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Life Cycle Assessment (LCA) for Municipal Solid Waste Management in Iran: A Case Study URMIA Metropolis

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Abstract

In recent decades, the world's population has grown substantially, resulting in a rise in municipal solid waste (MSW) generation. This trend poses a significant challenge. This study utilizes Life Cycle Assessment (LCA) as a framework for identifying effective waste management solutions. The scenarios evaluated include composting, incineration, landfilling, and recycling. Scenarios were analyzed in terms of ten environmental indicators that include abiotic depletion potential, ozone layer depletion potential, global warming potential, human toxicity potential, freshwater toxicity potential, marine toxicity potential, terrestrial toxicity potential, acidification, photochemical oxidation, and eutrophication. The employed software for this analysis was SimaPro. Results indicated that the landfilling scenario had the highest pollution ratio in eight indicators, after that, the incineration scenario was the most polluting in two ozone layer depletion and global warming potential indicators. Recycling emerged as the most favorable scenario, demonstrating the least impact on global warming and human toxicity potential indicators. Composting, on the other hand, had the smallest environmental footprint across seven indicators. Furthermore, this scenario exhibited the lowest pollution burden in terms of ozone layer depletion potential among all the evaluated indicators. In general, according to the findings of this study, composting is recognized as the appropriate method for municipal solid waste management in the Urmia metropolis of Iran.

key words

Life Cycle Assessment (LCA)

MSW

Recycling

Composting

Landfilling

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Introduction

Human activities lead to the production of bulky residues most of which are municipal solid waste. In general, waste is the materials that the producers do not need them anymore [1]. Many diseases arise from the absence of an effective waste management system, leading to a host of additional problems for both citizens and authorities. To address municipal solid waste management, it is essential to adopt innovative and practical tools, techniques, and technologies. Recycling, which involves transforming waste into usable materials, stands out as one of the best solutions to this issue [2]. Municipal solid waste is a compound mass, so it is essential to realize exactly the components. Generally, MSW consists of organic wet wastes so-called kitchen wastes, metal wastes containing many kinds of metal alloys from commercial and production activities, paper and cardboard wastes that come from marketing activities, wood and plant residues, garbage, glass, clothes, etc. [3]. These variable components make the managing process more complicated.

Life Cycle Assessment is a tool to assess the potential environmental impacts and used resources throughout a product's life cycle [4]. Recycling and disposal are both included in the waste management procedure in LCA, the term 'product' includes both goods and services [5]. LCA is a comprehensive assessment and considers all attributes or aspects of the natural environment, human health, and resources [6]. A Life Cycle Assessment (LCA) is a comprehensive analysis of the potential environmental impacts associated with products or services throughout their entire life cycle. This assessment evaluates the environmental consequences during all phases, including production, distribution, use, and end-of-life. It also encompasses both upstream processes, such as those involving suppliers, and downstream processes, including waste management. Specifically, LCA considers the production of raw, auxiliary, and operational materials, as well as the use phase and disposal methods like waste incineration.

Life Cycle Assessment (LCA) examines the entire lifespan of a product, improving resource efficiency and reducing liabilities. It can be utilized to evaluate either the environmental impact of a product itself or the functions it is designed to fulfill. Commonly known as "cradle-to-grave" analysis, LCA encompasses several essential elements: 1) identifying and quantifying environmental loads, including energy and raw material usage, as well as emissions and waste produced; 2) assessing the potential environmental impacts associated with these loads; and 3) exploring strategies for minimizing these impacts [7].

A Life Cycle Assessment was used first in 1969 about soda bottles, the main purpose of this study was the determine of bottles had the least effect on the environment [8]. Numerous studies have employed LCA across various approaches, and reviewing these relevant works can enhance our understanding of LCA. In the context of MSW in Ankara, five distinct scenarios were proposed, each undergoing an inventory analysis. Throughout the study, a comprehensive life cycle assessment was conducted, and after comparing the results from the inventory analysis, the most suitable scenario was selected and presented to the authorities. The method of waste reduction at the source was identified as the optimal municipal waste management strategy due to its minimal environmental impact [9]. A comprehensive waste management system (WMS) was presented on a tourism island. Some indicators like technical, financial, social, and environmental indicators were noticed in selecting the WMS type. Life cycle assessment showed the most effective method in reducing environmental impacts and costs is compost production from MW's organic section [10].

Two management methods were exerted for recycling and incinerating the packing boxes cardboards and LCA was used as a supporting tool. Scenarios were analyzed from the environment point of view and their environmental impacts inventory was listed. The extracted results show if the substitution fuel for incinerators were fossil fuels, burning the paper waste for energy extraction led to a decrease in the CO_2 emission rate. In addition, if the substitution fuel were the extracted biogas from the landfill, paper waste incineration would depend on managers' decisions for a long period that is related to reduction and recycling [11]. LCA was applied for energy from waste production in Thailand. The focus was on the environmental approach. Anaerobic digestion and energy production in incinerators were the presented scenarios. The results show incinerators' potential effects against the same produced electric energy is more than anaerobic digestion [12]. To investigate the waste status at Mashhad city in Iran, LCA was implemented. The obtained results proved, that establishing transmission stations, composting and recycling can help MSW management in this

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city [13]. Another study was done in Tehran Iran, which, has reached these outputs: composting and recycling have an important role in decreasing leachate emissions and fuel consumption [14]. In a study at Sakareya in Turkey, these data found: that LCA could be a useful tool for WM. This tool gives the possibility managers for MSW to manage and compare different technologies to achieve the best results [15].

The LCA technique has been utilized in various countries, yielding beneficial results. In Iran, it has been applied in several cities and organizations with diverse scenarios, producing a range of outcomes. However, this methodology has not been employed in the case study region. Urmia, the capital of West Azerbaijan Province and one of Iran's most populous cities, lacks integrated waste management systems, relying instead on outdated methods. This deficiency has led to significant challenges. To address these issues, it is crucial to develop a comprehensive strategy that can effectively manage waste and mitigate its negative impacts, enabling managers to make informed decisions. With Urmia's population continuously increasing and municipal waste generation on the rise, there is a pressing need to establish facilities and make strategic decisions for the future. Therefore, this study aims to consider all aspects of waste and its management pathways.

Materials and methods

The aim was to select a method that is reliable, versatile, and initiative in the case study place. In this study, a metropolis in Iran's northwest was selected as the study region. Whereas LCA can expose any small area or entire the globe [16]. This metropolis produces more than 50,000 kg of waste per day, and all of it is treated by using initial methods such as landfilling. This city was chosen due to the extent of the waste stream and the critical requirement for MSW treatment. Local assessment and data analysis revealed the waste production rate and its components. Given that, the majority of waste was formed of organic components, it was helpful to choose appropriate scenarios and gather the necessary data for assessment. Evaluating the impact effects needs complimentary tools. For this reason, some software is employed in LCA processes, and each one has a special structure and features. In the current study, SimaPro 9.0.0.33 version and CML 2 baseline 2000 V2.05 method were employed and set for the next stages. This software supplies many professional tools for assessing a product's life cycle [17].

Scenarios

Landfilling, incineration, recycling, and composting are the presented scenarios in this research. The presented scenarios should align with the requirements of the intended audience, for instance, one of the best solutions for reducing the environmental pollution from organic wastes is to convert them into compost due to their primary nature. Presented scenarios in the life cycle assessment process are similar to the solutions that are seen in all problem-solving procedures and after analyzing, one or more of them enter the implementation phase, which was also an approach in this study [18]. Consequently, the intention was for these scenarios to enter the implementation phase following a thorough analysis using the designated software and subsequent comparisons among them. LCA provides insights into the entire life cycle of materials, from production to disposal. This comparative analysis allows for a confident selection of the most effective scenarios [18]. We attempted to realize the scenarios' advantages and disadvantages by interpreting and illustrating the results. Overall, this study represented a collaboration between researchers and authorities aimed at generating results that could aid in controlling waste pollution. To evaluate the effectiveness of each scenario in mitigating environmental pollution, an analysis of four scenarios was performed using the same materials. Consequently, the chosen waste management scenario was the one that demonstrated the highest level of pollution control, effectively minimizing the environmental pollution burden.

Waste Components

Determining the composition of municipal waste in the case study place was the next stage following the definition of suitable scenarios. According to the annual measurements by the waste management organization in this metropolis, up-to-date data were obtained in this regard. Table 1 shows the composition of municipal solid waste in the Urmia metropolis, based on this table, the existing compounds were classified into nine major categories, and each one's portion was indicated as a percentage of the total. Since organic compounds constitute the majority of municipal solid waste in Iran, as was previously indicated, it was essential to consider the definition of compatible scenarios before beginning any evaluation of them.

As can be seen from the data in Table 1, over

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Table 1: waste components in Urmia metropolis

Waste kind	Percentage
organic materials	72.04
paper, cardboard, carton	6.43
plastic	7.77
rubber	1.14
glass	2.03
metals	2.52
textiles	2.86
wood and foliage	1.1
others	4.11

70% of the wastes under investigation are composed of organic components. This percentage is so high that it is possible to overlook the contribution of other materials. The primary character of wastes should be taken into account while managing them, which is why they were examined during the data collection procedure.

Data Gathering

One of the main advantages of life cycle assessment is the use of available data related to each scenario in databases, which means during the assessment of a specific material with the specialized software, the data related to those materials are obtained from databases and entered in the evaluation process [19]. During this study, the necessary data were sourced from the Urmia municipal waste management organization's statistical reports, yearbooks, and relevant documents, as well as associated databases. It was possible to import this data into SimaPro software, allowing for free access to the databases required for the research. However, a license must be purchased for extended studies. Table 2 presents the databases utilized for the CLM method. Direct data selection was performed through the user interface, where the appropriate databases were identified based on the characteristics of 1000 kg of waste. This process was repeated twice to ensure the accuracy of the selected databases. One of the most important things that should be considered in choosing databases, is the consistency of each of them with the purpose and process of the study. [20]. For this purpose, before selecting them, the connection of these databases with this study was ensured by reviewing other similar research.

In the end, each data set was merged and analyzed to generate the ultimate data sets that functioned as the basis for the investigation.

Environmental indicators

The abiotic depletion potential, ozone layer potential, global warming potential, human toxicity potential, freshwater toxicity potential, marine toxicity potential, terrestrial toxicity potential, acidification, photochemical oxidation, and eutrophication were ten indicators. Abiotic depletion potential is associated with the consumption of fossil fuels, while ozone layer depletion potential

Table 1: waste components in Urmia metropolis

Database	Address
Agri-footprint	www.Agri-footprint.com
Ecoinvent	www.ecoinvent.org
BUWAL	www.umweltschweizch.com
ELCD	www.eplca.jrc.ec.europa.eu
US LCI	www.lcacommons.gov

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results from activities that contribute to its destruction. Global warming refers to the greenhouse gases responsible for this phenomenon, and human toxicity highlights the potential harmful effects of toxic substances on human health. The section on fresh and marine water toxicity potential addresses the products and activities that significantly contribute to pollution in both types of water. Terrestrial toxicity potential indicates pollutants that contaminate fertile soils, while acidification pertains to the causes of acid rain. Lastly, summer smog, or secondary air pollution, arises from photochemical oxidation processes [21]. Eutrophication is mainly generated in the troposphere by sunlight reacting with emissions from consuming fossil fuels to create other molecules. The ultimate definition of eutrophication potential is the capacity to result in excessive fertilization of soil and water, which could boost the growth of biomass [22].

The steps of an LCA

An LCA study consists of four main steps: Step 1; defining the goal and scope of the study, Step 2; making a model of the product life cycle with all the environmental inputs and outputs. This data collection effort is usually referred to as life cycle inventory (LCI), Step 3; understanding the environmental relevance of all inputs and outputs. This is referred to as life cycle impact assessment (LCIA), and Step 4; is the interpretation of the results. The aforementioned steps perfectly depict the LCA framework, thus users must consider all of them. Every step functions in conjunction with the others. This is what we used when writing this paper.

Step 1

The reason for the present study was the achievement of a practical and pre-evaluated method in the direction of managing solid and in particular organic wastes in the case study place. Comparative options were presented in four scenarios and the required data was collected from statistical methods and databases. The boundary of the system in this study started from the waste production phase and continued until its final processing phase. A scientific report additionally presents the study's findings.

Step 2

All the elements and sources contributing to the generation of the mentioned wastes in the Urmia metropolis were identified and measured during the Life Cycle Inventory (LCI) step, by the ISO framework. In this step, relevant data from databases was loaded into SimaPro software libraries and processed by defining every element involved in waste production processes while considering into account every scenario. This enabled the impacts of waste production on people and the environment to be gathered from the databases that were used and input into the software that was previously discussed. All the elements that comprise up the waste were investigated as inputs to the inventory process, and these materials were used in the analysis process of each scenario, but the

Table 3: the environmental indicators with their abbreviations and units

Indicator	Abbreviation	Unite
Abiotic depletion	AD	kg Sb $_{eq}$
Global Warming	GW	kg $CO_{2\ eq}$
Ozone Layer Depletion	ODP	kg CFC-11 $_{eq}$
Human Toxicity	HTP	kg 1.4-DB $_{eq}$
Fresh Water Ecotoxicity	FEP	kg 1.4-DB $_{eq}$
Marine Ecotoxicity	MEP	kg 1.4-DB $_{eq}$
Terrestrial Ecotoxicity	TEP	kg 1.4-DB $_{eq}$
Photochemical Oxidation	POFP	kg $C_2H_{4\ eq}$
Acidification	AP	kg $SO_{2\ eq}$
Eutrophication	EP	kg PO_4^{-1} eq

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obtained results for each scenario were completely distinct.

Step 3

This section of the work involved the analysis of all materials and resources utilized in the production of solid waste, as well as the emissions released from these wastes. The results obtained were analyzed through two approaches. During this phase, efforts were made to interpret the findings multiple times to ensure greater validity and reliability of the results. This process significantly reduced the likelihood of human errors and software-related inaccuracies during the evaluation. Moreover, the analyst gained confidence in the results from the earlier phases. The LCI has been developed using various methodologies across different countries. In this study, the optimized model of the CML 2 baseline 2000 V2.05 method was utilized. The selection of this method was based on the organic part of the waste. Because the basis of this method is founded on the calculation of the life cycle of this type of material. In this method, the focus is on biological processes and the used data are often related to these types of processes [23].

As mentioned, the basic CML method was implemented to evaluate the effects. Firstly, five main impact categories (global warming, ozone depletion, acidification, photochemical oxidation, and eutrophication) were evaluated. Then, this method revealed the ecological effects of the five middle point indicators, and finally, all the values of the ten indicators were calculated. In Ekisehir city, In an attempt to present the best scenario for municipal solid waste management, a life cycle assessment with the CLM method was used, the results showed that composting scenario was the best one from the environmental point of view [16]. Because the organic material composition of the wastes was factored seriously throughout the evaluation phase, it was anticipated that the composting scenario would significantly reduce the environmental pollution caused by municipal solid waste. Additionally, it was assumed that the incineration and recycling scenarios provide the same results, and the landfilling scenario without a biogas generation system is known as the worst solution.

Step 4

The findings were analyzed and a comparison between scenarios was done. Results were interpreted and reported data on the system was reviewed and monitored. The comparative interpretation plan was studied, and the reason for this was to pay attention to the principle of comparison in this research because the purpose was to compare several presented scenarios and choose the best one. Furthermore, during this process, the impact of each indicator on each scenario was checked and results were reported in charts. However, because there were so many different charts that must be produced, we presented the outputs in an arrangement that would allow the results to be easily compared.

Initially, an analysis was conducted for each functional unit, demonstrating how each of the ten environmental indicators we established was affected by 1000 kg of solid waste. Subsequently, the software facilitated a comparison of the four scenarios, generating charts that are discussed

Table 4 the obtained data from SimaPro analysis for each scenario

Indicator	Unit	Incineration	Recycling	Landfilling	Composting
Abiotic depletion	kg Sb eq	1.438	2.54	4.872	2.25
Global Warming	kg CO2 eq	6247.71	2908.28	4293.54	2995.14
Ozone Layer Depletion	kg CFC-11 eq	0.000995	0.000348	0.0000753	0.0000246
Human Toxicity	kg 1.4-DB eq	328.542	268.964	658.951	286.275
Fresh Water Ecotoxicity	kg 1.4-DB eq	86.5154	73.6135	98.6862	67.5646
Marine Ecotoxicity	kg 1.4-DB eq	3.546318	2.458634	5.9875	1.7341
Terrestrial Ecotoxicity	kg 1.4-DB eq	3.598798	2.938645	5.538987	2.146523
Photochemical Oxidation	kg C2H4 eq	1.255889	0.987878	1.985623	0.975585
Acidification	kg SO2 eq	475.5985	355.9854	657.6841	301.9852
Eutrophication	kg eq	94.6897	105.6864	245.8955	90.5985

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in the following section. After completing these steps, normalization was performed, utilizing a data source that could represent the population of a city, country, or continent [24]. Normalization changes an indicator result by dividing it by a selected source amount. [4]. The final step was the final environmental indicator computation, which offers a comprehensive chart that helps in identifying the most effective scenario. In the section that follows, we talk about it in further detail.

Results and Discussion

All data for each scenario is arranged in Table 4. In this table, any environmental indicator effect on each scenario is visible obviously. To compare findings accurately, after extracting them from the software, we organized them in a chart.

Fig. 1 shows the results of this study. Analyzing it reveals employing life cycle assessment for municipal solid waste management in the Urmia metropolis by presenting four scenarios of landfilling, incineration, recycling, and composting reached these outcomes: The landfilling scenario demonstrated the highest pollution burden across nearly all indicators, except for those related to global warming and ozone layer depletion. In terms of pollution impact, the incineration scenario followed closely behind, exhibiting a greater burden than both recycling and composting scenarios. Notably, it only resulted in lower ecological pollution than the recycling scenario in the areas of abiotic depletion and etherification. The recycling scenario had a greater impact on environmental pollution than the composting scenario in eight categories but in two global warming potential and human toxicity potential had the least pollution burden against the other three scenarios. Nevertheless, the outcomes for the composting scenario were entirely different. Because of this, its pollution levels were lower than all of the other scenarios in the eight effect categories.

Infiltration of leachate into surface and underground water sources and emission of methane gas are among the most important factors of severe pollution in the landfilling scenario. In the analysis of the incineration scenario, the focus was primarily on the combustion of solid waste in incinerators, with no consideration given to how the energy generated from this process would be utilized. This indicates that the objective was solely to incinerate the waste rather than to recover energy from it. Therefore, releasing a significant amount of gaseous pollutants into the air, which are also called exhaust gases, has caused an increase in the number of polluting indicators related to it. The main factor contributing to rising environmental pollution in the recycling scenario is the usage of resources, particularly fossil fuels during the waste recycling process, which releases gaseous pollutants. Organic waste releases gases due to microbial activity and corruption; these gases include small amounts of CO_2, CH_4, N_2O, sulfur compounds, and volatile organic compounds. In addition, during the fermentation process leachate flows. Despite these disadvantages, composting was the best scenario, as the application of life cycle assessment for municipal waste management. For instance, in Macau City of China, the assessments showed that composting with recycling is 85% more beneficial than other scenarios [25].

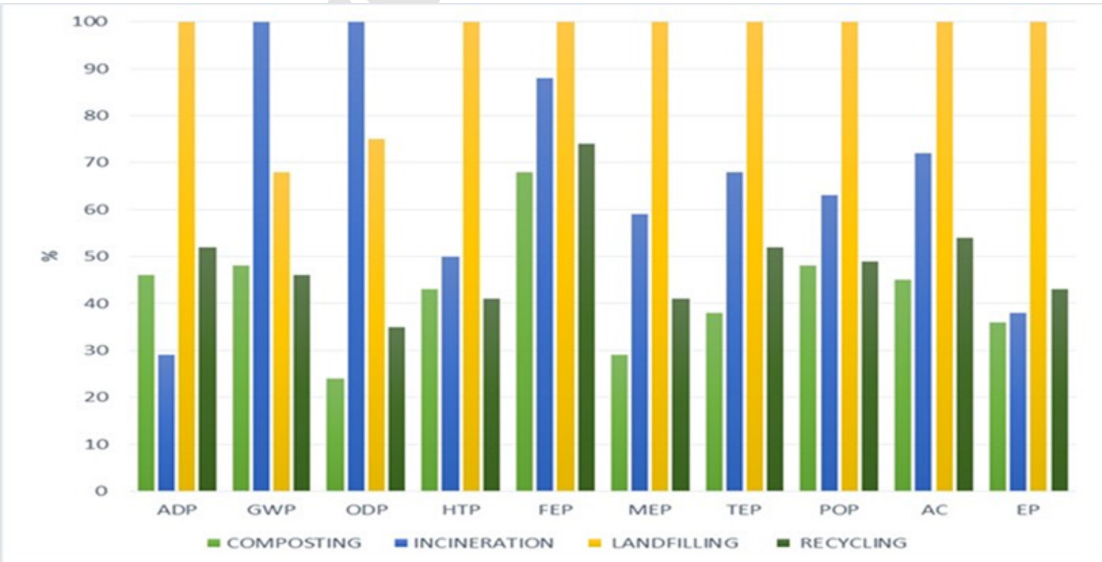

Fig. 1: the scenario status in each indicator

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However, additional optional steps are discussed to thoroughly review the scenarios and ascertain how a scenario differs from the others in any given work category.

Fig. 1 displays the overall findings from the analysis of the scenarios given by the SimaPro software, where the scenarios were compared with each other in any environmental indicators. The extent of environmental pollution in each scenario can primarily be assessed by comparing the collected data. However, to enhance the accuracy of the results and provide a comprehensive final report, it is advisable to analyze the normalization and the final environmental index. The findings from these two analyses were illustrated in separate figures that offer further insights. Normalization facilitates a clearer understanding of the relationship between the results and the system index. It is calculated based on reference data, which may pertain to the population of a city, country, or continent. By dividing the index result with a chosen reference value, normalization modifies the result. In other words, in this section, the importance or value of the analyzed indicators is evaluated according to the reference information [9].

In this paper, normalization was done by dividing the data in the case study place's population. The purpose of choosing the case study as a reference was to increase the accuracy of the obtained results, because the intended study only focused on a specific geography, and the obtained outputs from doing it were only for using in that area. Fig. 2 shows the normalized results in the form of percentages, the effect of the highest rate of environmental burden is evident in four indicators, which include global warming potential, human toxicity potential, freshwater toxicity potential, and acidification. In the global warming indicator, the incineration scenario was the most polluting scenario and the landfilling scenario is the second one. Recycling and composting scenarios stand in the next ranks. The gaseous pollutants released during the incineration process or the leachate leak and polluting gases released into the soil and fresh water from the waste landfill cause these outcomes. This analysis disclosed that the obtained results were correct absolutely, as can be observed; the two scenarios' amounts differ significantly from the others. Normalization helped us to be more confident about the study results. Since this step in LCA has an effectual role on the outcomes, it was better to do so.

By doing the final environmental indicator, we could realize the scenarios of pollution and their effectiveness on the pollution emission. To better understand the obtained results and increase their reliability we analyzed them. This index helped us to better identify the suitable scenario from the environmental point of view and report the results in a graph. The values obtained from the calculation of this index may be different from the normalized values, and that is due to the difference in the process of performing, because, the normalization was done according to the case study place's population. The final index was based on the difference in the values obtained in the impact evaluation stage. The results for this phase are displayed in Fig. 3. According to this index, the scenario that includes a larger amount has a higher environmental burden and should be tried to correct the causes of its occurrence. Therefore, landfilling at 84%, incineration at 48%, recycling at 31%, and composting at 28% got the highest and lowest pollution burden respectively.

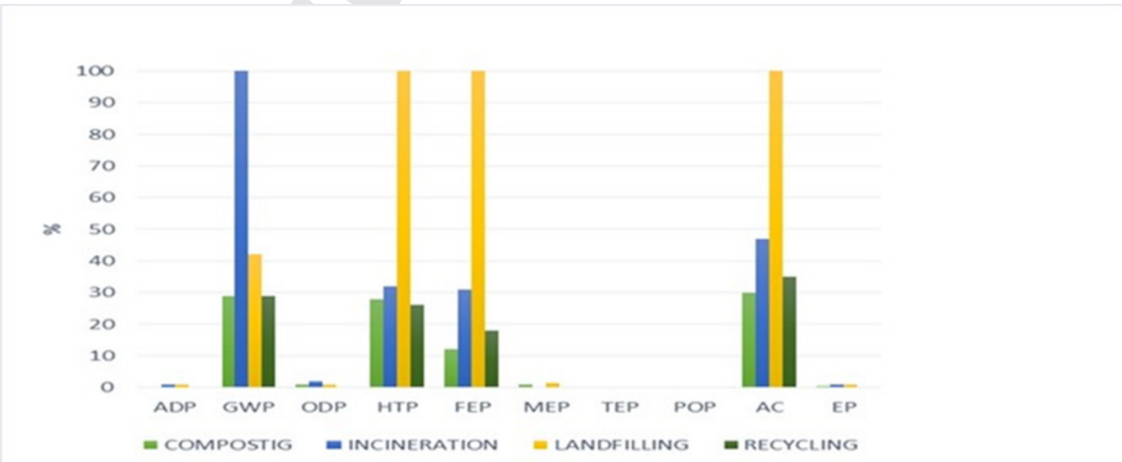

Fig. 2: the results of normalization

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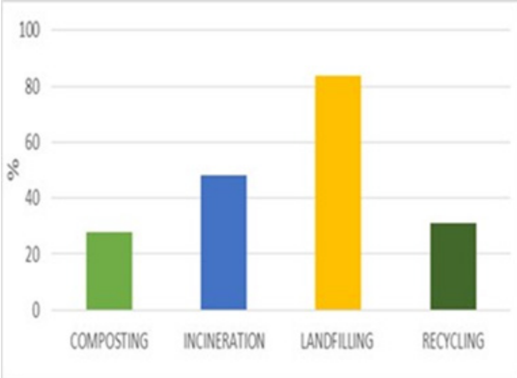

Fig. 3: the results of the final environmental indicator

Based on this index, it is essential to address the contributing factors responsible for the highest pollution levels in one or more scenarios. The landfilling scenario exhibited the highest pollution ratio, which aligns with previous assessments confirming this finding. Consequently, we recognize that the optional LCA steps were beneficial, as completing them enhances the reliability of the study's results, allowing researchers to present their findings with confidence. However, the results for the final environmental indicator and normalization may vary. For instance, the global warming indicator in this study is influenced by elevated emissions associated with the incineration scenario.

Conclusion

The results of this research indicated that, among all evaluated scenarios, landfilling produced the highest pollution levels across eight environmental indicators. Only in the cases of GWP and ODP did landfilling exhibit lower pollution levels when compared to incineration. The incineration scenario in GWP and ODP had the most pollution than others and it was more pollutant than recycling and composting scenarios in six indicators. Moreover, this scenario in the AD indicator was the best. Furthermore, in the EP indicator, its environmental burden was less than the recycling and landfilling scenarios. The recycling scenario was the second polluting scenario in AD and EP indicators. However, this scenario in GWP and HTP indicators had the lowest environmental burden in comparison with others. In addition, this scenario against the landfilling and incineration scenarios had a better controlling effect in six indicators. The composting scenario was distinct from the others. This scenario in seven environmental indicators proved as the best scenario and in ODP indicator had the lowest rate among all indicators in this study. This scenario weakness is in three AD, GW, and HTP indicators. Since, in the GW and HTP indicators, its amounts were more than in the recycling scenario, and in the AD indicator its controlling effect on the environment was less than in the incineration scenario. In summary, the results indicated that the composting scenario emerged as the most effective solution for MSW in the metropolis of Urmia, Iran. Throughout the research, a comparative evaluation method was utilized to assess municipal solid waste management practices. This method has a long-standing history and has been applied in various contexts. However, in this particular research, it was adopted as a practical strategy, focusing on its application in a new setting and addressing the pressing need for effective MSWM solutions in the case study area.

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