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Life Cycle Assessment of Medical Waste Management: Case Study for Istanbul

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Abstract: The amount of medical waste is anticipated to increase significantly with population growth. Ineffective medical waste management has resulted in adverse impacts on environmental and human health. Therefore, this study aimed to develop the current medical waste management strategy in Istanbul. GaBi Education version 7.3 was used to conduct a life cycle assessment (LCA) to compare the current medical waste management system (baseline scenario) with alternative scenarios including different proportions of waste disposal methods from an environmental perspective. Global warming, acidification, eutrophication, ozone layer depletion, freshwater aquatic ecotoxicity, and human toxicity were selected as the environmental impact categories found in CML 2001 within GaBi software. Scenarios with a higher proportion of incineration had more negative environmental impact, whereas the scenario incorporating waste segregation/minimization contributed to reducing the environmental impact. Therefore, Scenario 4 (waste segregation at the generation points/waste minimization + incineration + steam sterilization + landfill) presented the best environmental performance with the lowest total environmental impact value of 14.21% among all scenarios and was recommended as the most sustainable alternative for medical waste management in İstanbul.

Keywords: healthcare waste; medical waste disposal technologies; environmental impact; GaBi Education; İstanbul

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1. Introduction

Medical wastes are generated by various healthcare institutions such as hospitals, laboratories, clinics, research centers, and blood banks [1,2]. Of these wastes, 85% are considered general and non-hazardous. However, the remaining 15% is hazardous to both human health and the environment because it includes infectious agents, sharp objects, heavy metals, pressurized containers, radioactive and pathological materials, and pharmaceutical products [3–5].

With the global population projected to increase by approximately 2 billion over the next three decades, coupled with enhanced access to healthcare facilities, medical waste production is expected to rise correspondingly [6–8]. Additionally, the COVID-19 pandemic significantly impacted the volume of medical waste generated. On average, hospitals in developed countries produced 0.5 kg of hazardous waste per hospital per day, while those in developing countries generated about 0.2 kg. However, during the pandemic, this amount surged to as much as 3.4 kg per person per day [5,8,9]. Between 2017 and 2022, Turkey experienced steady population growth, rising from 80,810,525 to 85,279,553 individuals. This demographic increase has correlated with a continuous rise in medical waste, escalating from 98,729 tons to 130,401 tons over the same period. Notably, medical waste saw a significant surge during the COVID-19 pandemic, increasing from 109,478 tons to 135,869 tons [10,11].

The amount of waste produced has significantly increased in recent years due to population growth, increased consumption, and industrialization [12], leading to the implementation of regulations aimed at reducing its detrimental influences on environmental and human health. The Ministry of Environment, Urbanization, and Climate Change is responsible for enforcing regulations related to waste management in Türkiye. Waste management policies and legislation have been developed with consideration of the European Union harmonization process. The Waste Management Legislation encompasses numerous regulations designed to monitor and control different categories of wastes, such as municipal solid waste, medical waste, packaging waste, etc. Furthermore, the National Action Plan for Waste Management 2023 was published in 2016 [13]. According to Environmental Law No. 2872, responsibility for waste management has been assigned to municipalities. In Türkiye, medical waste is regulated under the “Regulation on the Control of Medical Wastes”, published in Official Gazette No. 29959 on 25 January 2017 [14]. The definition of medical waste in the Medical Waste Control Regulation is “infectious waste, pathological waste and sharp-edged waste originating from health institutions”. However, in Annex-2 of the same regulation, wastes are divided into four main categories under the title of “classification of waste originating from health institutions”:

- Domestic waste: general waste and packaging waste.
- Medical waste: infectious waste, pathological waste, and sharp-edged waste.
- Hazardous waste.
- Radioactive waste.

According to this regulation, the waste producer must collect medical, hazardous, non-hazardous, packaging, and municipal waste and other waste separately at the source without mixing them with each other.

Several studies on medical waste management worldwide have been published in the available literature. The environmental impact of hospital waste disposal in Arizona was investigated, and waste segregation at the generation point and waste minimization were emphasized [15]. The relationship between the amount of waste generated from hospitals and healthcare institutions and the population was estimated using data from 2000 to 2017 to improve medical waste management in İstanbul [16]. The study recommended waste segregation and minimization strategies as the trend in medical waste generation increases with future population growth. Ref. [17] emphasized waste separation at the source and suggested the sterilization and incineration of sharp and infectious materials for comprehensive medical waste management in southern Iran. A cross-sectional questionnaire was administered to healthcare workers in a public teaching hospital in Ghana to identify the types and quantities of waste generated and to assess current medical waste management practices. The study recommended segregating infectious waste from solid waste at the source and implementing measures to mitigate air pollutants emitted from incineration [18]. Ref. [19] presented the relationship between effective medical waste management and the United Nations Sustainable Development Goals by emphasizing the former’s role in reducing environmental pollution. Nevertheless, further improvements in medical waste management strategies and integrated solutions are required, particularly from a circular economy perspective. Circular hospital waste management is supported by [4], which evaluated combined steam sterilization and gasification in Australia.

The common processes for treating medical waste are steam sterilization, incineration, and landfilling. Inadequate management of medical waste could lead to serious environmental issues, including the release of infectious materials into the environment, water pollution by landfill leachate, and the emission of dangerous gases [20]. Therefore, sustainable medical waste management, including collection, segregation, transportation, and disposal, has become critical to avoid the spread of infectious diseases in humans [1,21]. Furthermore, factors such as the amount of waste, waste minimization, and environmental emissions should be considered in medical waste management [22].

There are various decision-making methodologies to determine the waste management system that performs best in terms of the environment and human health. Life cycle assessment (LCA) is an effective standardized method used to evaluate the environmental impacts of a product, a process, or a service from production to disposal. In support of life cycle assessment in waste management, the environmental benefits and burdens of the packaging waste management system were evaluated via an LCA [23], which compared the packaging waste management system with two hypothetical scenarios: one where all packaging waste was transferred for incineration and another where it was sent to landfill. The study revealed that the current packaging waste management system presented better environmental performance. Recently, studies have focused on conducting LCA for medical waste management. The application of LCA in medical waste disposal was highlighted in the study of [24], and the mitigation of the amount of hospital waste generated, the separation of infectious waste from domestic waste, and the use of incineration as a disposal method were emphasized. Ref. [25] compared two different medical waste disposal technologies, incineration and steam autoclave sterilization followed by landfill, by using LCA. The waste disposal alternative, incineration with 30% energy recovery, presented the lowest environmental influence. In another study, LCA was used for medical waste management, assessing the disinfection performance of three different methods followed by landfill: microwave, autoclave, and lime. The results showed that the microwave disinfection technique had the least environmental impact [26].

Most studies in the medical waste management field conduct questionnaires to identify the amount of medical waste generated and the disposal technologies used in healthcare facilities. However, a limited number of studies evaluate the influence of medical waste disposal on environmental and human health, and some of them focus on alternative treatments or only a particular type of medical waste, such as infectious waste, etc. Therefore, this research aims to assess the environmental performance of different waste management alternatives for medical waste disposal and investigate opportunities to improve medical waste management in İstanbul, Türkiye. In this context, the current medical waste management system in İstanbul was considered the baseline scenario and compared with four different waste management scenarios with varying ratios of disposal methods, such as incineration, steam sterilization, and landfilling, and implementing waste segregation at the point of generation was also considered. A life cycle assessment was conducted to identify which medical waste management alternative presented the least impact on the environment and human health.

2. Materials and Methods

2.1. Case Study

Medical waste generated in healthcare facilities located on both the European and Asian sides of Istanbul was considered in this study. Istanbul is located in the northwest of Turkey and covers a total area of 5343 km^2, comprising 39 districts, 25 of which are located on the European side, while the remaining are on the Asian side.

Medical waste is collected by the Istanbul Environmental Management Industry and Trade Inc. (İSTAÇ), a subsidiary of the Istanbul Metropolitan Municipality (İBB). İSTAÇ disposes of medical waste at 2 landfill plants (Kömürcüoda landfill site on Asian side, Odayeri landfill site on European side), an incineration plant, and a sterilization plant. The first Medical Waste Incineration Plant in Türkiye was established in 1995, whereas the Medical Waste Steam Sterilization Plant has been in operation for 12 years **[27]**.

There are 16,248 healthcare facilities generating medical waste in Istanbul, 256 of which are hospitals, while the remaining provide medical services other than those of hospitals. Pathological waste is disposed of by being collected separately from other infectious wastes. Medical waste is collected by 64 licensed trucks and transported to Medical Waste Disposal Plants [27].

Pathological and medical wastes collected by licensed medical waste collection trucks are incinerated at a temperature between 850 and 1200 °C in the rotary furnace at the Medical Waste Incineration Plant. The waste volume is decreased by 95%, whereas the mass of waste is reduced by 75%, through incineration. The capacity of the plant is designed to be 24 tonnes/day. Heat recovery is achieved by the thermal energy released during the incineration process, and around 540 kW of electricity is produced. Flue gases are controlled in the treatment units and continuously monitored by the emission measurement system installed on the chimney [27].

Medical wastes transported to the Medical Waste Sterilization Plant are sterilized with four autoclaves whose capacities are approximately 1.5 tonnes per hour. The sterilization process takes place at 145 °C under 3 bar pressure for 45 min, which is continuously controlled to ensure the elimination of any infection risks. The sterilized medical wastes are sent to the 2nd class landfill for disposal by specially designed waste transport vehicles [27].

2.2. Life Cycle Assessment

LCA was performed in line with International Organization for Standardization [ISO] numbers 14040:2006, Environmental Management—Life Cycle Assessment—Principles and Framework, and 14044:2006, Environmental Management—Life Cycle Assessment—Requirements and Guidelines [28,29]. The scope of ISO 14040:2006 is listed as follows: (i) Goal and Scope Definition, (ii) Inventory Analysis, (iii) Life Cycle Impact Assessment, and (iv) Interpretation [28]. In this study, GaBi Education software developed by PE International GmbH, Leinfelden-Echterdingen, Germany, thinkstep, was used to perform LCA [30]. The CML 2001 impact analysis method was conducted for impact assessment.

2.2.1. Goal and Scope Definition

The objectives of this study are to evaluate the environmental impacts of the current medical waste management system in İstanbul through an LCA and to investigate the environmental improvement potential of alternative waste management strategies by creating scenarios with varying proportions of disposal methods such as landfill, incineration, and sterilization. Therefore, this study aims to identify the medical waste management system with the least environmental impact among the baseline and alternative scenarios.

In this context, each scenario was assessed from environmental and human health perspectives; however, no economic analysis was conducted.

The functional unit was chosen to be 1 ton of medical waste generated in Istanbul to compare the baseline and alternative scenarios.

System boundary: In this study, each scenario includes waste collection from healthcare facilities, transportation to disposal sites, the use of different disposal technologies such as incineration, sterilization, and landfilling, as well as energy recovery (electricity generation) from these methods. The system excludes the disposal of hazardous wastes such as ash–slag, filter cake, etc., during the incineration process, the consumption of fuel during transportation, sterilization, and incineration, the treatment of leachate in the landfill, and the distribution of the electricity produced to the customer. The system is presented in Figure 1.

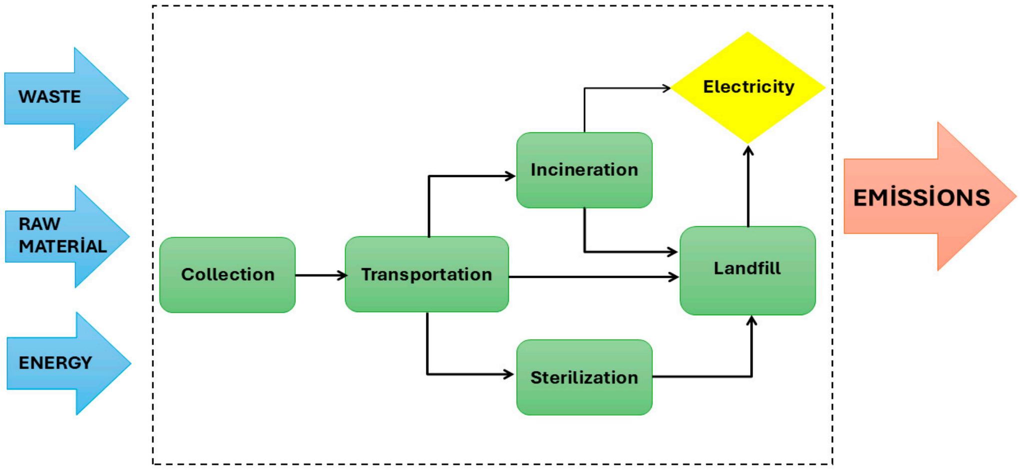


Figure 1. The system boundaries used for LCA.

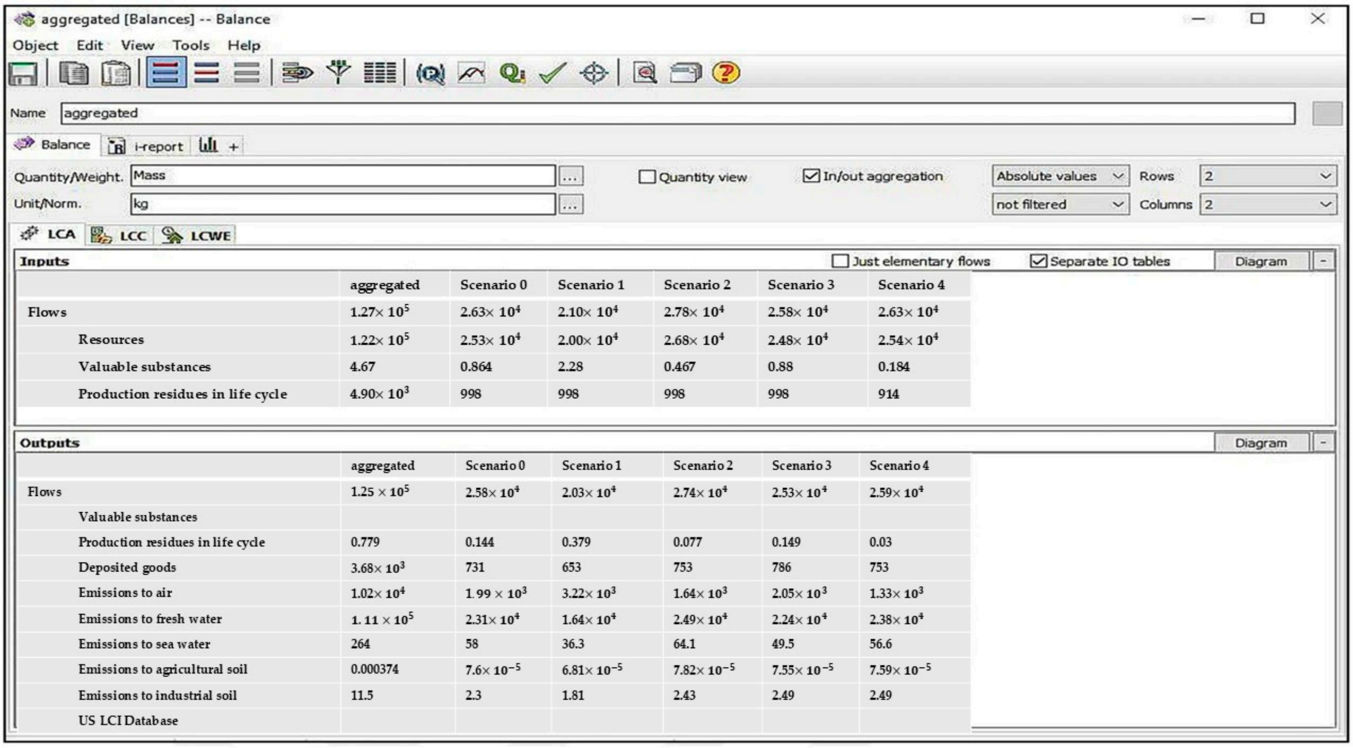
Impact Categories: global warming potential, acidification potential, eutrophication potential, ozone layer depletion potential, freshwater aquatic ecotoxicity potential, and human toxicity potential are among the categories found through the CML 2001 impact analysis method selected for LCA application in this study.

2.2.2. Inventory Analysis

Inventory analysis consists of data collection and data calculation procedures. Data collection should be conducted for each process within the system boundaries. The inputs and outputs consist of the data collected and calculated. The inputs in this study include waste, raw material, and energy, which are obtained using the GaBi software database and a literature review. The outputs are emissions and energy produced. Figure 2 presents a screenshot of the GaBi software demonstrating the inputs and outputs of all scenarios as main categories. The assumptions made in the scope of this study are listed below.

- Of the waste collected in İstanbul, 63% is from the European side, whereas the ratio of waste collected on the Asian side is 37%.
- Waste collected from healthcare facilities in İstanbul is mainly classified into two categories: (i) municipal solid waste (non-hazardous) and (ii) medical waste (hazardous).
- Waste generated is collected by İSTAÇ's licensed trucks and disposed of at the Odayeri and Kömürcüoda Plants on the European side and Asian side, respectively.
- Non-hazardous municipal solid wastes are directly sent to the landfill sites.
- Medical waste is defined as infectious, pathological, and sharp waste from healthcare facilities in Annex 2 to the Regulation on the Control of Medical Wastes. Waste collected from healthcare facilities is classified into 4 main categories: (i) non-hazardous municipal solid waste, (ii) medical waste, (iii) hazardous waste, and (iv) radioactive waste [14]. Each waste category is collected in a different-colored waste bag as determined by the relevant regulation. Furthermore, it is forbidden to open waste bags collected from healthcare facilities according to the Regulation on the Control of Medical Wastes. Therefore, waste characterization could not be conducted in this study. Furthermore, 38% of medical waste is incinerated while the remaining, non-hazardous municipal solid waste is disposed of through sterilization in the current situation.

- Scenario 0, the baseline scenario, represents the current medical waste management system in Istanbul.
- Waste transportation was assumed to operate in a one-way direction, and the return was not considered. Average distances between the waste generation points and waste disposal sites were determined as follows: (i) the transportation distance of waste generated on the Asian side to the Kömürcüoda landfill site is 25.2 km; (ii) the transportation distance of waste collected from the European side to the Odayeri landfill site is 38.2 km; and (iii) the transportation distance of waste generated on both the Asian side and European side to the Odayeri incineration and sterilization facilities is 44.2 km.
- “Truck, diesel driven, Euro 0–5 mix, 7.5 t gross weight/3.3 t payload capacity” data in the GaBi database were used to calculate the fuel consumption of trucks during waste transportation and the emissions.



Name: aggregated

Quantity/Weight. Mass

Unit/Norm. kg

☐ Quantity view ☑ In/out aggregation

Absolute values · Rows 2

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Inputs ☐ Just elementary flows ☑ Separate IO tables

	aggregated	Scenario 0	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Flows	1.27×10^5	2.63×10^4	2.10×10^4	2.78×10^4	2.58×10^4	2.63×10^4
Resources	1.22×10^5	2.53×10^4	2.00×10^4	2.68×10^4	2.48×10^4	2.54×10^4
Valuable substances	4.67	0.864	2.28	0.467	0.88	0.184
Production residues in life cycle	4.90×10^3	998	998	998	998	914

Outputs

	aggregated	Scenario 0	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Flows	1.25×10^5	2.58×10^4	2.03×10^4	2.74×10^4	2.53×10^4	2.59×10^4
Valuable substances						
Production residues in life cycle	0.779	0.144	0.379	0.077	0.149	0.03
Deposited goods	3.68×10^3	731	653	753	786	753
Emissions to air	1.02×10^4	1.99×10^3	3.22×10^3	1.64×10^3	2.05×10^3	1.33×10^3
Emissions to fresh water	1.11×10^5	2.31×10^4	1.64×10^4	2.49×10^4	2.24×10^4	2.38×10^4
Emissions to sea water	264	58	36.3	64.1	49.5	56.6
Emissions to agricultural soil	0.000374	7.6×10^{-5}	6.81×10^{-5}	7.82×10^{-5}	7.55×10^{-5}	7.59×10^{-5}
Emissions to industrial soil	11.5	2.3	1.81	2.43	2.49	2.49
US LCI Database						

Figure 2. Main categories for the inputs and outputs.

2.2.3. Impact Assessment and Interpretation

Life cycle impact assessment analysis identifies and evaluates the amount and importance of potential environmental effects obtained by the inventory analysis. The chosen impact categories, global warming potential, acidification potential, eutrophication potential, ozone layer depletion potential, freshwater aquatic ecotoxicity potential, and human toxicity potential, are stated as kg CO_2-equivalent, kg SO_2-equivalent, kg PO_4-equivalent, kg R11-equivalent, and 1,4-dichlorobenzene (DCB)-equivalent, respectively.

The environmental impacts of each scenario were comparatively evaluated using GaBi software and the CML 2001 impact analysis methods within the software. The outputs obtained from GaBi software were interpreted, and the scenario with the best environmental performance was proposed as an alternative to the medical waste management system in Istanbul.

2.2.4. Waste Management Scenarios

Scenario 0 (baseline scenario) represents the current medical waste management system in Istanbul. Waste segregation at the generation point and waste minimization were not considered. Of the total waste, 38% consists of medical waste, whereas the remaining 62% comprises municipal solid waste. Municipal solid waste is directly transferred to the landfill. Of the total medical waste, 38% is disposed of by incineration, while steam sterilization is applied to the remaining 62%. Medical waste converted into municipal waste after stream sterilization is transferred to the landfill. Electricity is generated after incineration and the production of landfill gas; therefore, energy is recovered. The flow scheme of scenario 0 is presented in Figure 3.

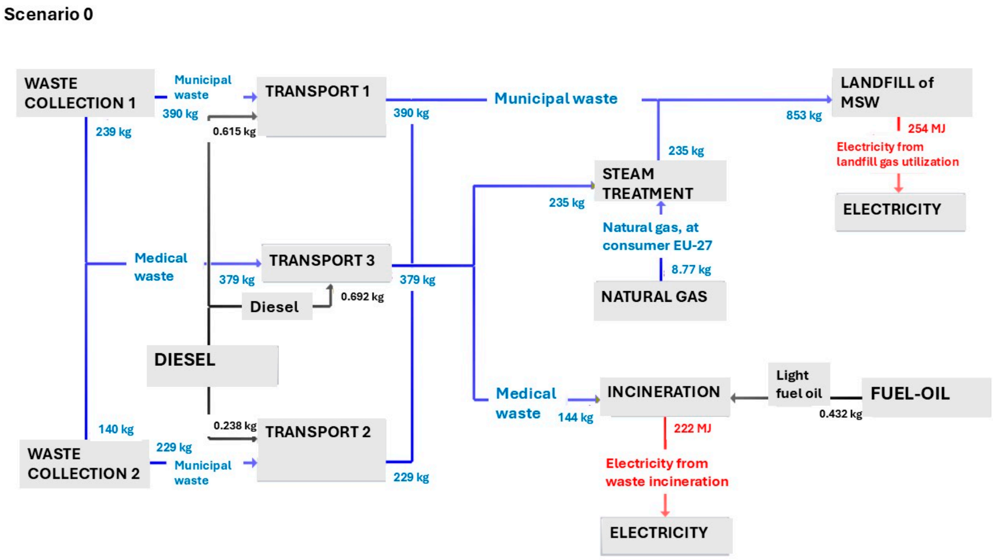

Figure 3. Flow scheme for baseline scenario (scenario 0).

In the flow scheme for the baseline scenario, the Waste Collection 1 and Waste Collection 2 processes represent waste collection from healthcare facilities on the European side and the Asian side, respectively. Municipal solid wastes among the collected waste are transported to İSTAÇ Odayeri and Kömürcüoda landfill sites by Transport 1 and Transport 2, respectively. The landfill of MSW represents the landfill. Hazardous medical wastes are collected by the licensed vehicles of İSTAÇ and transported to the sterilization and incineration plants in Odayeri by Transport 3. Steam Treatment and Incineration represent the sterilization and incineration processes, respectively. The energy generated from incineration and landfill is represented by Electricity. The Diesel process, Natural Gas process, and Fuel Oil represent the fuel consumed during transportation, natural gas used in the steam sterilization process, and fuel used in the incineration process, respectively.

Scenario 1 is created as the first alternative to the current medical waste management system in İstanbul, in which all of the hazardous waste generated from healthcare facilities is disposed of through incineration. Neither waste segregation nor waste minimization is assumed in this scenario. Of the total waste, 38% consists of medical waste, while the remaining 62% comprises municipal solid waste. In the context of this scenario, municipal solid waste is directly transferred to the landfill, whereas all medical waste is incinerated. Electricity is generated from incineration and the production of landfill gas; therefore, energy is recovered. The flow scheme of scenario 1 is displayed in Figure 4.

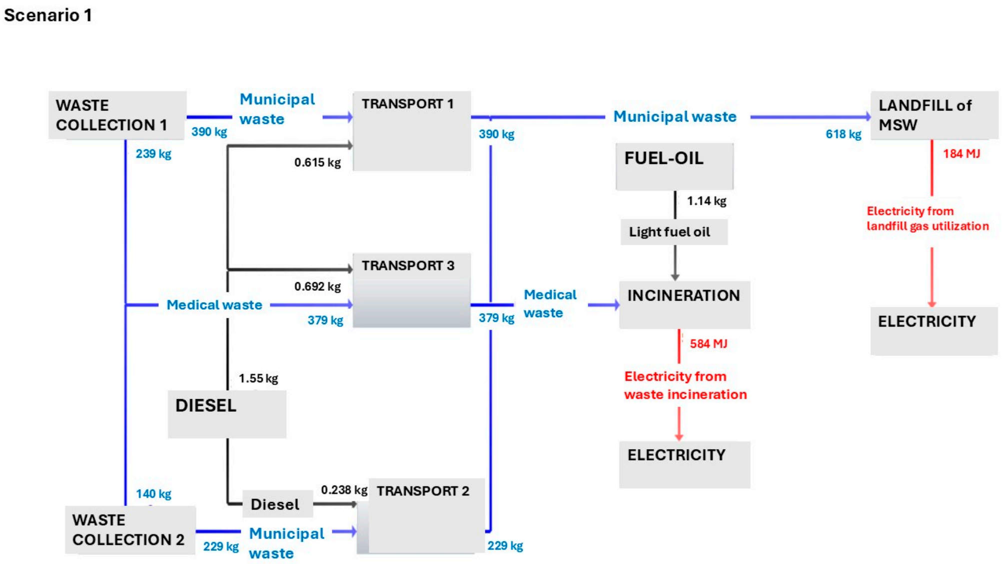

Figure 4. Flow scheme for scenario 1.

In the second alternative scenario (Scenario 2), it is assumed that medical waste, except for pharmaceuticals, pressurized containers, and chemicals, is disposed of through steam sterilization. Waste including pharmaceuticals, pressurized containers, and chemicals is collected separately from the other wastes according to the Regulation on the Control of Medical Wastes and disposed of by incineration as per the Regulation on the Control of Hazardous Waste. Waste segregation at the generation point and waste minimization were not considered. Of the total waste, 38% includes hazardous medical waste, while the remaining 62% consists of non-hazardous municipal solid waste. Municipal solid waste is directly transferred to the landfill. Electricity is generated from the incineration process and the production of landfill gas; therefore, energy is recovered. The flow scheme of scenario 2 is shown in Figure 5.

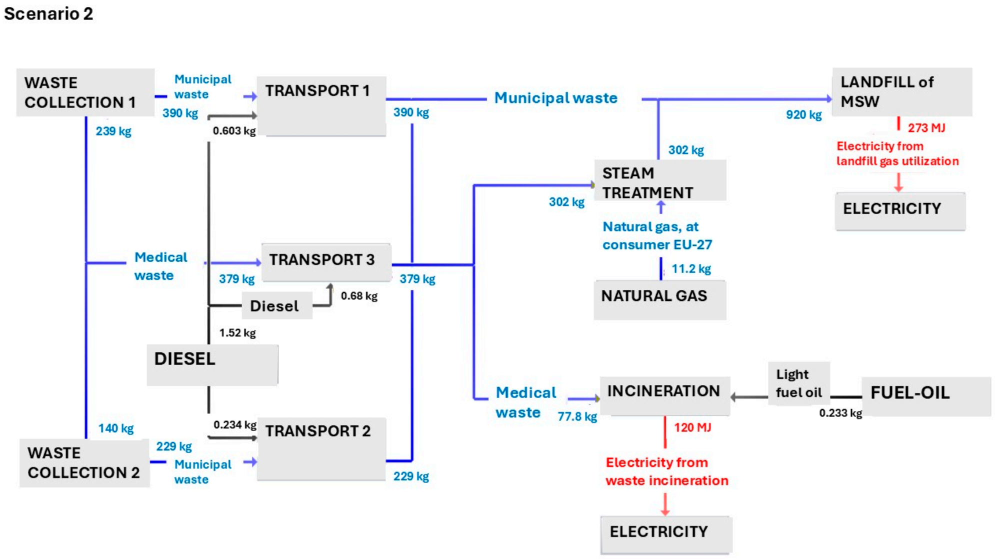

Figure 5. Flow scheme for scenario 2.

Scenario 3 is the first scenario comprising waste segregation at the generation point and waste minimization in medical waste management as an alternative to the baseline scenario. It is assumed that the medical waste ratio decreases to 15% from 32% by waste segregation and waste minimization in this scenario, so the ratio of municipal waste reaches

85%. In addition, it is assumed that the amount of medical waste generated is reduced with waste minimization, starting from the planning stage. In this context, all medical waste is incinerated, while non-hazardous municipal solid waste is disposed of by directly transferring it to the landfill. Electricity is generated from incineration and the production of landfill gas; therefore, energy is recovered. The flow scheme of scenario 3 is illustrated in Figure 6.

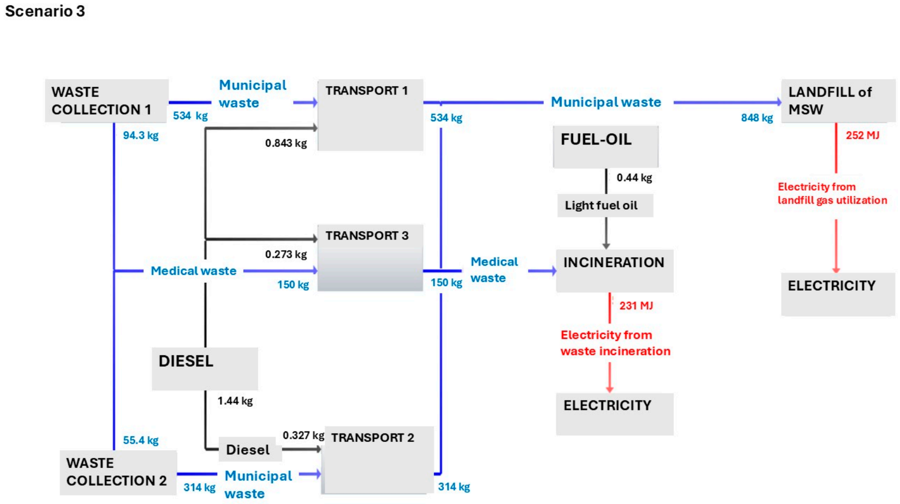

Figure 6. Flow chart for scenario 3 (waste segregation at the generation point/waste minimization + incineration + landfill).

Scenario 4: The last alternative scenario includes waste segregation at the generation point and waste minimization. While the medical waste ratio is 15%, the remaining 85% is characterized as municipal waste. In the context of this scenario, steam sterilization is implemented for all medical waste except pharmaceuticals, pressurized containers, and chemicals as a disposal technique. Waste including pharmaceuticals, pressurized containers, and chemicals is collected separately from the other wastes according to the Regulation on the Control of Medical Wastes and disposed of by incineration as per the Regulation on the Control of Hazardous Waste. Municipal solid waste is directly transferred to the landfill. Electricity is generated from incineration, and with the production of landfill gas, energy is recovered. Figure 7 presents the flow chart for scenario 4.

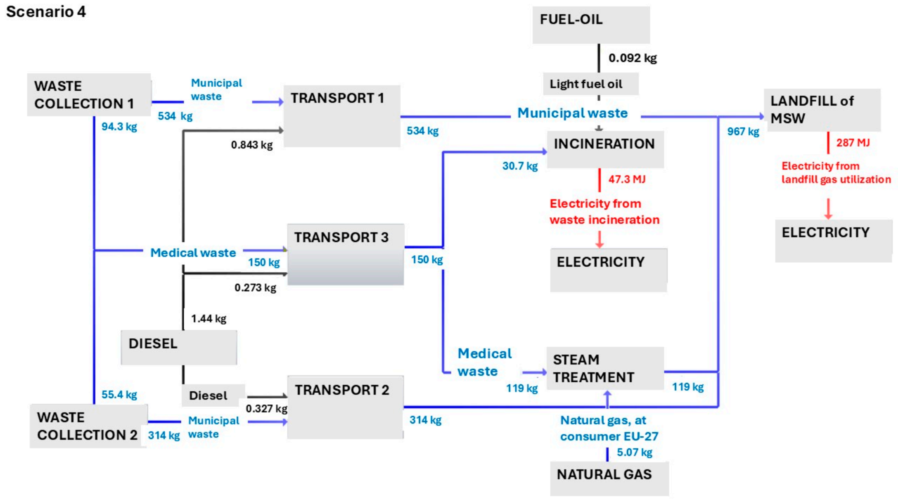

Figure 7. Flow chart for scenario 4 (waste segregation at the generation point/waste minimization + incineration + steam sterilization + landfill).

3. Results and Discussion

The environmental impacts of five alternatives for medical waste management in Istanbul were investigated using life cycle analysis. Table 1 summarizes the LCA results of each impact category obtained for each scenario.

Table 1. Environmental impact assessment for each medical waste scenario.

	Scenario 0	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Global warming [kg CO_2-Eq.]	728.64	509.03	793.52	695.21	807.56
Acidification [kg SO_2-Eq]	0.76	1.52	0.53	0.76	0.37
Eutrophication [kg PO_4-Eq]	0.81	0.77	0.81	0.8	0.82
Ozone layer depletion [kg R11-Eq]	2.251×10^{-9}	1.303×10^{-9}	2.518×10^{-9}	1.761×10^{-9}	2.275×10^{-9}
Freshwater aquatic toxicity [kg DCB-Eq]	4.07	9.74	2.47	4.19	1.33
Human toxicity [kg DCB-Eq]	518.83	1361.16	281.17	538.19	112.31

3.1. Global Warming Potential

The main impact factor contributing to global warming potential is the methane (CH_4) emitted from landfills.

The distribution of global warming potential, expressed as a percentage, is presented in Figure 8. The lowest global warming impact was recorded at 509.03 kg CO_2-Eq in scenario 1, corresponding to 14.4%. All medical waste was disposed of through incineration, while non-hazardous municipal solid waste was sent to landfill sites. Additionally, waste segregation at the generation point and waste minimization were not considered in scenario 1. In other words, the least amount of waste was transferred to the landfill among all scenarios; therefore, methane emissions from the landfill were lower compared to those observed in the other scenarios. In contrast, the greatest global warming potential was recorded at 807.56 kg CO_2-Eq, corresponding to 22.85%, in scenario 4. This situation is attributed to higher methane emissions, as the largest volume of waste was transported to the landfill. A similar trend was observed in the study in [31], which reported a higher global warming impact in the scenario including landfill compared to the scenario where all waste was incinerated. Additionally, a significantly lower global warming impact was achieved with the recovery process. In contrast, these results are inconsistent with the findings of the research in [25], which found that incineration without energy recovery caused the highest global warming potential. A similar combination of findings, with a higher global warming impact for incineration and a decrease in it by recycling, was reported in the study in [32]. CO_2 is the primary contributor to global warming in incineration processes, while landfilling is associated with methane emissions. However, the characterization factor of CH_4 is 21 in the CML method, indicating that its global warming potential is 21 times more than that of CO_2 [30]. Regarding the fluctuations in the global warming potential of the remaining scenarios (scenarios 0, 2, and 3), the consumption of liquid natural gas (LNG) during sterilization, as well as emissions from transportation and incineration, are considered primary contributors to the global warming potential. The global warming impact of LNG used in the steam sterilization process was found to be 71.3% in the study in [33]. Notably, in scenario 2, the contribution of CO_2 emissions to the global warming potential was highest when sterilization was performed using LNG as fuel. Nevertheless, electricity generated from landfill gas with higher methane concentrations is more suitable from both technical and economic perspectives. Methane and carbon dioxide are produced at the highest expected concentrations (30–40%) during the first 20 years of landfilling, while emissions continue for 50 years or even longer afterward. However, the landfill gas collection system generally does not operate at 100% efficiency, and thus, methane can be emitted due to gas leakages [34]. The global warming potential was calculated over a 100-year lifespan, considering landfill gas leakage using the CML 2001 methodology within GaBi software. Despite the generation of electricity from landfill gas, methane emissions have a significant adverse impact on environmental health, making landfills the primary contributors to global warming potential.

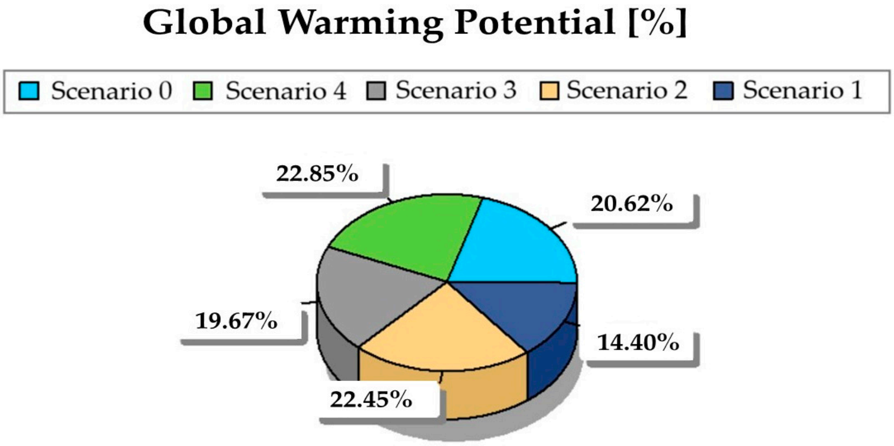

Figure 8. The percentage of global warming potential for each scenario.

3.2. Acidification Potential

Nitrogen oxide and sulfur dioxide emissions from the incineration process are the main contributors to acidification potential [31]. The percentage of acidification potential in each scenario is shown in Figure 9. Both scenario 2 (incineration + steam sterilization + landfill) and scenario 4 (waste segregation at generation points/waste minimization + incineration + sterilization + landfill) had the least impact, measuring 0.53 and 37 kg SO_2-Eq, corresponding to 13.46% and 9.42%, respectively, since the incineration process was implemented in the lowest proportion. The acidification potential in scenarios 0 (sterilization + landfill + incineration) and 3 (waste segregation at generation points/waste minimization + landfill + incineration) showed a slight increase, with similar impacts of 0.76 kg SO_2-Eq, corresponding to 19.28% and 19.19%, respectively. Although the incineration ratios in these scenarios were close, the sterilization process in scenario 0 increased the acidification potential somewhat due to emissions from LNG used as fuel. The greatest acidification impact was observed to be 1.52 kg SO_2-Eq, corresponding to 38.64%, in scenario 1 (incineration of all medical waste + landfilling of non-hazardous municipal solid waste). Similarly, the studies in [25,35] reported that incineration had a greater impact on acidification compared with landfilling. This situation is attributed to the more frequent use of the incineration process compared to other scenarios, resulting in the highest emissions of sulfur dioxide and nitrogen oxides. While the incineration process is regarded as the main contributor to acidification potential, the use of LNG as fuel in the steam sterilization process and emissions from transportation also contribute to the acidification potential [33].

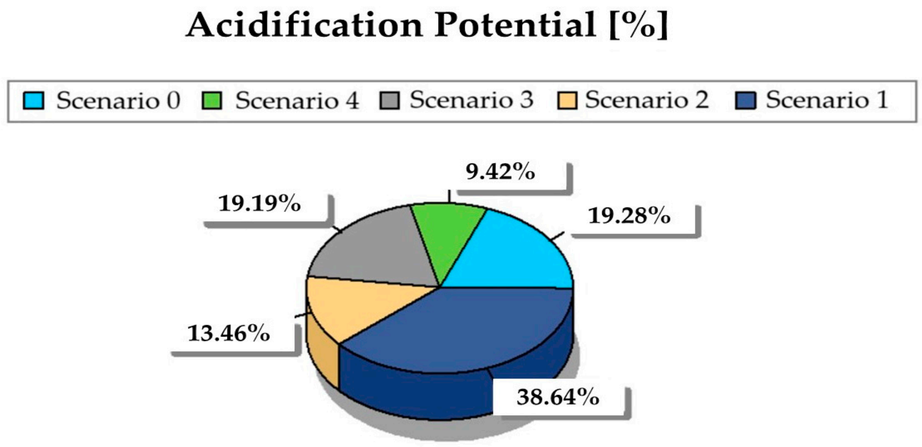

Figure 9. The distribution of percentages of acidification potential in the scenarios.

3.3. Eutrophication Potential

Nutrients such as nitrogen and phosphorus, as well as the emission of nitrogen oxides, are regarded as the primary factors contributing to eutrophication potential. Figure 10 illustrates the percentages of eutrophication potential obtained across different scenarios. The variations noted in the eutrophication potential are relatively minor, ranging from 0.77 to 0.82 kg Phosphate-Eq, which corresponds to 19.25% and 20.42%, respectively. Scenario 4, which involves the highest amount of waste transported to the landfill, has the most significant impact, followed by scenario 2, due to the landfill process containing a high concentration of nutrients. The baseline scenario, which consists of a greater proportion of incineration compared to scenarios 2 and 4, has a slightly increased contribution to eutrophication potential through nitrogen oxide emissions from the incineration process. These results are consistent with the research in [25,35], which obtained a greater eutrophication potential in landfill than in incineration. A similar pattern was observed in scenario 1 and scenario 3. This situation can be attributed to the use of LNG in the sterilization process and the fuel consumption during transportation. The impact of the sterilization process exceeds that of the incineration process because of nitrogen conversion [33]. This finding is supported by the findings of the study in [25], which reported that 99% of nitrogen is converted into nitrogen gas during incineration, while 28% of nitrogen is transferred to leachate. Leachate contains high concentrations of nutrients and is therefore considered the primary contributor to the eutrophication impact category. However, the effect of leachate on eutrophication potential was not calculated in this research.

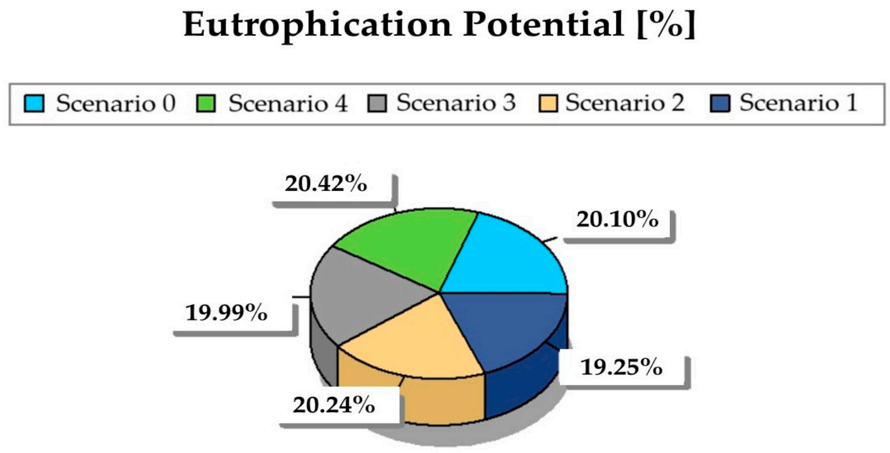

Figure 10. The percentage of eutrophication potential for each scenario.

3.4. Ozone Layer Depletion Potential

Ozone layer depletion results from methane bromo trifluoro-halone 1301 from raw petroleum production, petroleum, and LNG [36]. It can be seen in Figure 11 that the lowest impact value was achieved in scenario 1 (incineration + landfill) at 1.303 × 10^{-9} kg R11-Eq, corresponding to 12.89%, due to lower emissions of chlorine and bromine gas from landfills, while the highest impact was obtained in scenario 2 (incineration + sterilization + landfill). The main contributor to the ozone layer depletion potential is the use of LNG for steam production in the sterilization process [33]. This finding differs from the results of the study in [25], which found that incineration contributed to ozone depletion more than landfills.

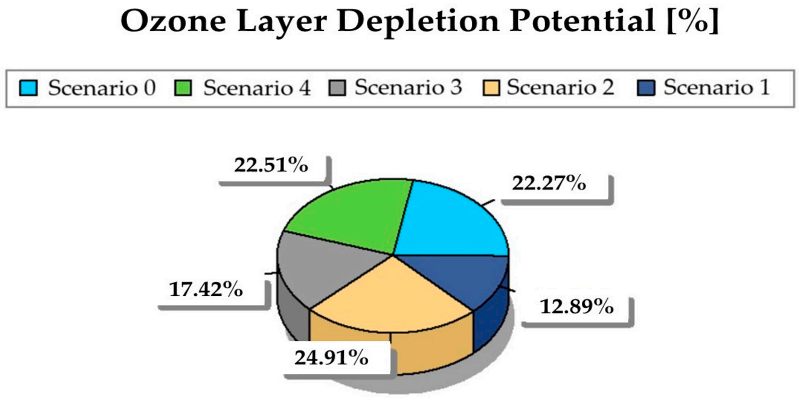

Figure 11. The distribution of percentages of ozone layer depletion potential in the scenarios.

3.5. Freshwater Aquatic Toxicity Potential

The direct discharge of heavy metals into freshwater and the transfer of heavy metal emissions in the atmosphere to aquatic environments are considered the main contributors to the freshwater aquatic ecotoxicity potential. The distribution of this impact category potential is presented in Figure 12. The highest impact obtained was 9.74 kg DCM-Eq in scenario 1 (incineration + landfill), corresponding to 44.65%, as 379 kg of medical waste was incinerated and, therefore, a greater concentration of heavy metals and dioxin was emitted. On the other hand, a lower amount of medical waste was subject to the incineration process in scenario 2 (incineration + sterilization + landfill), and particularly scenario 4 (waste segregation at the generation point/waste minimization + incineration + sterilization + landfill), achieving a limited impact on freshwater aquatic ecotoxicity. The research in [35] demonstrates that incineration contributed significantly more to freshwater aquatic ecotoxicity compared to landfill. This finding is consistent with the study in [25], which found that landfill had a lower freshwater aquatic ecotoxicity impact in the short-term time frame, while a sharp increase was observed in the long-term time frame.

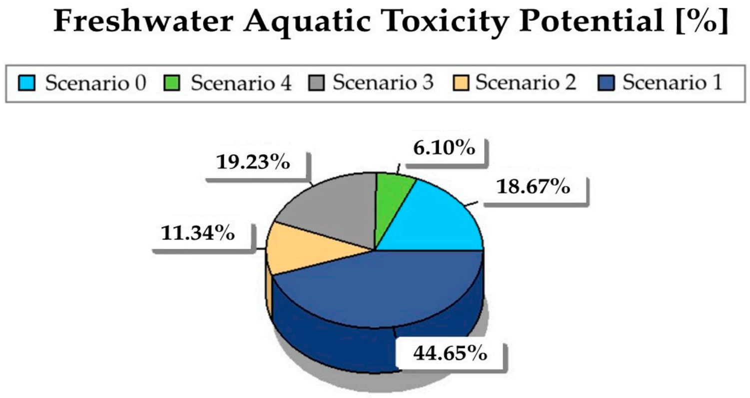

Figure 12. The percentage of freshwater aquatic toxicity potential for each scenario.

3.6. Human Health Toxicity Potential

The main contributors to human health toxicity potential are the emissions of sulfur dioxide and heavy metals from the incineration process [36]. As seen in Figure 13, there is a similar trend in this compact category to that for freshwater aquatic toxicity. Scenario 1 has the highest impact, followed by scenario 3, scenario 0, scenario 2, and scenario 4. This situation is attributed to the amount of waste incinerated and the concentration of toxic gases emitted. The lowest impact on human health toxicity potential is 112.31 kg DCM-Eq, corresponding to 3.99%, whereas the impact value of 1336.16 kg DCM-Eq is the highest, corresponding to 48.41%. This situation is supported by the studies in [25,35], which reported a greater contribution to human health toxicity impact from incineration compared to that from landfill.

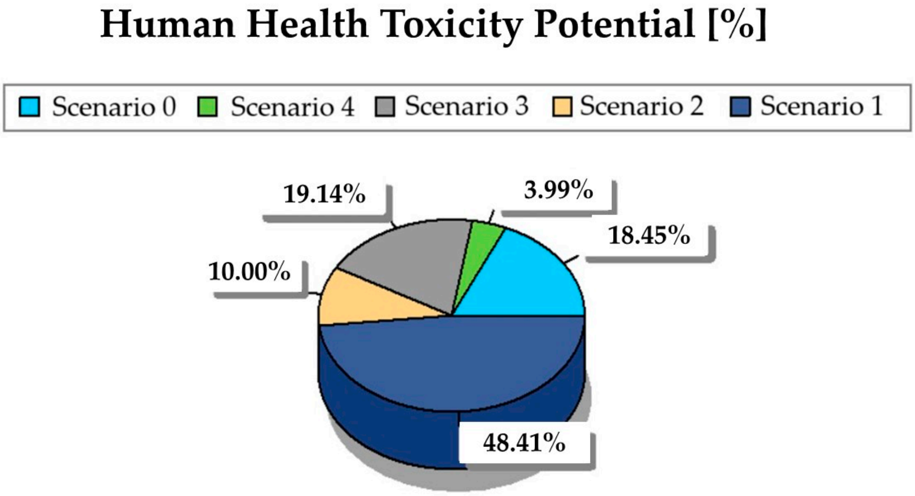

Figure 13. The distribution of human health toxicity potential.

It can be seen in Table 2 that scenario 4 (waste segregation at the generation point/waste minimization + incineration + sterilization + landfill) presents the best environmental performance, with 14.21% of the impact value, among all scenarios. Additionally, scenario 4 has the least impact on human health toxicity, freshwater aquatic toxicity, and acidification categories. There is a slight increase in global warming, eutrophication, and ozone layer depletion compared to the baseline scenario. This situation is attributed to a higher amount of waste being transported to the landfill site; therefore, the amount of waste incinerated or sterilized is decreased by separating non-hazardous municipal solid waste and medical waste and minimizing hazardous medical waste. Unfortunately, waste segregation at the generation points results in an increase in the amount of non-hazardous municipal solid waste transported to the landfill. Therefore, it is highly recommended to take reuse, recovery, and recycling processes into account in the medical waste management system and to limit the amount of waste sent to landfill sites [35], resulting in a reduction in methane emissions as well as a decrease in adverse impacts on the global warming, eutrophication, and ozone layer depletion categories.

On the other hand, the total impact ratio obtained in scenario 1 (incineration + landfill) is 29.79%, the highest, which is worse than that in the baseline scenario (the current medical waste management system in İstanbul). However, scenario 1's global warming impact is the lowest at 14.4%. This situation is attributed to less methane emissions from the landfill site. Thus, it is recommended to invest in the sterilization process. Emissions from incineration present adverse effects on many environmental impact categories. Therefore, the incineration process should be considered the last resort, used when there are operational issues in the landfill and/or energy cannot be generated from landfill gas.

Finally, regulators of medical waste management in İstanbul should consider building sterilization and/or incineration plants on the Asian side to reduce the detrimental environmental impacts and the cost of transportation. In this context, sterilization should be preferred rather than incineration.

Table 2. Impact values of each scenario for the impact categories.

Environmental Impact Category	Impact Value				
	Scenario 0	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Global Warming	20.62	14.4	22.45	19.67	22.85
Acidification	19.28	38.64	13.46	19.19	9.42
Eutrophication	20.1	19.25	20.24	19.99	20.42
Ozone Layer Depletion	22.27	12.89	24.91	17.42	22.51
Freshwater Aquatic Toxicity	18.67	44.65	11.34	19.23	6.1
Human Health Toxicity	18.45	48.41	10	19.14	3.99
Total Impact Value	119.39	178.324	102.4	114.64	85.29
Impact Ratio (%)	19.89	29.79	17.06	19.10	14.21

4. Conclusions

Sustainable medical waste management aims to reduce the amount of waste produced from healthcare facilities, particularly hazardous waste. Medical waste management alternatives were evaluated using life cycle assessment analysis in this research. Scenario 4 (waste segregation at the generation points/waste minimization + incineration + sterilization + landfill) had the lowest total environmental impact in comparison with the baseline and alternative scenarios. In the environmental impact categories of acidification, freshwater aquatic toxicity, and human health toxicity, scenario 4 presented significantly better environmental performance than the current medical waste management system in İstanbul, while the global warming impact of the baseline scenario was lower than that of scenario 4. The main limitations of this study are listed as follows: (i) an economic analysis for each scenario was not conducted, and (ii) recycling and leachate treatment were not considered in LCA analysis. Therefore, it is highly recommended to implement a more comprehensive model for a further decrease in the environmental impacts of medical waste management. Furthermore, decision-makers should consider incorporating the recycling process into the current medical waste management system and building a sterilization facility on the Asian side of İstanbul.

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Abbreviations

The following abbreviations are used in this manuscript:

LCA	Life Cycle Assessment
İSTAÇ	Istanbul Environmental Management Industry and Trade Inc. (İSTAÇ)
İBB	İstanbul Metropolitan Municipality

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