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Waste in humanitarian Operations:
Reduction and Minimisation

D1.3. LCA of waste treatments

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LIST OF ACRONYMS

ACRONYM	FULL NAME
EC	European Commission
CH_4	Methane
CO_2	Carbon dioxide
GHG	Greenhouse gas
GWP	Global Warming Potential
HW	Hazardous waste
HWM	Hazardous waste management
HOs	Humanitarian organisations
KG	Kilogram
WHO	World Health Organisation
KLU	Kuehne Logistics University
WM	Waste management
WPs	Work Packages

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BACKGROUND ABOUT WORM

WORM aims to design guidelines and support actions for circular economy in the humanitarian sector. It integrates bio-based technological solutions, leverages procurement for waste reduction, improves waste management methods and prioritises the sustainable livelihoods of waste pickers. WORM focuses on two selected settings: field hospital deployments and humanitarian livelihood programmes with a waste picking component. Following a collaborative and multi-actor approach, WORM brings together medical and humanitarian organisations, procurement service providers, logistics providers, waste management services and academic partners.

EXECUTIVE SUMMARY

This document is a deliverable of the WORM Project, funded under the European Union’s Horizon Europe research and innovation programme under the grant agreement No 101135392.

The aim of this document is to present the findings from Kuehne Logistics University’s (KLU’s) Life Cycle Assessment (LCA) comparing different hazardous waste management (HWM) methods in humanitarian field hospital settings. This includes measuring the environmental impacts associated with incinerating hazardous waste (HW), the common method today, and comparing it to less/non-destructive methods to sterilize HW before it is sent to sanitary landfill – autoclaving, chemical disinfection, and microwaving. The data to model the different HWM scenarios was gathered through relevant LCA studies in the scientific literature.

The findings indicate that incinerating HW implies a large environmental footprint, especially in terms of climate change, particulate matter, freshwater ecotoxicity and eutrophication, as well as fossil resource use. In contrast, the alternative scenarios have a much lower environmental footprint across all categories. While the results for the alternative scenarios are relatively similar, autoclaving consistently implies the lowest environmental impacts of all the alternative methods, followed by microwaving, and then chemical disinfection.

NON-TECHNICAL SUMMARY

Treating HW results in damage to the environment and human health. Incinerating (burning HW at high temperatures) is the most common method, but this option is much worse for the environment than other options such as disinfecting waste and then sending it to a landfill.

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INTRODUCTION

As described in D1.1 and D4.1, waste comes in many different forms. Medical waste represents a distinct category due to it containing potentially harmful materials that are hazardous, infectious, and can pose significant risks to the environment and human health. According to the World Health Organisation (WHO), hazardous waste (HW) (i.e., infectious, toxic or radioactive) accounts for approximately 15% of all solid medical waste (Abukmeil et al., 2022). This includes items such as needles, syringes, bandages, examination gloves, blood bags, drug ampoules, and sharps (Abukmeil et al., 2022; Ali et al., 2015; Tilley & Kalina, 2020). In humanitarian settings, field hospitals play the critical role of providing medical care to communities in need during crisis. However, waste management (WM) at field hospital settings is typically limited or inadequate, resulting in the improper treatment of waste and hazardous materials and significant environmental consequences (e.g., pollution) (WHO, 2024).

This deliverable expands on the research presented in D1.2 to measure the environmental impacts of alternative waste treatment processes for HW. As described in D1.2 and D4.1, incineration in the most common hazardous waste management (HWM) methods. However, this process results in significantly high environmental impacts, especially when not properly managed. Thus, we aim to identify the potential for less environmentally destructive methods of HWM in humanitarian field hospital settings. To do so, we measure the environmental impacts associated with various HWM methods using Life Cycle Assessment (LCA). LCA is a commonly used methodology to quantitatively measure environmental impacts of products and their life cycle (De Laurentiis et al., 2023), and there is a need for more LCAs relevant to the humanitarian sector (Anjomshoae et al., 2023).

We first measure the environmental impacts of incinerating one kilogram (kg) of hazardous waste and then compare this to three alternative scenarios: (1) autoclaving with sanitary landfill; (2) chemical disinfection with sanitary landfill; and (3) microwaving with sanitary landfill. These methods were selected based on the analysis presented in D4.1 regarding less/non-destructive methods for HWM. We gathered data using the scientific literature to model the alternative HWM scenarios and supported this analysis with data from the LCA database Ecoinvent to model incineration and sanitary landfill.

The rest of the document is structured as follows: in the next section we describe less/non-destructive HWM methods. Then we present the LCA methodology and define how we apply it to this research. This is followed by a discussion of the results and the main conclusions, assumptions and limitations, and next steps.

1. NON-DESTRUCTIVE HAZARDOUS WASTE MANAGEMENT METHODS

Building off the findings of D4.1, we test the potential for non/less-destructive waste treatment processes for hazardous medical waste. This starts with disinfection methods such as autoclaving, microwaving, and chemical disinfection. Following sterilization, the waste can then be sent to a sanitary landfill. Each of the processes for less-destructive HWM are described in the following paragraphs.

1.1. Autoclave

Autoclaving is a widely practice method of HWM in many regions of the world. This entails sterilizing waste in a highly pressurized, steam-heated chamber. When the waste has been fully autoclaved, it is often shredded and then disposed of in a landfill along with general waste. It is also extremely effective, with relatively low operating costs, and minimal emissions released when performed correctly. However, operating the machinery requires substantial installation costs and significant energy and water to run for extended periods (Kollu et al., 2022). It is also difficult to acquire and implement in humanitarian field

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hospital settings. Nonetheless, it is an effective way to treat HW with minimal environmental impact, especially if renewable energy is used to run the machinery.

1.2. Microwave with shredder

Several studies suggest that microwaving is one of, if not the most, environmentally friendly WM methods that also retains an extremely high level of disinfection (Kollu et al., 2022). Microwaving operates at a temperature range of 177 °C to 540 °C to break down organic matter. This process is described in detail in D4.1. Microwaving is also an effective treatment method to disinfect HW (Zimmermann, 2017).

1.3. Chemical disinfection

Chemical disinfection works by killing or inactivating infectious microorganisms by mixing waste with chemicals such as bleach, ammonium salts, or lime (Wang et al., 2020). The disinfected waste is then mixed with general waste for further disposal. It offers several advantages such as being relatively cheap, straightforward, accessible, effective, and fast (Alkhursani et al., 2023). However, chemical disinfection is a less common method to treat HW and can also create several unexpected challenges. Namely, the chemicals can be dangerous and release toxins when mixed with certain types of waste after disinfection. The waste is also not reduced in size or volume, which can contribute to further WM challenges long-term (Zimmermann, 2017).

1.4. Sanitary landfill

A sanitary landfill refers to a method of disposing waste in a controlled way (opposed to open dump pits) that aims at protecting the environment. This includes spreading the waste in thin layers, compacting it to the smallest practical volume, and covering it with compacted soil when necessary (EEA, 2024). As described in D4.1, sanitary landfill is an efficient method for WM, but is expensive to develop and implement, and dumpsites often remain the existing infrastructure. In some cases, sanitary landfill is not appropriate due to the lack of land for set up. It also may pose a risk of leaching in the case of HW that has not been previously sterilised (El-Saadony et al., 2023).

2. LIFE CYCLE ASSESSMENT (LCA) APPROACH

Life cycle assessment (LCA) is a methodology used to measure the environmental footprint of products (or services) considering their entire life cycle – from raw materials extraction to the use and disposal of the product itself – across multiple environmental dimensions – e.g., global warming, land use, water use, water pollution, fossil resource use, etc., and is thus a comprehensive methodology. LCA can also be used to model a specific phase in the life cycle, such as end-of-life, which will be used for our study. The steps of LCA are illustrated in Figure 1, and those shown in dark green are not included in the study (resources, processing, manufacturing, distribution, and use).

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Organisations typically perform LCAs to identify environmental "hotspots" in the life cycle of their products and act upon these, or to compare the environmental performance of similar products. An LCA consists of four main steps: (1) goal and scope definition; (2) life cycle inventory; (3) life cycle impact assessment; and (4) results interpretation.

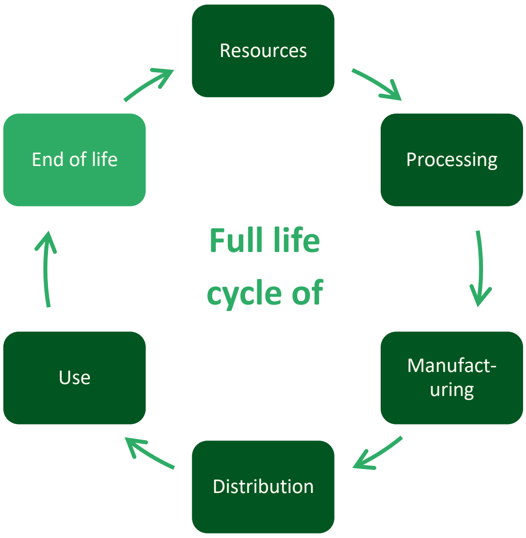

Figure 1 Product life cycle steps that can be considered as part of an LCA. The steps shown in dark green are not included in the study.

WORM uses LCA to quantify the environmental impacts resulting from different HWM scenarios. Specifically, we measure and compare the environmental impacts associated with disposing of one kilogram (kg) of HW according to four scenarios: (1) HW incineration; (2) autoclave and sanitary landfill; (3) chemical disinfection and sanitary landfill; and (4) microwave and sanitary landfill. As previously discussed, HW incineration represents the most common method to treat HW in humanitarian field hospital settings. The other scenarios (autoclaving, chemical disinfection, and microwaving) are intended to represent alternative non/less destructive methods as defined in D4.1. In the next subsections, we describe each step in theory and then apply it to this study.

2.1. LCA step 1: Goal and scope definition

2.1.1. Step 1 in theory

The first step of an LCA is to define the goal and scope of the study. The goal outlines the objective of the LCA, while the scope defines the functional unit and system boundaries. The functional unit describes the product and the function it is intended to fulfil (e.g., incinerating a facemask). The system boundaries define which steps of the life cycle to be considered (e.g., WM), as well as the enabling inputs (e.g., electricity).

2.1.2. Step 1 applied to T1.3

The goal of T1.3 is to understand the potential to reduce the environmental impact of HWM by implementing alternative, less/non-destructive HWM treatments. The first step of defining the goal was to identify the alternative methods for HWM (D4.1). This resulted in the functional unit representing process of treating one kg of HW according to different HWM methods. In this case, we assume that the waste has been contaminated and is classified as HW. The system boundaries are defined as the end-of-life step, including the enabling inputs. The system boundaries for T1.3 are illustrated in Figure 2.

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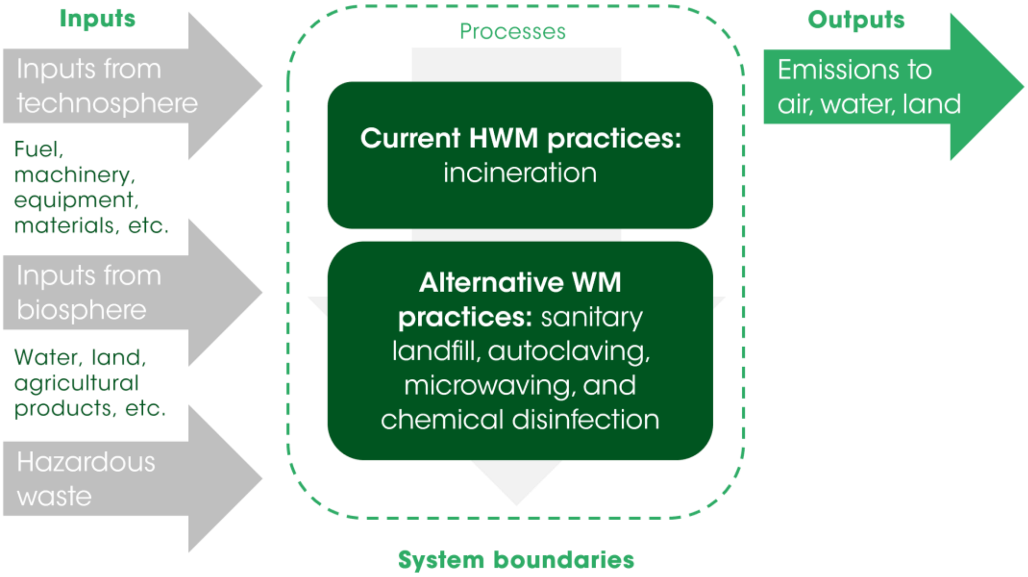

Figure 2 System boundaries for T1.3

2.2. LCA step 2: Inventory analysis

2.2.1. Step 2 in theory

The second step of an LCA is to model the life cycle steps including all the inputs as defined in the scope and their corresponding outputs. Inputs can come from the technosphere (e.g., electricity) or the biosphere (e.g., maize-based starch). Outputs are the direct environmental consequences of the inputs, such as emissions to air, land, and water, as well as the depletion of natural resources. Input data must be gathered for each step within the system boundaries, either as foreground or background data.

Foreground data is specific to the study and typically gathered directly with the relevant actors (e.g., manufacturer). Background data refers to generic processes (e.g., incinerating *x* kg of polyethylene plastic) and comes from specialized databases (checked for quality and accuracy) embedded into the LCA software. Background data can also be defined at different spatial aggregation levels (e.g., the average energy to produce maize in France vs. the average energy to produce maize globally), although this is less common for waste management. Input data is used to build the model in the LCA software, which then converts this into output data (e.g., *y* kg CO_2 emissions) based on a corresponding emission factor, as defined in the impact assessment methodology (Step 3).

2.2.2. Step 2 applied to T1.3

We used the LCA software Simapro, combined with the EcoInvent database, and collected both foreground and background data to model the HWM processes, as illustrated in Figure 3. Foreground data on common and less/non-destructive HWM was collected via literature review, as well as interviews with key stakeholders such as HOs, hospitals, government agencies, environmental experts, and research institutions. This is described in D4.1.

This includes data on:

- Common types of HWM practices
- Alternative less/non-destructive HWM practices

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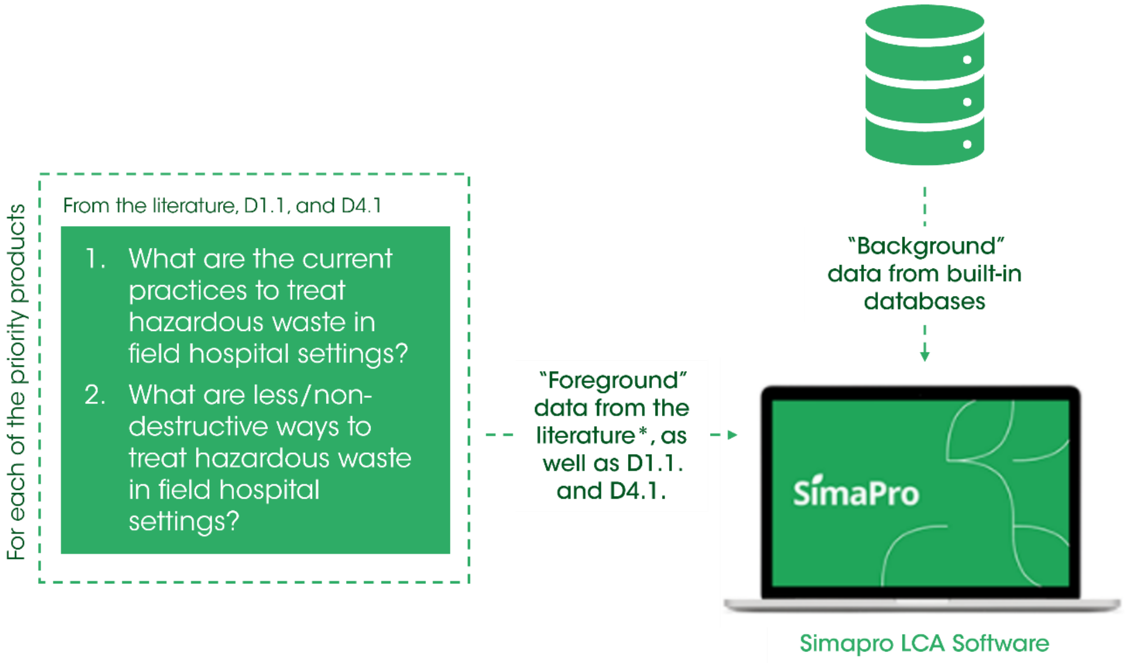

Figure 3 Illustration of data collection process.
**Literature refers to scientific literature as well as industry reports.*

Four HWM methods were selected for this analysis. This includes HW incineration, which is the common HWM methods as identified in D4.1. Furthermore, we model three further methods to disinfect HW – autoclaving, microwaving, and chemical disinfection. Once the HW has been disinfected, it is then sent to a sanitary landfill. In some cases (incineration and sanitary landfill), it was possible to use the Ecoinvent background database to model the HWM process. For the alternative less/non-destructive processes we needed to use external sources from the literature, namely scientific studies which used LCA to model the various HWM processes. The sources of data for each process are presented in Table 1.

Table 1 Description of data sources to model priority products.

HWM practice	SOURCE(S)
Common HWM practices	
Incineration	Ecoinvent database
Less/non-destructive HWM alternatives	
Sanitary landfill	Ecoinvent database
Autoclave	Zhao et al. (2021)
Microwave	Zhao et al. (2021)
Chemical disinfection	Hong et al. (2018)

2.3. LCA step 3: Impact assessment

2.3.1. Step 3 in theory

The third step is to translate output data (e.g., emissions) to environmental impacts. The impact assessment methodology defines which environmental challenges (referred to as environmental impact categories) are considered as part of the LCA. The methodology also defines which output element contributes to which impact category and to what extent (e.g., which emissions to air contribute to global warming and the extent of their contribution based on the global warming potential of each emission type). Additionally, results may also be normalized to a reference value to ease interpretation and compare across damage categories.

2.3.2. Step 3 applied to T1.3

We use the Environmental Footprint 3.1 (EF3.1) impact assessment methodology to convert outputs (e.g., emissions to air, water, and soil) to environmental impact categories (referred to as "damage categories" in EF3.1) (EC, 2021). EF3.1 is the European Commission's reference method and commonly used in research and practice to measure the environmental performance of products (De Laurentiis et al., 2023; Sala et al., 2020). This method considers sixteen impact categories: acidification, climate change, freshwater ecotoxicity, particulate matter, eutrophication (marine, freshwater, and terrestrial), human toxicity (cancerous and non-cancerous), ionizing radiation, land use, ozone depletion, photochemical ozone depletion, resource use (fossil and mineral), and water use.

Additionally, we use the approach presented in De Laurentiis et al. (2023) and Sala et al. (2020) to normalize the results in relation to planetary boundaries (i.e., the limits of the earth's system to self-regulate) (Richardson et al., 2023). The normalized results can be interpreted as the relative contribution of the HWM process per capita to the specific planetary boundary allotment per capita. To simplify the results, we report only the results for the categories with the highest normalized environmental impact. An overview of the damage categories, units, and normalization values we report is presented in Table 2 based on De Laurentiis et al. (2023).

Table 2 Planetary boundaries (PB) per capita adapted to the EF3.1 framework, based on De Laurentiis et al. (2023).

DAMAGE CATEGORY	ABBREVIATION	UNIT	INDICATOR	PB PER CAPITA
Climate change	CC	kg CO2-eq.	Radiative forcing as Global Warming Potential (GWP100)	8.51E+02
Freshwater ecotoxicity	ECOTOX	CTUe	Comparative Toxic Unit for ecosystems	1.64E+04
Particulate matter	PM	Disease incidence	Impact on human health	6.45E-05
Freshwater eutrophication	FEU	kg P eq.	Fraction of nutrients reaching freshwater end compartment (P)	7.26E-01
Fossil resource use	FRD	MJ	Abiotic resource depletion – fossil fuels	2.80E+04

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2.3.3. Description of selected damage categories

2.3.3.1. Climate change

Climate change addresses the contribution of greenhouse gas (GHG) emissions to Global Warming Potential (GWP). Specifically, it focuses on the potential of the product or activity to release GHGs, consequentially increasing the concentration of these gases in the atmosphere. This includes GHG emissions such as carbon dioxide (CO_2) resulting from burning fossil fuels, as well as methane (CH_4), often released by agriculture and waste. Over time, this leads to rising global temperatures and related climate impacts, such as extreme weather, sea level rise, and ecosystem disruptions.

2.3.3.2. Freshwater ecotoxicity

Freshwater ecotoxicity assesses the harmful effects of toxic substances on freshwater ecosystems, such as rivers and lakes. It focuses on pollutants like heavy metals, pesticides, and industrial chemicals that harm aquatic organisms (e.g., fish, algae, invertebrates), disrupt ecosystems, and reduce biodiversity. This category helps explain the impact of chemical pollution on aquatic life and freshwater quality.

2.3.3.3. Particulate matter

Particulate matter evaluates the release of fine particles (e.g., dust, soot, and aerosols) into the air. These particles can cause respiratory and cardiovascular issues in humans and contribute to environmental damage. This category considers the impact of particulate pollution from sources like transportation, industry, agriculture, and WM on human health and the environment.

2.3.3.4. Freshwater eutrophication

Freshwater eutrophication assesses the excess enrichment of freshwater bodies (rivers, lakes, wetlands) with nutrients, primarily nitrogen and phosphorus. This over-fertilization can lead to harmful algal blooms, oxygen depletion, and loss of biodiversity. It evaluates the impacts of nutrient runoff from agriculture, wastewater, and other sources on freshwater ecosystems.

2.3.3.5. Fossil resource use

Fossil resource use evaluates the depletion of non-renewable fossil resources, such as coal, oil, and natural gas. This category measures the consumption of these resources over time, considering their extraction, use, and the environmental impacts associated with their depletion, such as climate change and resource scarcity.

2.4. LCA Step 4: Results interpretation

2.4.1. Step 4 in theory

The fourth step of an LCA is the interpretation of its results. During this step, there are several tests to determine if the conclusions are aligned with the data and model: (1) uncertainty analysis; (2) sensitivity analysis; (3) contribution analysis; and (4) inventory analysis. The uncertainty analysis is intended to assess if there are any challenges related to variation in the data, representativeness of the model, or incompleteness of the model. This also includes determining if the correct modelling choices were made to represent reality as closely as possible. Next, a sensitivity analysis evaluates the influence of the most important assumptions on the results. This includes testing further scenarios, which could be relevant to

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affect the results. During the contribution analysis, the "top" processes are identified and defined as focus areas to check if these processes are sufficiently representative, complete, and include relevant assumptions. The final test is an inventory analysis, which entails assessing if there are any discrepancies in the inventory result (the list of substances that are emitted to air, soil, and water). This is done by evaluating the inventory result table, which is included in the results of the LCA.

2.4.2. Step 4 applied to T1.3

We conducted each of these tests to ensure proper results interpretation. Firstly, we used scientific studies to collect data on the non-destructive HWM methods (autoclaving, microwaving, and chemical disinfection). For the background data, we use the Ecoinvent database, which provides a score for reliability, completeness, temporal correlation, geographical correlation, and further technical correlation (e.g., processes and materials). This was used to model general HW incineration and sanitary landfill. Next, for the sensitivity analysis, we were slightly limited by the lack of data on HWM for specific materials (e.g., hazardous PP). To overcome this, we compared our results to previously published studies. Furthermore, the contribution analysis feeds into the identification of "hotspots" in the WM scenarios. During this step, we also check the network behind the processes which result in the highest environmental impacts. Finally, we examined the inventory result table to assess if there any discrepancies in the environmental impact assessment results.

3. LCA RESULTS

The results of the LCA are presented in the sections below. Here, we focus on disposal of average HW, typically comprised of fossil-based plastics, metals, and other synthetic materials. First, we report the normalized environmental impacts of disposing one kg of HW according to selected treatment methods for HWM: (1) incineration; (2) autoclaving and sanitary landfill; (3) chemical disinfection and sanitary landfill; and (4) microwaving and sanitary landfill. The results are normalized to planetary boundaries per capita, which can be interpreted as the relative contribution of the process per capita to the specific planetary boundary allotment per capita, as previously described.

Next, we report the environmental impacts with the corresponding unit of measurement for each of the HWM scenarios and then dive deeper into climate change impacts. To simplify the results, we present the categories which are the top contributors across several or all the products. The results of the LCA for all environmental impact categories are presented in Annex 1.

3.1. Normalized results

The normalized results for treating one kg of HW are presented in Figure 4. A clear observation is that incinerating HW (the common method today) has the highest environmental impacts across all categories. On the other hand, the results for the three alternative methods which include first disinfecting waste and then placing it in a sanitary landfill are relatively aligned to each other. Autoclaving outperforms all other HWM methods for climate change, freshwater ecotoxicity and eutrophication, and particulate matter. Chemical disinfection, however, results in the highest emissions across all categories for the alternative less/non-destructive methods. Microwaving produces impacts that score generally between autoclaving and chemical disinfection. Furthermore, for climate change and freshwater ecotoxicity, the sanitary landfill is the main source of emissions in comparison to the disinfection method.

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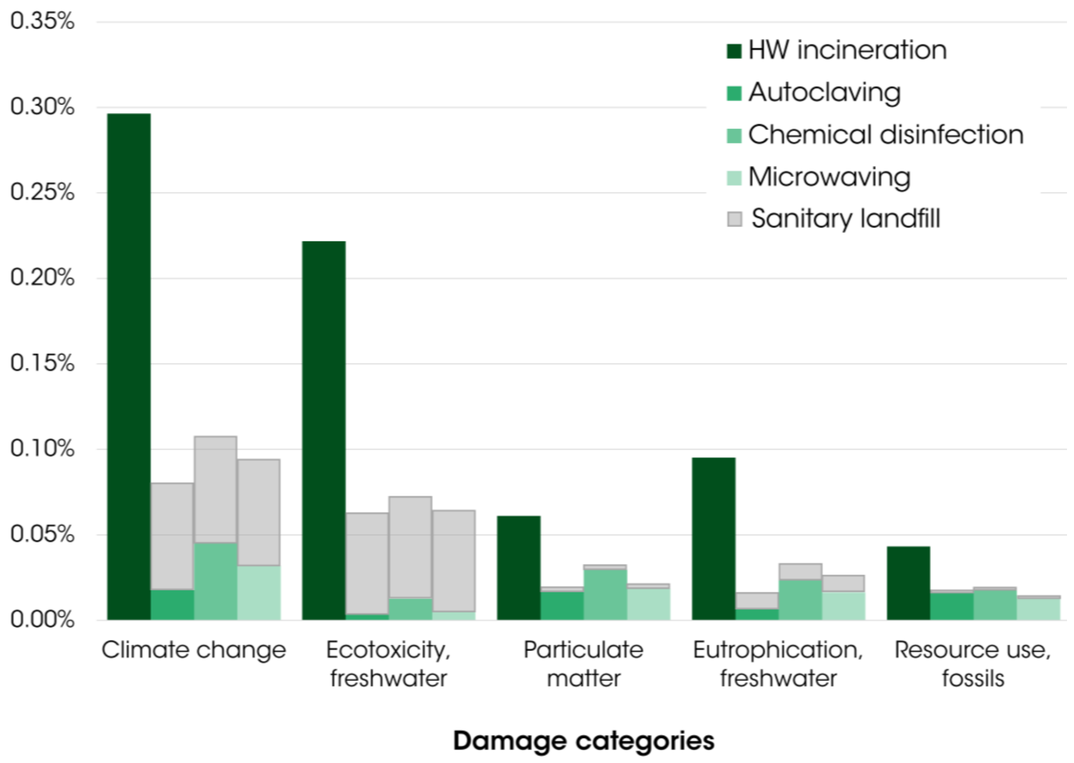

Figure 4 LCA results relating to disposing of one kg of HW according to identified HWM scenarios based on selected damage categories.

3.2. Environmental impact categories

Diving deeper into specific impact categories, Figure 5 illustrates the contribution of the various HWM methods to climate change, expressed as kg CO_2 eq. HW incineration implies roughly two to three times more climate change related emissions than the other HWM strategies. The heat required for HW incineration is the main driver for climate change impacts. In this case, the input of fossil fuels as an energy source is the culprit. For autoclaving, the inputs of electricity and diesel for processing are the top contributors, while electricity is the top climate change driver for chemical disinfection and microwaving. Additionally, after disinfection, the waste is assumed to be sent to sanitary landfill. During this process, the electricity required to treat leachate as well as the diesel required to install the landfill are the main sources for climate change emissions. Furthermore, as shown in Figure 4, sanitary landfill plays a significantly larger role than the disinfection process in terms of climate change emissions. This is especially true for autoclaving. Figure 5

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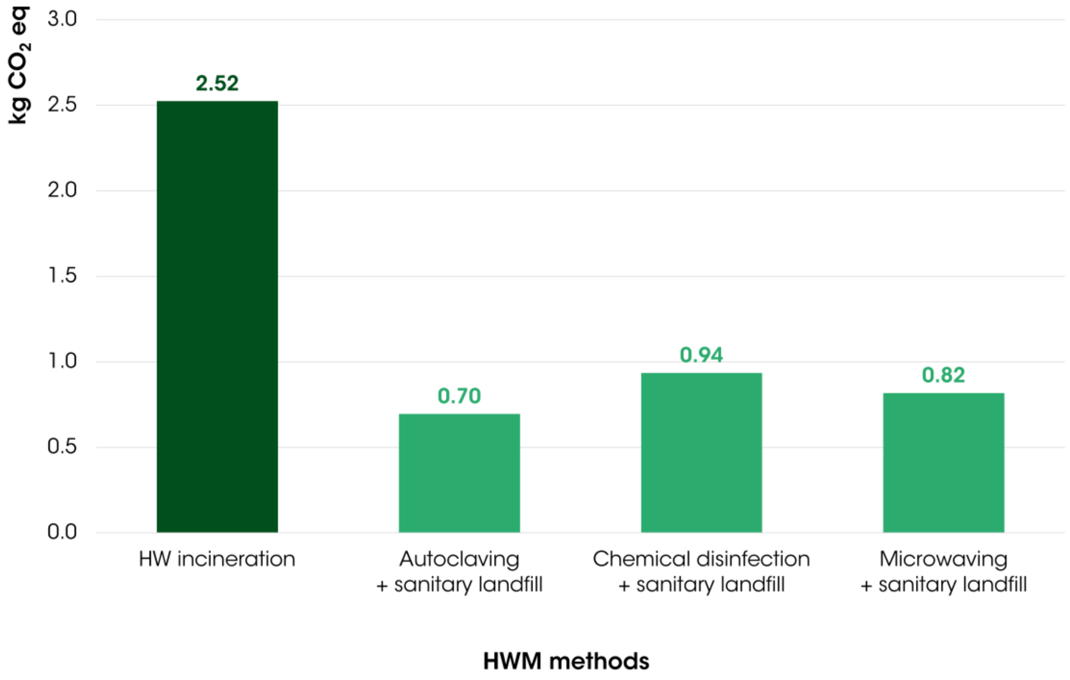

Figure 5 LCA results describing the climate change impacts (kg CO2 eq.) associated with disposing of one kg of HW according to different HWM scenarios.

To provide a more comprehensive overview, Table 3 reports the environmental impacts according to the different HWM methods across all the top impact categories. This allows improved understanding of not only how the results compare to each other across categories, but also the quantitative value of emissions generated, expressed in units (e.g., kg CO2 eq.) intended to represent the different categories. This value can also be used for further research on this topic, as it describes the total emissions generated from treating one kg of general HW.

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Table 3 Environmental impacts associated with disposing of one kg of HW according to different HWM scenarios.

DAMAGE CATEGORY	UNIT	HAZ. WASTE INCIN.	AUTOCLAVE + SANITARY LANDFILL	CHEMICAL DISINFECTION + SANITARY LANDFILL	MICROWAVE + SANITARY LANDFILL
Climate change	kg CO_2 eq	2.52E+00	6.95E-01	9.35E-01	8.18E-01
Freshwater ecotoxicity	CTUe	3.63E+01	1.05E+01	1.21E+01	1.08E+01
Particulate matter	disease inc.	3.95E-08	1.29E-08	2.14E-08	1.42E-08
Freshwater eutrophication	kg P eq	6.91E-04	1.22E-04	2.48E-04	1.95E-04
Fossil resource use	MJ	1.21E+01	4.78E+00	5.25E+00	3.83E+00

In terms of freshwater ecotoxicity, HW incineration results in roughly three times more emissions than the alternative methods. This is mostly driven by chemicals required during the incineration process, which can be released into ground or waterways. As with climate change, electricity and diesel use during the autoclaving process are the top contributors to freshwater ecotoxicity for the HWM method. Similarly, electricity is also a main source of ecotoxicity emissions during chemical disinfection, in addition to chemicals that are released during the process. Regarding microwaving, electricity is the input with the highest contribution to freshwater ecotoxicity. Finally, for sanitary landfill, leachate released over time is the main driver for freshwater ecotoxicity emissions. In comparison to the disinfection phase, sanitary landfill results in significantly larger emissions for this category, as illustrated in Figure 4.

HW incineration performs worse than the alternative scenarios again regarding particulate matter. This is again due to the heat required to reach sufficient incineration levels (using fossil fuels as energy sources), as well as the use of chemicals to facilitate the process. For autoclaving, electricity and diesel are again the top drivers. Electricity use is also the main driver for particulate matter emissions resulting from chemical disinfection and microwaving. Additionally, diesel used to install the sanitary landfill is a main source of emissions, in addition to treating the leachate. However, unlike climate change and freshwater ecotoxicity, sanitary landfill plays a much smaller role than the disinfection process in terms of contribution to particulate matter.

The alternative scenarios also imply significantly lower emissions that drive freshwater eutrophication in comparison to HW incineration. The use of chemicals during the incineration process, and the electricity to produce those chemicals, are the main contributor in this case. For autoclaving, chemical disinfection, and microwaving, electricity use is again the input resulting in environmental impacts. Furthermore, leachate is the challenge area for sanitary landfill in terms of freshwater eutrophication.

The last damage category is fossil resource use. Here, HW incineration again performs worse than the alternative scenarios, however to a lesser extent than the previously discussed categories. Specifically, HW incineration results in roughly twice the environmental impacts associated with fossil fuel use. The main factor is again the heat to produce the necessary temperature, which is powered by fossil fuels. For the alternative methods, electricity is again the top driver. For sanitary landfill, leachate continues to be the main source of emissions related to HWM.

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4. DISCUSSION AND INTERPRETATION

HW disposal is a crucial aspect of environmental management, and various treatment methods are used to manage different types of HW. Incineration, while widely used, implies significant environmental impacts. While HW incineration can effectively destroy hazardous substances found in medical waste, it can also generate harmful air pollutants and particulate matter, raising concerns about air quality and the long-term environmental effects. Furthermore, incinerators require significant energy input, typically powered by fossil fuels. Less destructive methods such as autoclaving, chemical disinfection, and microwaving (followed by sanitary landfill) are more environmentally friendly. This is evidenced in the results, as HW incineration performs worse than the alternative HWM methods for all reported impact categories.

In contrast, autoclaving is in general the most environmentally friendly way of treating HW, although there may be specific challenges associated with implementing this HWM strategy. Autoclaving is commonly used for medical and biological waste but may not be suitable for treating chemicals in certain types of HW. Microwaving performed the second best across the selected environmental impact categories. This is also a suitable method for medical and biological waste management, but, like autoclaving, may not be suitable for certain types of chemicals. Chemical disinfection implied the greatest environmental impacts in comparison to the other alternative HWM methodsbut still scored significantly lower than HW incineration. While this is a highly effective method of neutralizing pathogens, it can result in chemical pollution which contributes to challenges such as freshwater ecotoxicity.

A key driver across almost all categories for the less/non-destructive HWM methods was the use of electricity. This however presents an opportunity to invest in renewable energies, which not only would lower the footprint of the HWM process but can also provide further benefits for users (e.g., decentralized source of electricity). Furthermore, it’s important to remember that following disinfection, the HW also needs to be sent to landfill for final disposal. Leachate is a main concern for sanitary landfill and thus it is vital to ensure all waste is thoroughly disinfected before being placed in the landfill.

Overall, each method of HWM has its strengths and weaknesses. Incineration is effective at reducing waste volume and destroying hazardous substances, but can create harmful emissions. In contrast, methods such as autoclaving, chemical disinfection, and microwaving (followed by sanitary landfill) offer more environmentally sustainable alternatives but may not be as effective for all types of hazardous materials and may be costly to install. The choice of treatment method depends on the specific characteristics of the waste and the balance between effectiveness, cost, and environmental impact.

5. CONCLUSIONS, ASSUMPTIONS AND LIMITATIONS, AND NEXT STEPS

In conclusions, it’s clear that incinerating HW implies a significant environmental impact in comparison to other, less destructive methods such as autoclaving, chemical disinfection, and microwaving. Although incineration is the most common method to treat HWM, it has a large contribution to climate change, freshwater ecotoxicity and eutrophication, particulate matter, and fossil resource use. Furthermore, incineration requires specific infrastructure to reach necessary temperature requirements, which may not be fully available or accessible in humanitarian field hospital settings. The results for the alternative options highlight the potential to reduce environmental impacts of treating HW, but there are several other factors to consider such as cost, effectiveness, and efficiency. Nonetheless, when possible, alternatives to incinerating HW should be considered.

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5.1. Assumptions and limitations

While this study presents a comprehensive overview on four methods for HWM, there were several limitations and necessary assumptions that had to be made. The most significant is the fact that there was a lack of sufficient data to model HWM of different materials. Unlike the results presented in D1.2, we could not find any sources that provided data on autoclaving, chemical disinfection, or microwaving specific materials. Therefore, we model the HWM of general hazardous waste, which includes plastics, as well as other conventional materials. Thus, the results can be seen as an average of treating general HW, rather than for specific products.

5.2. Next steps

The findings of this research provide a valuable foundation for several next steps. Most importantly, it is necessary to understand the potential for using alternative methods for HWM in humanitarian field hospital settings. This includes identifying constraints and actions to support implementation. This is also described in D4.1. It’s clear that HW is a pressing topic, especially considering the high environmental impact of incinerating HW. Shifting towards less destructive ways should be a key focus area for the future.

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ANNEX 1

Table 4 LCA results for environmental impacts associated with the HWM according to different WM scenarios.

DAMAGE CATEGORY	UNIT	HW INCIN.	AUTOCLAVE	CHEM. DISINFECT.	MICROWAVE	SAN. LANDFILL
Acidification	mol H+ eq	3.53E-03	1.46E-03	2.06E-03	1.34E-03	1.71E-04
Climate change	kg CO2 eq	2.52E+00	1.50E-01	3.90E-01	2.72E-01	5.45E-01
Ecotoxicity, freshwater	CTUe	3.63E+01	5.46E-01	2.07E+00	7.79E-01	9.99E+00
Particulate matter	disease inc.	3.95E-08	1.06E-08	1.91E-08	1.20E-08	2.29E-09
Eutrophication, marine	kg N eq	8.26E-04	1.74E-04	3.96E-04	2.68E-04	1.43E-03
Eutrophication, freshwater	kg P eq	6.91E-04	4.64E-05	1.72E-04	1.19E-04	7.60E-05
Eutrophication, terrestrial	mol N eq	8.15E-03	1.78E-03	3.91E-03	2.73E-03	5.31E-04
Human toxicity, cancer	CTUh	4.62E-09	3.45E-10	5.44E-10	2.99E-10	1.04E-10
Human toxicity, non-cancer	CTUh	8.45E-09	8.38E-10	2.91E-09	1.52E-09	4.74E-09
Ionising radiation	kBq U-235 eq	3.16E-02	1.40E-02	4.83E-02	3.69E-02	7.95E-04
Land use	Pt	2.02E+00	3.98E-01	8.04E-01	5.21E-01	5.99E-01
Ozone depletion	kg CFC11 eq	3.92E-08	4.06E-09	2.65E-09	1.82E-09	3.41E-10
Photochemical ozone formation	kg NMVOC eq	2.99E-03	8.74E-04	1.16E-03	7.91E-04	3.35E-04
Resource use, fossils	MJ	1.21E+01	4.46E+00	4.93E+00	3.51E+00	3.21E-01
Resource use, minerals and metals	kg Sb eq	3.42E-06	1.34E-07	1.36E-06	2.48E-07	3.51E-08
Water use	m3 depriv.	2.10E-01	4.27E-02	7.99E-02	4.01E-02	-1.62E-01

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