environments

MDPI

Article

Analyses of the Environmental Sustainability of Two Infectious Hospital Solid Waste Management Systems

Alessia Amato [1], Mario Caroli [1,2], Susanna Balducci [1,3], Giulia Merli [1], Gianluca Magrini [1,4], Eleonora Zavoli [1] and Francesca Beolchini [1,*]

[1] Department of Life and Environmental Sciences, Polytechnic University of Marche, 60131 Ancona, Italy; a.amato@univpm.it (A.A.); mario.caroli@regione.marche.it (M.C.); susanna.balducci@regione.marche.it (S.B.); g.merli@univpm.it (G.M.); gmagrini@newstergroup.com (G.M.); ele.zavoli@gmail.com (E.Z.)

[2] Regional Health Officer for Emergencies-GORES Coordinator-(Regional Health Emergencies Operational Group) Marche Region, 60100 Ancona, Italy

[3] Special Planning of Emergency and Operating Room, Civil Protection of Marche Region, 60100 Ancona, Italy

[4] Newster System Srl, Via Giovanni Pascoli 2, 47853 Cerasolo, Italy

* Correspondence: f.beolchini@staff.univpm.it

Abstract: The priority during an emergency, regardless of the type, is to rescue as many lives as possible. Field hospitals are usually installed to provide the primary relief to the affected population when hospitals are compromised or absent. There are several sanitary units worldwide ready to be transported to disaster areas. An average field hospital is equipped with an operating room, laboratory, and radiological equipment, but it does not include a unit for the infectious hospital solid waste treatment, which results in improper management with high infection risks and emissions due to incorrect operations (e.g., open incineration). Therefore, the present study identified two market-available solutions (an incinerator and a sterilizer) designed to be transported even under the challenging conditions typical of disasters and are suitable for treating infectious waste. The systems were assessed by a life cycle assessment (LCA), proving an emission savings >90% (considering all impact categories) using the sterilization system. The avoided combustion allows to halve the effect on climate change due to a portable incinerator. This study supplies interesting food for thought for the emergency managers, proving the possibility of integrating the sustainability also in the planning of the response to catastrophic events.

Keywords: LCA; emergency waste; field hospital; sterilizer

check for updates

Citation: Amato, A.; Caroli, M.; Balducci, S.; Merli, G.; Magrini, G.; Zavoli, E.; Beolchini, F. Analyses of the Environmental Sustainability of Two Infectious Hospital Solid Waste Management Systems. *Environments* **2024**, *11*, 284. https://doi.org/10.3390/environments11120284

Academic Editors: Yixuan Wang, Manuel Soto and Yingqian Lin

Received: 19 November 2024
Revised: 6 December 2024
Accepted: 7 December 2024
Published: 10 December 2024

1. Introduction

Humanity has always faced different kinds of emergencies with the greatest challenges of the identification of the most effective management strategy. In the past, these events have included natural phenomena, such as floods, earthquakes, and volcanic eruptions. After the industrial revolution, they also included events resulting from human activities, like major industrial accidents, which are known as NaTechs (Natural Hazards Triggering Technological Accidents) [1]. Emergency management consists of four phases: mitigation and preparedness, which take place before the emergency to identify risks and vulnerabilities; and response and recovery, which occur during and after the emergency. Managing disasters is a social process that requires the involvement of various stakeholders, such as technical experts and citizens. In a rapidly changing world, successfully and sustainably addressing emergencies depends on effective planning, long-term vision, and the ability to connect the different elements of emergency response into clear and coordinated strategies [2,3].

During an emergency (irrespective of the typology), the preservation of human life has priority, and health facilities play an essential role. However, these facilities are often compromised or completely absent (in poor and underdeveloped countries), and field hospitals are the recommended solutions. They are constituted after the disasters with the aim of providing safe healthcare services to disaster victims and the continuation of treatment of hospitalized patients temporarily in pre-determined, safe areas close to the existing hospitals [4]. These temporary units are composed of containers, tents, and inflatable modules, and they have at least ten beds, an operating room, a basic laboratory, and mobile radiological equipment [4,5]. The field hospital must meet critical criteria, such as energy independence and self-sufficiency in the resulting waste management [4]. The healthcare waste category is added to the other types of waste inevitably generated after a disaster (e.g., masonry materials, asbestos, metals, vegetation waste, soils and sediments, vehicles or ships). Such waste often affects the response and recovery activities during an emergency (e.g., debris or waste can obstruct rescuers and emergency services from reaching survivors) [6]. Furthermore, waste causes potential risks for public health: for example, organic waste and stagnant water pools can trigger disease-carrying vectors, which are commonly communicable, especially when there are large numbers of displaced people [7]. It is evident that inadequate waste management can have an immediate impact, but it also results in slow and costly recovery with long-term effects [8]. However, due to operative issues, inadequate coordination between responsible government departments, lack of stakeholder engagement and, most notably, insufficient financial and technical capacity often occur [9]. The challenging management of infectious hospital solid waste is linked to its composition, which includes the following:

- Infectious waste, resulting from the contact with any biological fluids secreted or excreted by an isolated patient;
- Sharp objects, such as needles, syringes, single-use scalpels, always considered potentially hazardous, both used and not;
- Pharmaceutical waste, including antibiotics and antifungals, as well as expired drugs or items contaminated with pharmaceuticals;
- Chemical waste, mainly from diagnostic and radiology labs, including washing solutions, solvent mixtures, and reagents;
- Heavy metals, highly toxic (e.g., Hg);
- Pressurized containers, which could explode if incinerated or punctured;
- Radioactive hospital waste from the preparation and administration of radiopharmaceuticals or laboratories [10].

The heterogeneous composition and the presence of hazardous microorganisms, pathogens, drugs and sharp objects, potentially leading to infections among healthcare workers, make the management of infectious hospital solid waste-handling systems an hot topic [11]. This is also confirmed by the WHO, which estimates that contaminated needle injections cause 21 million hepatitis B infections, 2 million hepatitis C infections, and 260,000 HIV infections [10].

Worldwide, there are no specific guidelines or protocols for healthcare waste management (or they are too general), and the standardization of a method is primary.

The technologies that are commonly used for the healthcare waste, in peacetime, are heating, disinfection and chemical approaches [12]. On the final disposal basis, the waste is pre-treated by mechanical operations, such as shredding, pelletizing, crushing, grinding, solid–liquid separation, and mixing. These steps aim at the reduction of waste volume (up to 80%) and dimension to increase the specific surface area of the solid portion, promoting further chemical or thermal treatments [8]. Thereafter, the waste is incinerated or co-incinerated to completely destroy pathogens and further reduce the material volume and amount, since only the resulting ash needs to be disposed of [10]. In the absence of incineration facilities (a common condition during emergencies), the infectious waste is often stored and burned in open dumps with environmental, social and health effects [10,13]. As an alternative, portable incinerators are confined systems that are designed to be transportable by truck, ship, or airplane. Knowledge about portable systems is very limited, unlike large-scale incinerators, particularly concerning emissions and the resulting human and environmental exposure, even if their use is well documented [13–16]. A recent study on mobile incinerators, carried out during the COVID-19 period in China, emphasized the virus elimination capability achieved by a mobile incinerator combined with a waste weight reduction by 95% [14]. The benefit of these devices is evident; however, they produce significant gas pollutants, including dioxins and furans, during their operation, since they are not equipped by effective emission containment systems, which is crucial to reduce the impacts on both the environment and human health [15,16].

As an alternative to heat treatment, there are technologies designed for the temporary storage and treatment of infectious waste and for minimizing the transmission of pathogens among waste handlers, steam disinfection and chemical treatments. Steam-based treatments, such as autoclaving and microwaving, sterilize highly infectious and sharp waste by exposure to moist heat and steam. Sterilization is able to eliminate all forms of sporogenous and non-sporogenous living organisms by operating temperatures between 121 and 135 °C (on technology bases) with the required time varying from 30–40 min to 2.5 h. This method needs significant amounts of energy and generates toxic and odorous gases and liquids, necessitating additional purification treatments to prevent the release into the air [11,17]. On the other hand, chemical treatments involve the use of disinfectants, ozone, and alkaline hydrolysis, which reduce the pathogenic microorganisms [10,18].

Despite many technologies being described in the literature from a technical point of view, poor information is related to the sustainability aspects.

In this regard, the life cycle assessment (LCA) methodology was identified as the best tool to evaluate the management of infectious solid waste during an emergency, particularly in situations requiring the installation of a field hospital. The analysis, able to include all the steps of life cycle, allowing a long-term perspective [19], considered two scenarios: the use of a portable incinerator and a portable sterilizer (both technologies are on the market).

Given the significant challenge of managing waste in a field hospital, the present paper aims to be a supporting tool for the strategic and sustainable planning of integrated waste management in an emergency context.

2. Materials and Methods

2.1. Technological Devices for Infectious Hospital Waste Management

This section describes the systems selected for the constructed scenarios: a portable incineration system, on the American market, and the Italian Sanifyco 19 NW5 designed for waste sterilization [20]. The choice was due to logistical factors since both the selected devices are transportable by air or sea, and they have proper size, weight, and volume, which are conditions necessary for transportation.

2.1.1. Portable Incinerator

The selected system is a portable cyclonic incinerator manufactured by an American company. It allows the material combustion, disintegrating waste materials to ash residue ranging from 3% (if only pharmaceuticals or documents are present) to 20% (for average hospital waste). It is a batch-loading system, powered by wood or coal, where the introduced material is quickly eliminated. Waste is supplied to the incinerator through an Easy-Feed cartridge once the fire has been ignited inside the drum. High-speed electric fans create an intense heat cyclone that reduces the burnt material to a small pile of ash with reduced atmospheric emissions. The device initially releases smoke due to wood combustion and produces particles from the incineration process.

2.1.2. Portable Sterilizer

SANIFYCO 19 NW5 is a preassembled unit used to treat both solid (patented Frictional Heat Treatment [21]) and liquid sanitary waste (patented Safe Water Treatment process) during emergencies, aiming to prevent the spread of pathogens. It consists of a container, housing a machine to treat solid infectious hospital waste (NW5 or NW15), and a second container for the infectious sewage water treatment (SWT) (not included in this study). Each container is equipped with electrical and water supply connections and necessary pipes for loading/unloading. The output is non-infectious and comparable to common urban waste. The process covered in this study is the Newster Frictional Heat Treatment, which takes place in a closed sterilization chamber under negative pressure, ensuring no risks for both environment and operator.

2.2. The System Boundaries

The functional unit considered for this analysis is 1 kg of an average infectious hospital solid waste from a field hospital. The scenarios assessed include the use of the portable incinerator (scenario 1) and the NW5 sterilizer (scenario 2). The system boundaries (Figure 1) establish the process units to be included in the analysis, defining the input and output flows in agreement with the material and energy balances.

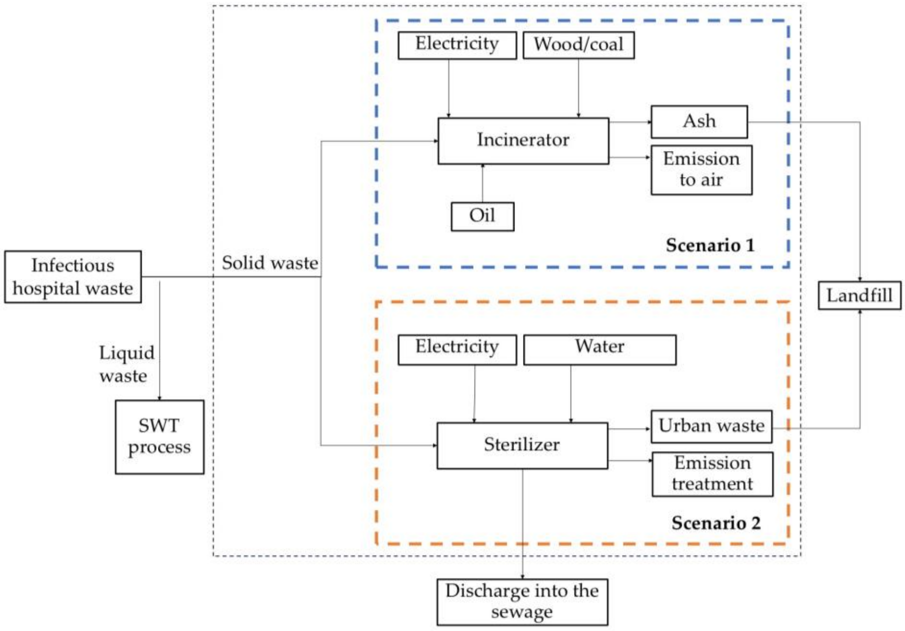

Figure 1. System boundaries.

This study only considers solid waste, so the liquid waste flow was excluded from the system boundaries. For the same reason, the kit necessary for wet waste treatment in the portable incinerator was not included within the assessment.

2.3. Life Cycle Inventory

Table 1 shows the life cycle inventory, including the mass and energy balances related to heat (scenario 1) and sterilization (scenario 2) treatments, to be translated into environmental burdens in the further impact assessment.

In agreement with the device description, we assumed a waste treatment cycle using the portable incinerator (scenario 1) of 45 min. The waste is supplied by a special cartridge once combustion begins. The resulting products are ashes, emissions, and consumables (able to ensure the equipment maintenance). A quantity of ash equal to 20% by weight of the input waste is assumed. The air emissions of the incinerator were estimated according to the literature, considering the absence of a structured abatement system [22]. Scenario 2 involves the use of a NW5 sterilization unit with a treatment cycle lasting 30 min based on the manufacturer guidelines [23]. In this treatment, the waste enters the system, is shredded, and then brought to a temperature of 150 °C, resulting in a dehydrated product. Emissions are not considered in scenario 2, since the entire treatment occurs in water, and the evaluation of emission parameters complies with the strict Italian legal limits [24]. Cast iron, steel, paper, copper, rubber, and silicone are consumable materials used in both devices. Their consumption was estimated by the manufacturing company of the sterilizer, and it was assumed to be the same for both devices. The CO_2 emissions from coal combustion were calculated in agreement with the factors estimated by Ministry of the Environment and Energy Security (ISPRA), i.e., 2.5 kg CO_2/kg of coal [25]. On the other hand, the emissions resulting from solid waste combustion were estimated in agreement with the European Environment Agency, and they are reported in the Supplementary Materials (Table S1) [22].

Table 1. Life cycle inventory (functional unit 1 kg of infectious hospital solid waste).

	Scenario 1	**Scenario 2**
Input		
Fuel (coal) (g)	820	-
Electricity (KWh)	0.04	0.63
Water supply (g)	-	3500
Cast iron (g)	1.8	1.8
Steel (g)	3.6	3.6
Paper (g)	0.013	0.013
Copper (g)	0.035	0.035
Rubber (g)	0.040	0.040
Silicone (g)	0.026	0.026
Output		
Solid residue in landfill/ash (g)	200	800
CO_2 emission (g)	1.1	-
CO_2 emission from fuel (g)	2100	-
Consumables (g)	3.4	3.4
Aqueous sewage in sewer (g)	-	3700

2.4. Software and Methods

The LCA was performed in accordance with ISO standards 14040 and 14044:2006 [26,27]. The software LCA (10.9.0.31) for expert by Shera and the related database (My Professional Database 2024.2) [28] were used for the production processes of energy and raw materials and the quantification of the environmental burdens of the considered scenarios.

The impacts were quantified in agreement with the most recent method Environmental Footprint 3.0, covering the classification, characterization, normalization, and weighting phases. This method is based on 16 impact categories that quantify effects on the environment issues (8 categories: acidification [mole of H+ eq.], climate change [kg CO2 eq.], ecotoxicity freshwater [CTUe], eutrophication freshwater [kg P eq], eutrophication marine [kg N eq.], eutrophication terrestrial [mole of N eq.], ozone depletion [kg C-11 eq.]); human health (4 categories: human toxicity, cancer and non-cancer [CTUh], ionizing radiation, human health [Bq U235 eq.], particulate matter [g PM2.5 eq.], photochemical ozone formation [kg NMVOC eq.]), and resource depletion (4 categories: land use [C deficit eq.], resource use, fossils [kg Sb eq.], resource use, mineral and metals [kg Sb eq.], water use [m3 eq.]), with the aim of including the broadest spectrum of issues potentially caused by each supply chain. Normalization and weighting were performed in agreement with the same method EF 3.0. The results were expressed in person equivalent (i.e., the average number of European citizens that generate the same impact in a year in terms of impacts from global to local as well resource consumptions) [29].

3. Results and Discussion

The results are divided into "classification and characterization", which analyzes all environmental aspects in detail, and "normalization and weighting", which provides an overall view of the sustainability of the two scenarios.

3.1. Classification and Characterization

Figure 3 reports that the incinerator is the worst scenario in more than 60% of the 16 considered categories. This outcome is justified by two main issues: the combustion of infectious hospital solid waste and the use of coal as fuel. Indeed, following the life cycle principle, all the aspects of the coal use were included in the analysis: from the extraction to the process production. In this regard, the main effects can be seen in the categories of freshwater ecotoxicity (Figure 3C), land use (Figure 3J), particulate matter (Figure 3L) and resource use fossil (Figure 3N). The incineration represents a significant burden in categories such as climate change (about 80% of the whole impact) due to the burning of fossil fuels (coal) and waste, which inevitably releases carbon dioxide, nitrogen oxides, and sulfur oxides—all contributors to global warming (Figure 3B). On the other hand, the health effects (Figure 3G,H) are mainly connected to toxic gases, such as carbon monoxide, which can cause symptoms like headache and disorientation, and sulfur dioxide, which irritates the eyes and upper respiratory tract [30]. On the other hand, the possible incomplete combustion of material and its composition justify the carcinogenic effects [31].

Although the incinerator is the worst scenario in many of the considered impact categories, the sterilizer also shows issues, mainly in the aspects of ionizing radiation (Figure 3I), mineral and metal use (2O), land use (2J), and ozone layer depletion (2K). For all these aspects, electricity consumption (necessary to guarantee the equipment operation) represents the greatest criticality. The burden due to energy supply is linked to the specific national grid mix, and so it varies based on the country where the equipment is installed. The average European energy mix (nuclear and natural gas as main resources, respectively, 24% and 22% of the whole mix) was used for the present study, explaining the effect on the ionizing radiation category. Indeed, this category is connected to the production of radionuclides (potentially toxic for humans) resulting from both the nuclear energy production and the mineral oil and gas extraction, which were used as energy carriers [32–34].

A small percentage of the impact (variable on the impact category basis) is attributable to the disposal of the resulting waste in landfilling sites. This contribution, highlighted in the categories of climate change and eutrophication freshwater, is mainly attributed to scenario 2, since NW5 allows a waste amount reduction of 20% compared to the incinerator, and it is able to reduce it by 80% due to the combustion process. The results in the water use category (Figure 3P, which favors the incineration) are explained by the water demand of the sterilizer.

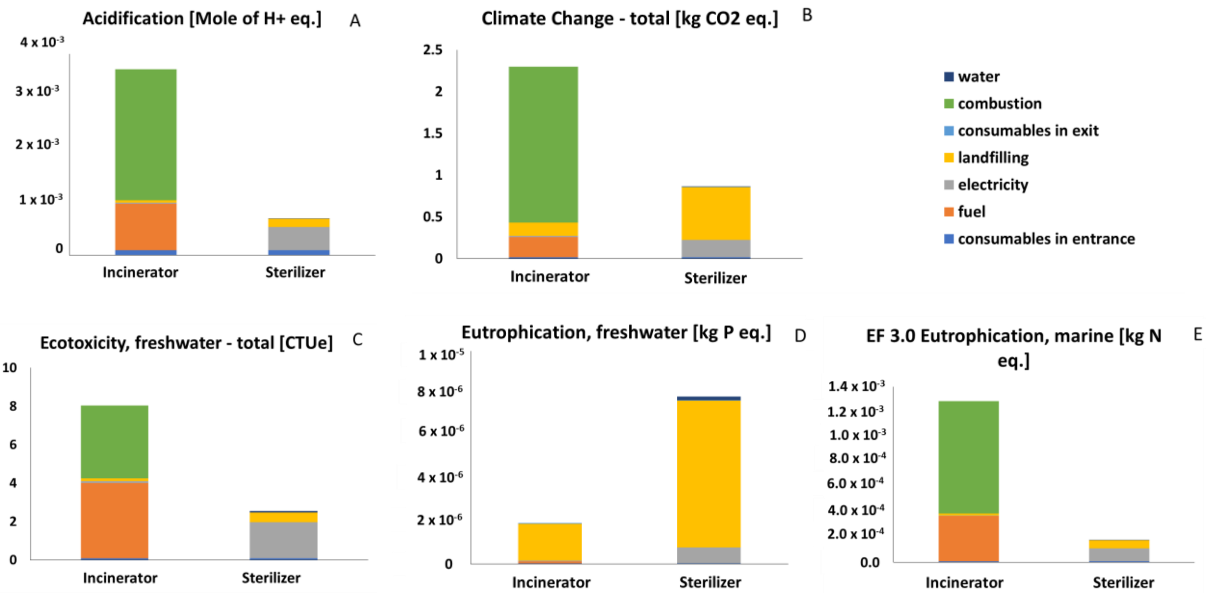

Figure 2. *Cont.*

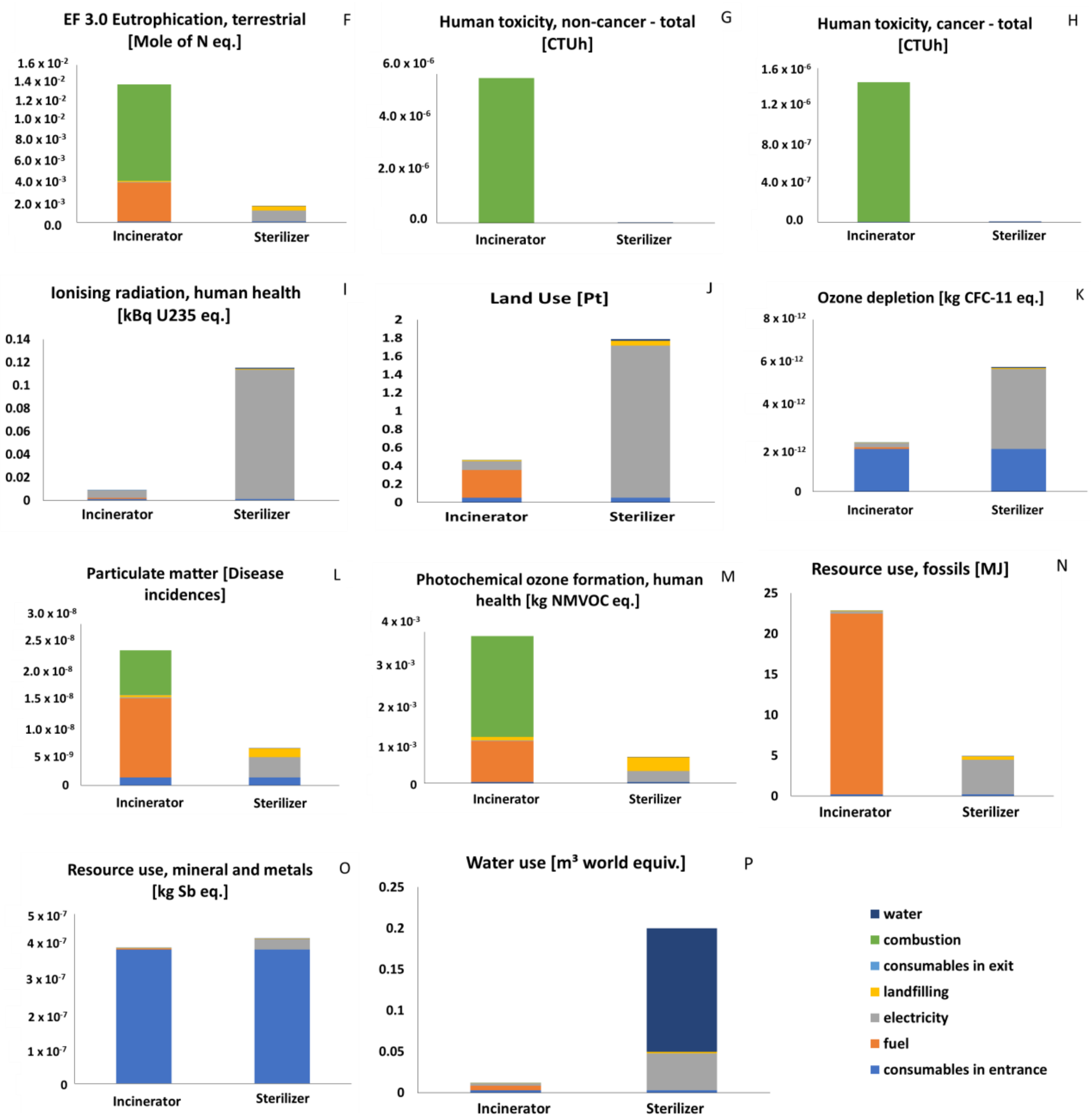

Figure 3. Results of classification and characterization, in the categories of (**A**) acidification; (**B**) climate change; (**C**) ecotoxicity, freshwater; (**D**) eutrophication, freshwater; (**E**) eutrophication, marine; (**F**) eutrophication, terrestrial; (**G**) human toxicity, non-cancer; (**H**) human toxicity, cancer; (**I**) ionizing radiation, human health; (**J**) land use; (**K**) ozone depletion; (**L**) particulate matter; (**M**) photochemical ozone formation, human health; (**N**) resource use, fossils; (**O**) resource use, minerals and metals; (**P**) water use. "Fuel" means coal (production and refining of the necessary quantity), chosen as fuel within the incinerator and "combustion" means the process of incineration of both waste and coal. Functional unit: 1 kg of an average infectious hospital solid waste from a field hospital.

3.2. Normalization and Weighting

Normalization and weighting phases, which provide synthetic indexes to compare the different impact categories, were useful to gain a more general overview of the results.

In this regard, Figure 4 shows the results for the two considered scenarios, which were expressed in person-equivalents (p.e.). This chart supports the interpretation of classification and characterization in most categories: the use of the incinerator device is less sustainable than the sterilization, primarily due to the significant emissions caused by waste and coal combustion, in the absence of an efficient emission retention system. Although in the classification and characterization phases, some impacts were higher for the sterilizer, the weighting applied during this phase of the analysis led to a flattening of the sterilizer's graph to the detriment of the incinerator.

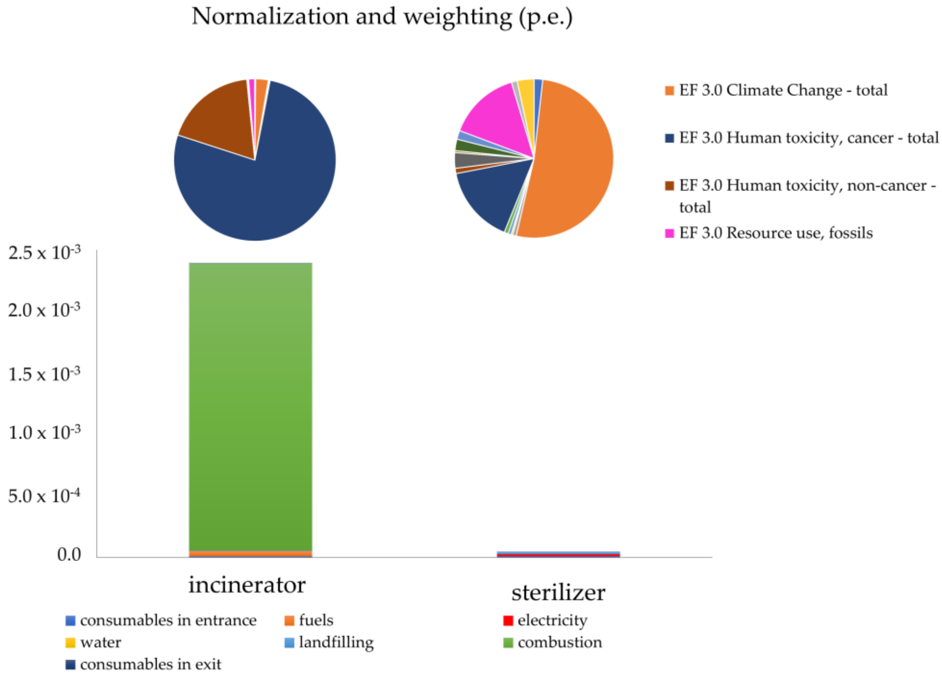

Figure 4. Results of normalization and weighting steps, comparison between the two considered scenarios. The pie charts show the contributions on the impact categories (the chart legend reports only the categories with percentages greater than 5%).

The weighting indexes used in the present paper are recommended by EF 3.0, and they considered the magnitude of the considered environmental issues. For example, the weighting factor of climate change is around three times higher than that of land use, so the result in Figure 3B has more relevance than that described in Figure 3J. This method aims at creating a priority scale in sustainability actions rather than underestimating some environmental issues. The pie charts on the top of Figure 4 describe the contribution of all the impact categories on the normalized and weighted results (2.4×10^{-3} p.e. for scenario 1-incinerator and 4.3×10^{-5} p.e. for scenario 2-sterilizer). The human toxicity results are the most affected by incineration (more than 90%, considering both cancer and non-cancer effects). On the other hand, the most relevant impact of sterilizer is on climate change, 52% of the whole impact, which is mainly linked to electricity demand and the final disposal in landfilling site of the resulting solid waste.

4. Conclusions

The current increase in extreme phenomena worldwide has made emergency planning increasingly important. It is evident that each event has its peculiarity; however, the installation of a field hospital is necessary to increase the number of saved human lives. There are several examples of well-structured mobile hospital units worldwide; however, the aspect of sanitary waste management is always underestimated. In this context, the present paper aimed at providing a solution able to fit both the technical needs and sustainability target. Concerning the technical aspects, both solutions are designed to be transportable by truck, ship, or airplane, and they do not present limitations related to policy restrictions. As regards the sustainability, the standardized LCA method estimated the impacts related to the whole life of the two considered options. The results proved a whole impact reduction higher than 90% achieved by the sterilizer despite its lower capacity to reduce the waste amount. The avoided combustion and the avoided use of coal as fuel allow to halve the effect on climate change resulting from the incinerator use, for instance. The achievements are affected by a variability mainly linked to the supplied grid mix (based on the country where the emergency takes place). However, they represent an important guide for the policymakers involved in emergency management.

Indeed, the present paper represents a real innovation, since it was able to integrate the environmental sustainability in the emergency planning sector, where often the long-term effects (for both human and environmental health) are neglected.

Supplementary Materials: The following supporting information can be downloaded at https://www.mdpi.com/article/10.3390/environments11120284/s1, Table S1: Emissions from incinerators without abatement systems.

Author Contributions: Conceptualization, A.A., M.C. and S.B.; methodology, A.A. and M.C.; software, A.A.; validation, G.M. (Gianluca Magrini) and F.B.; formal analysis, A.A. and E.Z.; investigation, A.A. and E.Z.; resources, F.B.; data curation, G.M. (Giulia Merli) and A.A.; writing—original draft preparation, G.M. (Giulia Merli); writing—review and editing, A.A., G.M. (Giulia Merli), G.M. (Gianluca Magrini); visualization, G.M. (Giulia Merli); supervision, A.A., M.C. and F.B.; project administration, A.A. and F.B.; funding acquisition, A.A. and F.B. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Data Availability Statement: The original contributions presented in this study are included in the article/Supplementary Materials. Further inquiries can be directed to the corresponding author.

Conflicts of Interest: The authors declare no conflicts of interest.

References

1. Gill, D.A.; Ritchie, L.A. Contributions of Technological and Natech Disaster Research to the Social Science Disaster Paradigm. In *Handbook of Disaster Research (Handbooks of Sociology and Social Research)*; Rodríguez, H., Donner, W., Trainor, J., Eds.; Springer: Cham, Switzerland, 2018.
2. The Joint Commission, 2019 Chapter Champion Emergency Management (EM)–Comprehensive Accreditation Manual for Nursing Care Centers (CAMNCC) published by Joint Commission Resources Oak Brook, Illinois 60523 USA. Available online: https://store.jcrinc.com/assets/1/14/EBCCEM19_sample_pages.pdf (accessed on 15 November 2024).
3. Alexander, D.E. *Disaster and Emergency Planning for Preparedness, Response, and Recovery*; Oxford University Press: Oxford, UK, 2015.
4. Tekin, E.; Bayramoglu, A.; Uzkeser, M.; Cakir, Z. Evacuation of Hospitals during Disaster, Establishment of a Field Hospital, and Communication. *Eurasian J. Med.* **2017**, *49*, 137–141. [CrossRef] [PubMed]
5. WHO. Classification and Minimum Standards for Foreign Medical Teams in Sudden Onset Disasters. 2013. Available online: https://www.who.int/docs/default-source/documents/publications/classification-and-minimum-standards-for-foreign-medical-teams-in-suddent-onset-disasters.pdf (accessed on 15 November 2024).
6. Brown, C. *Disaster Waste Management: A Systems Approach*; University of Canterbury: Canterbury, UK, 2012. Available online: https://ir.canterbury.ac.nz/server/api/core/bitstreams/9ab3675a-3a30-4b5f-9206-d2b8dec3ea3b/content (accessed on 15 November 2024).
7. Liang, S.Y.; Messenger, N. Infectious Diseases After Hydrologic Disasters. *Emerg. Med. Clin.* **2018**, *36*, 835–851. [CrossRef] [PubMed]
8. Mazzei, H.G.; Specchia, S. Latest insights on technologies for the treatment of solid medical waste: A review. *J. Environ. Chem. Eng.* **2023**, *11*, 109309. [CrossRef]
9. Memon, A.H.; Rahman, I.A.; Abdullah, M.R.; Azis, A.A.A. Factors affecting construction cost in Mara large construction project: Perspective of project management consultant. *Int. J. Sustain. Constr. Eng. Technol.* **2010**, *1*, 41–54.
10. Janik-Karpinska, E.; Brancaleoni, R.; Niemcewicz, M.; Wojtas, W.; Foco, M.; Podogrocki, M.; Bijak, M. Healthcare Waste—A Serious Problem for Global Health. *Healthcare* **2023**, *11*, 1–14. [CrossRef] [PubMed]
11. WHO. Safe Management of Wastes from Health-Care Activities. 2014. Available online: https://www.who.int/publications/i/item/9789241548564 (accessed on 15 November 2024).
12. World Health Organization. Overview of technologies for the treatment of infectious and sharp waste from health care facilities. 2019. Available online: https://iris.who.int/bitstream/handle/10665/328146/9789241516228-eng.pdf (accessed on 15 November 2024).
13. Pour, M.S.; Hakkaki-Fard, A.; Firoozabadi, B. Numerical Investigation of a Portable Incinerator: A Parametric Study. *Processes* **2020**, *8*, 923. [CrossRef]

14. Miao, J.; Li, J.; Wang, F.; Xia, X.; Deng, S.; Zhang, S. Characterization and evaluation of the leachability of bottom ash from a mobile emergency incinerator of COVID-19 medical waste: A case study in Huoshenshan Hospital, Wuhan, China. *J. Environ. Manag.* **2022**, *303*, 114161. [CrossRef] [PubMed]
15. Batterman, S. Findings on an Assessment of Small-scale Incinerators for Health-care Waste. *World Heal. Organ. Prot. Hum. Environ.* 2004. Available online: https://www.ircwash.org/sites/default/files/Batterman-2004-Findings.pdf (accessed on 15 November 2024).
16. Wajs, J.; Bochniak, R.; Golabek, A. Proposal of a Mobile Medical Waste Incinerator with Application of Automatic Waste Feeder and Heat Recovery System as a Novelty in Poland. *Sustainability* **2019**, *11*, 4980. [CrossRef]
17. McGain, F.; Moore, G.; Black, J. Hospital steam sterilizer usage: Could we switch off to save electricity and water? *J. Health Serv. Res. Policy* **2016**, *21*, 166–171. [CrossRef] [PubMed]
18. Musmeci, L. Manuale Operativo Per La Gestione Dei Rifiuti Prodotti All 'Interno Dell'Iss. 2005. Available online: https://www.iss.it/documents/20126/2050463/Manuale+Oper.Gest.1205242430.pdf/0cb6a3c2-2ed4-1c9f-6940-1ae2e8aec15a?version=1.2&t=1576435661394&download=true (accessed on 15 November 2024).
19. Rigamonti, L.; Falbo, A.; Zampori, L.; Sala, S. Supporting a transition towards sustainable circular economy: Sensitivity analysis for the interpretation of LCA for the recovery of electric and electronic waste. *Int. J. Life Cycle Assess.* **2017**, *22*, 1278–1287. [CrossRef]
20. United Nations Environment Programme. Compendium of Technologies for Treatment/Destruction of Healthcare Waste. 2012. Available online: https://wedocs.unep.org/20.500.11822/8628 (accessed on 15 November 2024).
21. Morgantini, G.; Pellegrin, R.; Bar, U. Treatment of Waste Having a Solid Matrix Containing Vaporizable Substances. WO9832548 (A1), 30 July 1998.
22. Nielsen, O.-K.; Hjelgaard, K.; Sully, J.; Woodfield, M. *Clinical Waste Incineration*; European Environment Agency: Copenaghen, Denmark, 2019; pp. 1–23.
23. Magrini, G.; Trevisson, L.; Pericoli, M.; Catapano, E.; Casalboni, G. Evaluation of Hazardous Air Emissions from Incinerators and Newster® Sterilizers. Available online: https://www.newstergroup.com/containerized-mobile-solutions/32/sanifyco-19 (accessed on 18 November 2024).
24. CNR.; IRSA. Linea Guida Per La Definizione Di Valori Limite Di Emissione (Vle) Per Le Sostanze Chimiche Prioritarie. 2023. Available online: https://www.irsa.cnr.it/wp/?p=6380 (accessed on 18 November 2024).
25. Ministero Dell'ambiente e Della Sicurezza Energetica. Monitoraggio delle Emissioni di CO_2. 2011. Available online: https://www.mase.gov.it/pagina/monitoraggio-delle-emissioni-di-co2 (accessed on 18 November 2024).
26. *EN ISO 14040:2006*; Valutazione del Ciclo di Vita Principi e quadro di Riferimento. International Standards Organization: Geneva, Switzerland, 2006. Available online: https://www.cittametropolitana.mi.it/export/sites/default/Responsabilita_sociale_impresa/Documenti/14040_2006.pdf (accessed on 18 November 2024).
27. *ISO 14044:2006*; Environmental management-Life Cycle Assessment-Requirements and guidelines. International Standards Organization: Geneva, Switzerland, 2006.
28. Sphera, LCA Database Server. 2024. Available online: https://lcadatabase.sphera.com/ (accessed on 15 November 2024).
29. Hauschild, M.Z.; Wenzel, H. *The European Person Equivalent: Measuring the Personal Environmental Space*; United States Environmental Protection Agency: Copenhagen, Denmark, 2001.
30. Ministero della Salute, Monossido di Carbonio. 2015. Available online: https://www.salute.gov.it/imgs/C_17_opuscoliPoster_283_ulterioriallegati_ulterioreallegato_2_alleg.pdf (accessed on 18 November 2024).
31. Sarofim, A.F.; Suk, W.A. Health effects of combustion by-products. *Environ. Health Perspect.* **1994**, *102*, 237–244. [CrossRef] [PubMed]
32. Stocker, T.; Qin, D.; Plattner, G.K.; Tignor, M.; Allen, S.; Boschung, J.; Nauels, A.; Xia, Y.; Bex, V.; Midgley, P. Climate Change 2013: The Physical Science Basis. In *Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*; Cambridge University Press: Cambridge, UK; New York, NY, USA, 2013.
33. Frischknecht, R.; Braunschweig, A.; Hofstetter, P.; Suter, P. Human health damages due to ionizing radiation in life cycle impact assessment. *Environ. Impact Assess. Rev.* **2000**, *20*, 159–189. [CrossRef]
34. Amato, A.; Mastrovito, M.; Becci, A.; Beolchini, F. Environmental sustainability analysis of case studies of agriculture residue exploitation. *Sustainability* **2021**, *13*, 3990. [CrossRef]