on the environmental impacts of the study locations. Recycling rates of 10 %, 40 %, and 90 % were considered in the sensitivity analysis, which showed that even a slight increase in recycling rates significantly reduced the environmental impacts, resulting in reduced emissions from MSW management for all of the study locations. Finally, it is important to mention that conducting an LCA for the state of Himachal Pradesh in India has some limitations, particularly in the context of the availability of suitable data for the four selected study regions. The input data used in the LCA assessment in this study were obtained from literature and different databases. Specifically, the input data utilized for the study included some experimentally determined values (such as waste generation rates, vehicle details for transport, physico-chemical

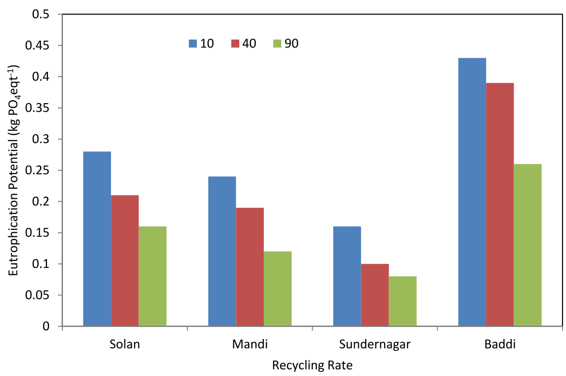

Fig. 9. Effect of recycling rate on EP under BAU scenario.

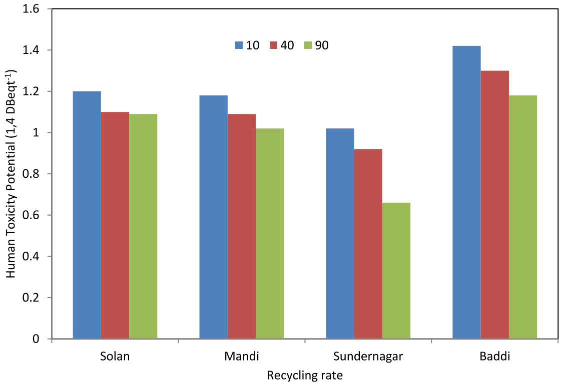

Fig. 10. Effect of recycling rate on HTP under BAU scenario.

parameters), relevant information from reported scientific literature representing our study conditions, and default values of certain parameters from different inventories associated with the SimaPro software.

It may also be concluded that a single technique meeting all requirements may not be possible in the considered scenarios, and therefore, an evaluation of cost-benefit analysis is necessary for each of the considered scenarios. Finally, as there are no literature studies on life cycle analysis for Himachal Pradesh, the existing study provides a comprehensive LCA for inspecting various management techniques and makes it potential for the municipal authorities of the selected study regions to improve current waste management strategies. In short, the present study provides baseline information on existing and possible future MSW strategies.

Data availability statement

Data included in article/supp. Material/referenced in article.

CRediT authorship contribution statement

Anchal Sharma: Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Writing – original draft. **Rajiv Ganguly:** Funding acquisition, Investigation, Methodology, Project administration, Resources, Software, Supervision, Writing – review & editing, Conceptualization. **Ashok Kumar Gupta:** Funding acquisition, Project administration, Resources, Software, Supervision, Validation, Writing – review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.heliyon.2023.e21575.

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