



RESEARCH ARTICLE

Comparison of incineration and autoclave methods in the treatment of medical wastes through life cycle assessment: A case study for Istanbul

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ABSTRACT

Medical waste management has always been an important topic due to its infectious status. Recently, more care has been given to it due to the COVID-19 pandemic throughout the world. Several methods are applied to handle medical wastes. Incineration and sterilization with autoclave are among the most common medical waste treatment methods. Among all methods, incineration serves the ultimate method of waste destruction since the waste is exposed to high temperatures (~800 °C) for about 2 hours. Because of the pandemic or some other reasons, administrations may want to shift their technology to incineration from autoclave. Therefore, in this study, we aimed to prepare a comparison of both technologies in terms of life cycle perspective. We used OpenLCA for calculations. Two different calculations were conducted. In the first one, the actual treatment methods and the waste amount were used. In the second one, a scenario was formed that included the treatment of the whole medical waste of Istanbul by only incineration process. The results indicated a higher mid-category life cycle impact for the combustion method. The highest contribution was for human toxicity with 3.8e4 kg 1,4-DB eq and 1.7e5 kg 1,4-DB eq for the current operation and scenario, respectively. The environmental impact of the sterilization process remained negligible relative to the combustion process.

Keywords: Medical waste, life cycle assessment, incineration, autoclave, OpenLCA

1. INTRODUCTION

Health services generate various types of waste. The World Health Organization (WHO) reported that approximately 10-25% of the waste produced in healthcare facilities can be considered hazardous [1]. Various treatment methods are available for medical wastes and they can be used for their disposal wastes [2]. Life Cycle Assessment (LCA) can be used to monitor the environmental impacts of similar activities [3].

In a study, the optimum municipal solid waste management strategy was investigated through an LCA study in Eskişehir in 2008 [4]. It was reported that 750 tons of waste per day was produced in Eskişehir and the city is among one of Turkey's developing cities. Five alternative scenarios were developed apart from the actual waste management system. These scenarios considered waste collection, transportation, handling, and disposal. According to

scenario comparisons and sensitivity analysis in SimaPro7, the composting scenario was found to be more environmentally friendly among the alternative scenarios.

LCA was applied in Aksaray, Turkey, to determine the best strategy for municipal solid waste management for the year 2017 [5]. As an alternative to the available waste management system, four different scenarios were generated and evaluated for the best environmental solution. The scenario with 75% landfilling and 25% composting had the least impact on the environment and human health. Carbon dioxide and methane emissions were estimated from the existing municipal solid waste facility. Annual emissions were 8674 and 3161 tons for CO₂ and CH₄, respectively.

Another study was conducted in Pakistan to determine the environmental impacts of different medical waste management scenarios using the LCA approach [1]. The scenarios included the

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transportation of the wastes and their disposal through material recycling, landfilling, composting, and incineration methods. These methods were evaluated according to greenhouse gas (GHG) emissions. Landfilling and incineration were the worst final disposal alternatives. An integrated system, including composting, incineration, and material recycling methods, was reported to be the best solution among all scenarios.

A preliminary LCA study was conducted in Bangladesh based on existing waste management scenarios [6]. The study was conducted in the city of Chittagong on the management of medical waste. For the available medical waste management system, three scenarios were generated based on previous data together with the previous scenario. Previously calculated scenario values were used as input to the LCA database. The collected data were analyzed using SimaPro7 to calculate terrestrial ecotoxicity potential, freshwater aquatic ecotoxicity, human toxicity, and global warming. It was indicated that incineration and open burning of the medical waste significantly contributed to human toxicity potential and global warming. The landfilling disposal method mainly contributed to terrestrial ecotoxicity potential and freshwater aquatic ecotoxicity categories. The suggested scenario had lower impacts on each category, compared to existing public and private medical waste management systems. The incineration of medical waste with 30% energy recovery had the lowest environmental impact for all impact categories.

Medical wastes are regularly collected and disposed of in sterilization (infectious and cutting wastes) and incineration (infectious and pathological wastes) facilities with an average of 77 tons of medical wastes per day from health institutions in Istanbul [7]. Annually 29,065 tons of medical waste were produced in Istanbul in 2019 [8]. In Istanbul, 22% of medical waste (pathological and infectious wastes) is sent to the incineration facility, and 78% of medical waste

(infectious and cutting wastes) is sent to the sterilization facility [9].

In this study, two cases are calculated through OpenLCA and discussed. In the first case, it is aimed to evaluate the existing medical waste disposal methods for Istanbul with LCA and in the second case, it is aimed to evaluate the disposal of Istanbul medical wastes only by incineration with LCA. The boundaries of the study is the disposal of Istanbul medical wastes collected in 2019 at the medical waste sterilization facility and medical waste incineration facilities. In the study, the transportation to the disposal facilities and the process after disposal were not considered. Because these parts are fixed regardless of disposal.

2. MATERIALS AND METHOD

The LCA methodology provides a "cradle to grave" perspective, keeping in mind that all stages involved in the life cycle of a product or activity have responsibility for its environmental consequences [10]. LCA application consists of four separate parts; target and scope definition, inventory analysis, impact assessment, and interpretation [3]. Fig 1 shows the LCA stages.

An important perspective of a waste management strategy is to identify areas where specific measures have to be taken to reduce the environmental impacts of waste management. LCA was used in several studies as an environmental tool to benchmark waste disposal options or management scenarios [12].

Medical wastes characterization is required for LCA, but no such study is available for Istanbul. According to a study, which reported the characterization of medical waste in Tabriz, Iran [13], is used in this study to represent the shares of waste type. The distribution of medical waste characterization calculated according to the percentages in Fig 2.

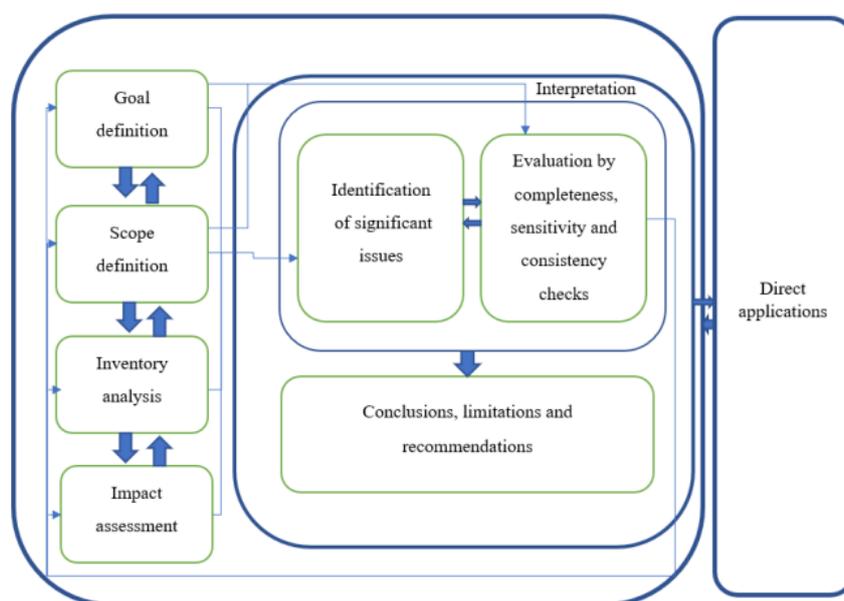


Fig 1. The elements of the interpretation phase and their relations to each other and to the other phases of the LCA [11]

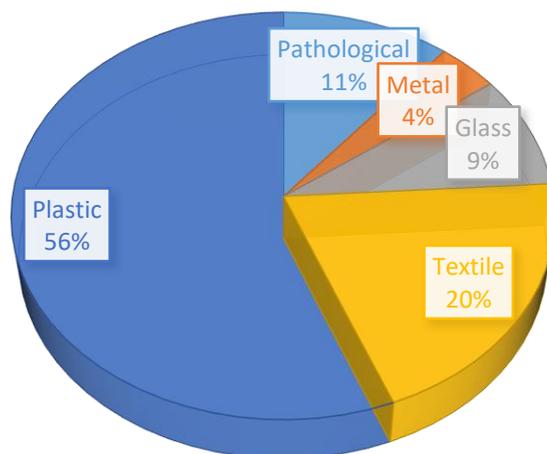


Fig 2. The medical waste share used in this study

The highest waste type was plastic with 56%. The remaining were textile, pathological, glass, and metal in the descending share order. These data were given an input to the software. In this study, the 1.10 version of the openLCA program and ELCD 3.2 database was used. OpenLCA is an open-source

software used for life cycle analysis and sustainability assessment[14]. In openLCA; flows, processes, product systems were created for the current disposal method and scenario. CML-IA method was used to perform the impact analysis. The impact categories in CML-IA is given in Table 1.

Table1. Impact categories and units of CML-IA impact analysis method

Name	Reference unit
Abiotic depletion	kg Sb eq
Abiotic depletion (fossil fuel)	MJ
Acidification	kg SO ₂ eq
Eutrophication	kg PO ₄ eq
Freshwater ecotoxicity	kg 1,4-DB eq
Global warming potential (GWP100a)	kg CO ₂ eq
Human toxicity	kg 1,4-DB eq
Marine aquatic ecotoxicity	kg 1,4-DB eq
Ozone depletion potential (ODP)	kg CFC-11 eq
Photochemical oxidation	kg C ₂ H ₄ eq
Terrestrial ecotoxicity	kg 1,4-DB eq

In the availability of different methods for the mandatory impact categories, a key indicator is selected based on the existing principle of best practice. These key indicators are category indicators at the "midpoint level" (approach to the problem)[15]. Depletion of abiotic resources includes depletion for elements, ultimate reserves, and abiotic depletion for fossil fuels as impact categories. The abiotic depletion of elements, ultimate reserves are related to the extraction of minerals due to inputs in the system. The abiotic Depletion Factor (ADF) is determined based on the concentration reserves and decrease rate for each mineral extraction (kg antimony equivalent/kg extraction). Abiotic depletion of fossil fuels is related to the Lower Heating Value (LHV), which has the unit of MJ per kg m³ of fossil fuel. Global Warming

Potential (GWP100) is calculated according to the characterization model generated by the Intergovernmental Panel on Climate Change (IPCC), which has the unit of kg carbon dioxide equivalent/kg emissions for a time horizon of 100 years. The characterization model for ozone depletion (steady state) was developed by the World Meteorological Organization (WMO) and describes the ozone depletion potential of different substances (in kg CFC-11 equivalent kg⁻¹ emission). The photochemical oxidation model was developed by Jenkin & Hayman and Derwent. It defines photochemical oxidation in kg ethylene equivalents per kg emission. Acidification potential model was developed by Huijbregts and it is expressed in kg SO₂ equivalents per kg. Eutrophication (fate not included) midpoint category

is expressed in kg PO₄ equivalents per kg emission. Characterization factors for human toxicity, freshwater aquatic ecotoxicity, marine aquatic ecotoxicology, and terrestrial ecotoxicity are expressed in terms of Human Toxicity Potentials (HTP), describing fate, exposure, and effects of toxic materials for an infinite time horizon. The unit of each toxic substance HTP's are expressed in 1,4-dichlorobenzene equivalents per kg emission.

3. RESULTS & DISCUSSION

3.1. Life cycle assessment of current operation conditions

For the existing medical waste sterilization and incineration facility in Istanbul province, the results were obtained by using the CML-IA impact analysis

method after entering the flows as input and output to the processes. The results of the impact analysis of the medical waste sterilization facility are given in Table 2.

According to Table 2, the highest impact of the medical waste sterilization facility occurs due to marine aquatic ecotoxicity, global warming, and human ecotoxicity, in descending order, respectively. It is the electricity use at the facility that contributes the most to the impact analysis results. Electricity consumption was the primary contributor to impact assessment results with 552.8 kg 1,4 DB eq. The results of the impact analysis of the medical waste incineration facility are given in Table 3.

Table2. Medical waste sterilization plant impact analysis results

Name	Impact result of sterilization
Marine aquatic ecotoxicity	552.8 kg 1,4-DB eq
Global warming potential (GWP100a)	3.3 kg CO ₂ eq
Human toxicity	0.1 kg 1,4-DB eq
Acidification	7.7e-3 kg SO ₂ eq
Freshwater ecotoxicity	2.6e-3 kg 1,4-DB eq
Terrestrial ecotoxicity	1.8e-3 kg 1,4-DB eq
Europhication	6.2e-3 kg PO ₄ eq
Photochemical oxidation	5.4e-4 kg C ₂ H ₄ eq
Abiotic depletion	1.4e-6 kg Sb eq
Ozone depletion potential (ODP)	5.2e-9 kg CFC-11 eq
Abiotic depletion (fossil fuel)	0 MJ

Table3. Medical waste incineration plant impact analysis results

Name	Impact result of incineration
Human toxicity	3.8e4 kg 1,4-DB eq
Marine aquatic ecotoxicity	2.1e4 kg 1,4-DB eq
Acidification	1.6e4 kg SO ₂ eq
Europhication	4.1e3 kg PO ₄ eq
Photochemical oxidation	438.7 kg C ₂ H ₄ eq
Global warming potential (GWP100a)	215.5 kg CO ₂ eq
Freshwater ecotoxicity	0.4 kg 1,4-DB eq
Terrestrial ecotoxicity	0.1 kg 1,4-DB eq
Abiotic depletion	9.2e-5 kg Sb eq
Ozone depletion potential (ODP)	2.0e-5 kg CFC-11 eq
Abiotic depletion (fossil fuel)	0 MJ

The highest three impacts of medical waste incineration facility are from human toxicity, marine aquatic ecotoxicity, and acidification in descending order, respectively. The mass values of each impact analysis of incineration remained much higher than the sterilization. The human toxicity contributions were 1.95e4, 1.80e4, 6.04, and 0.57 kg 1,4-DB eq from secondary incineration, rotary kiln, process water, and electricity grid, respectively. Secondary combustion in waste incineration is a vital part of the system since the generated persistent organic pollutants are removed from the stack gas via this unit [16]. The contributors for marine aquatic ecotoxicity were 1.82e4 and 3.22e3 kg 1,4-DB eq for process water and electricity grid, respectively. As acidification and eutrophication have major mass impacts, their contributions were also evaluated according to the operation unit. Secondary combustion chamber and rotary kiln were the highest contributors. The study results showed that the highest contribution for acidification and eutrophication was caused by the secondary

combustion chamber and the rotary kiln. Contributions for photochemical oxidation originated from the secondary combustion chamber, process water use, electricity use, and rotary kiln, respectively.

The relative results of combustion and sterilization is provided in Fig 3.

Combustion process was the dominant process for all environmental impacts relative to sterilization process. Only sterilization has 3% contribution for marine aquatic toxicity.

3.2. Life cycle assessment of combustion scenario

As an alternative to current operation conditions, we considered only combustion treatment. In this scenario, all medical waste is assumed to be treated in a rotary kiln process. The results of the impact analysis of the medical waste incineration facility in the new scenario are given in Table 4.

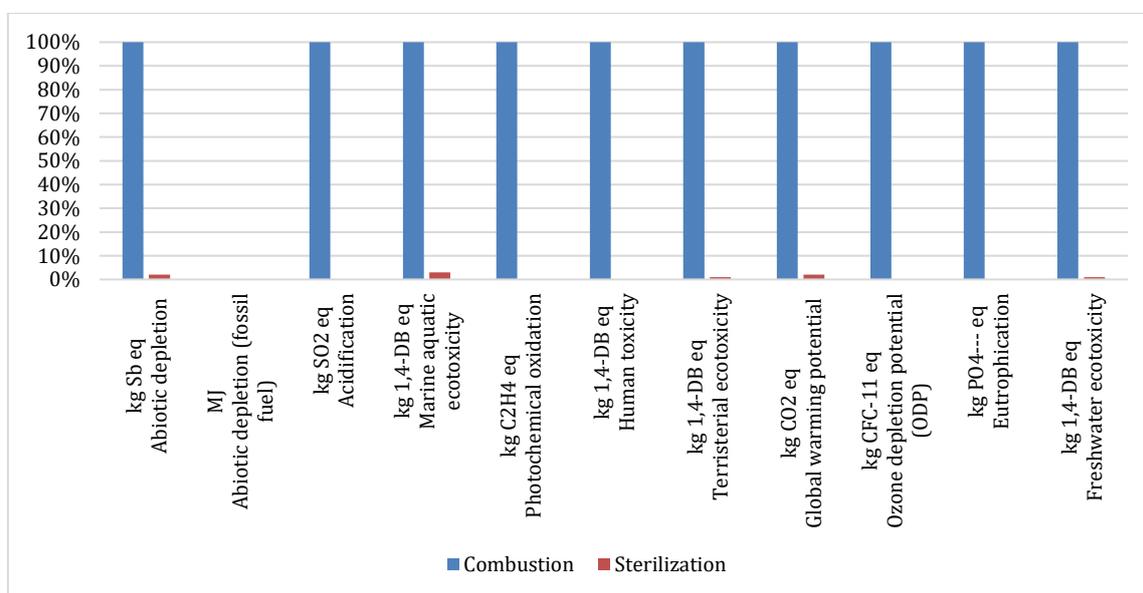


Fig 3. Relative impact assessment results of combustion and sterilization

Table 4. Impact analysis results of the scenario of only combustion

Name	Impact result of the scenario
Human toxicity	1.7e5 kg 1,4-DB eq
Acidification	7.1e4 kg SO ₂ eq
Marine aquatic ecotoxicity	2.1e4 kg 1,4-DB eq
Eutrophication	1.8e4 kg PO ₄ eq
Photochemical oxidation	1.9e3 kg C ₂ H ₄ eq
Global warming potential (GWP100a)	215.5 kg CO ₂ eq
Freshwater ecotoxicity	0.4 kg 1,4-DB eq
Terrestrial ecotoxicity	0.1 kg 1,4-DB eq
Abiotic depletion	9.2e-5 kg Sb eq
Ozone depletion potential (ODP)	2.0e-5 kg CFC-11 eq
Abiotic depletion (fossil fuel)	0 MJ

The highest impact is calculated for human toxicity. Since it is mostly due to combustion process, its value increased significantly with the only combustion treatment scenario. Other considerable changes were observed for acidification, human toxicity, eutrophication, and photochemical oxidation. The results remained the same for global warming potential, freshwater ecotoxicity, terrestrial ecotoxicity, abiotic depletion, and ozone depletion potential. The relative results of current operating conditions and scenario are provided in Fig 4.

The scenario had the highest impact for all categories. In the current operation conditions, acidification, eutrophication, human toxicity, and photochemical oxidation impacts were 22% on a quantity basis relative to scenario operation. This is due to lower mid-category impact of the sterilization process.

According to a study conducted in Pakistan, two scenarios were used to calculate the current medical waste disposal method, that is, incineration and the storage of medical wastes without classification (Scenario A and Scenario B) with LCA [17]. Scenario C, which included disposal by pyrolysis and chemical disinfection, was considered as an alternative. Existing applications (Scenario A and Scenario B) were the worst for all categories. Especially, the greatest impact from existing methods were for human toxicity produced from incineration. Human toxicity and marine aquatic ecotoxicity were found to be the categories with the highest impact for all selected treatment processes. It was observed that Scenario C would have lower effects. More specifically, in the case of incineration, the highest impact was on human toxicity. In the storage state, seawater ecotoxicity had the highest impact. Regarding sterilization, autoclaving of medical wastes was considered to be the most suitable technology according to the assessment criteria. However, it seems that their costs will be higher than incineration. Therefore, large amounts of infectious waste cannot be disposed of by sterilization technology. In addition, some chemicals and infectious substances cannot be treated by autoclaving, such as mercury, chemotherapy-derived compounds and materials, volatile and semi-volatile organic compounds, and radioactive waste. When we compare our study with the Pakistan example, the highest environmental impact for either incineration processes was for human toxicity and seawater ecotoxicity. In the Pakistan case, $7.5e-5$ kg 1,4-DB eq human toxicity and $1.53e-3$ kg 1,4-DB eq marine aquatic ecotoxicity were calculated. In our study, human toxicity of the existing incinerator plant was calculated as $3.8e4$ kg 1,4-DB eq and marine aquatic ecotoxicity was $2.1e4$ kg 1,4-DB eq. When the populations of both cities are considered, the results are in agreement.

In a study in China, environmental impacts and LCA of three mobile disposal scenarios (incinerator, mobile steam, and microwave sterilization equipment, followed by incineration with urban solid waste) were studied in the post-COVID-19 outbreak [18]. The results showed that incineration along with municipal solid waste had the lowest environmental impact due to the environmental benefits generated by energy recovery, and that incineration with hazardous waste has the highest environmental impact due to high energy

consumption. Energy consumption (ie kerosene, electricity and diesel) were key factors for the three mobile disposal scenarios. In Scenario 1, the combustion process, direct emissions, electricity, and kerosene were the primary contributors to most categories. Direct emissions during incineration of medical waste included acidic gases (e.g. SO_2) and particulate matter, which contributed greatly to acidification potential and respiratory inorganics. In Scenario 2, in the sterilization process, the highest energy consumption was through the boiler in the steam generation system, which consumed diesel to generate steam at high temperatures for sterilization. Electricity consumption also had a significant adverse impact on global warming, acidification potential, respiratory inorganics, ionizing radiation-human health effects, CO_2 , and SO_2 . According to the results of the study, energy recovery was regarded an option to reduce the environmental impact for the waste disposal vehicle. The results showed that incineration with municipal solid waste had the lowest environmental impact due to electricity generation, and incineration with hazardous waste had the highest environmental impact. Co-incineration plants were not recommended to dispose of infectious medical waste due to the risk of infection from disposal. Compared to our study, both exhibited a significant negative effect of acidification potential due to incineration process. When sterilization processes are examined, the electricity used, contributed to the impact categories in both studies. It was observed that electricity consumption in the sterilization facility had a significant effect on global warming in both studies.

In a study conducted in China, the environmental and economic impacts of three medical waste disposal scenarios (pyrolysis, steam sterilization, and chemical disinfection) were measured through a cost-related LCA to determine the effective technique for medical waste disposal [19]. The results showed that, the steam sterilization and chemical disinfection scenarios had the highest overall environmental and lowest economic impacts, respectively, due to differences in energy consumption. Energy (e.g. electricity and diesel) contributed the highest contributor to each impact category for steam sterilization scenario. This outcome was the same for also our study. Global warming was the highest calculated impact category for the Chinese sterilization scenario. However, in our study, the highest value for sterilization was calculated for seawater ecotoxicity, followed by global warming.

A study was conducted in Northern Italy (Emilia Romagna Region) to evaluate the effects of waste incineration plants by applying the LCA methodology and highlight the most effective steps in the incineration process [20]. The management of solid residues and heavy metal emissions were the most important environmental concerns. In addition, a temporary comparison with the environmental impact of landfills for the same amount of waste indicated that incineration should be considered environmentally preferable. The most important effects were identified for carcinogenic and inorganic pollutants that produce respiratory diseases. In comparison, disposal with landfills has resulted in worse human health or ecosystem quality in terms of resource utilization.

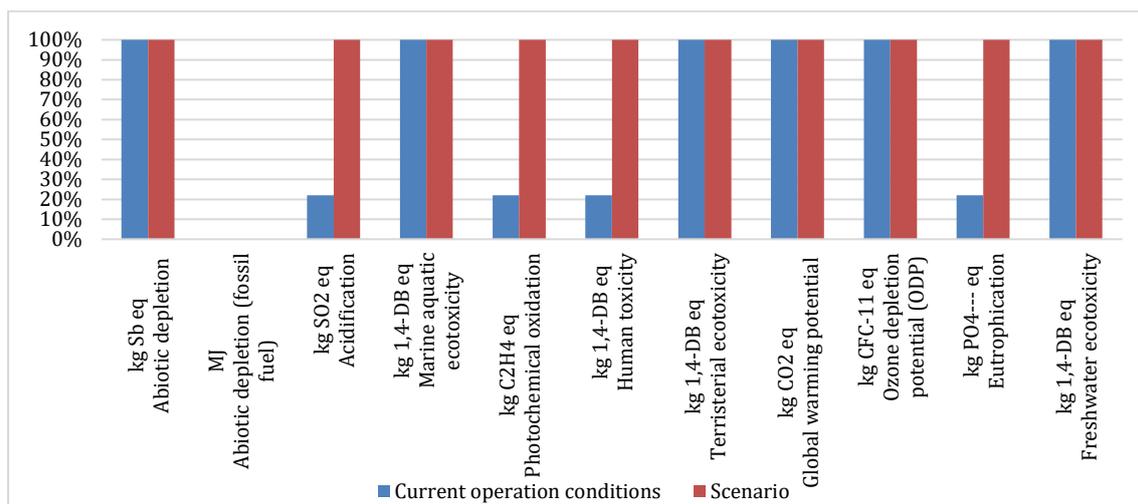


Fig 4. Relative impact assessment results of considered operation options

There has been a large increase in Personal Protective Equipment (PPE) kit use to reduce the likelihood of infection during the COVID-19 outbreak [21]. The used PPE kits, which are potentially infectious, pose a threat to human health, terrestrial and marine ecosystems unless scientifically addressed and destroyed. In a study conducted in China, LCA of PPE kits was performed using GaBi version 8.7 for two disposal scenarios for six environmental impact categories covering general impacts on both terrestrial and marine ecosystems. Three situations with different disposal options were considered. Two of these are centralized and decentralized incineration and the other is landfilling. The combustion process (central - 3816 kg CO₂ equivalent and decentralized - 3813 kg CO₂ equivalent) showed high global warming potential. Human toxicity potential of decentralized combustion was calculated as 250.3 kg DB eq and central combustion as 250.2 kg DB eq. Decentralized incineration was found to be a suitable option for the destruction of PPE both in terms of environment and health. The least viable option was identified as landfilling. Considering the above, it is important to point out that LCA impact categories also produce high footprint values for the decentralized system, so there is always a need to improve systems at hand to reduce overall impacts.

4. CONCLUSIONS

The COVID-19 pandemic is causing global concern and an increase in medical waste production. The disposal of medical waste is an urgent need to prevent the spread of the epidemic. Emergency disposal scenarios of medical waste generated during the COVID-19 pandemic require a systematic assessment to measure potential environmental impacts. Several medical waste treatment methods are employed all around the world. Among these methods, incineration and sterilization are the most common medical waste treatment techniques. In order to determine the environmental impact in different mid-categories LCA is employed in this study. Our aim was to perform a scenario which is alternative to current operation conditions in Istanbul for medical waste treatment.

The environmental impact of incineration remained higher relative to sterilization process. Significant differences were calculated for acidification, eutrophication, human toxicity, and photochemical oxidation. Effective measures can be taken to reduce environmental impact include improving the efficiency of electricity consumption, reducing the use of chemicals (eg sodium hydroxide, lime and chlorine oxide), selecting clean energy and providing energy recovery and incineration of medical waste. Extensive studies have shown that energy recovery is a key factor in reducing the overall environmental burden for solid waste incineration. The results herein can be exploited as a quick reference guide for those who want to apply medical waste treatment method for different purposes. The LCA method compares only treatment stage of incineration and sterilization. Firms and municipalities may decide the best available method for their ultimate purpose according to the results presented herein.

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