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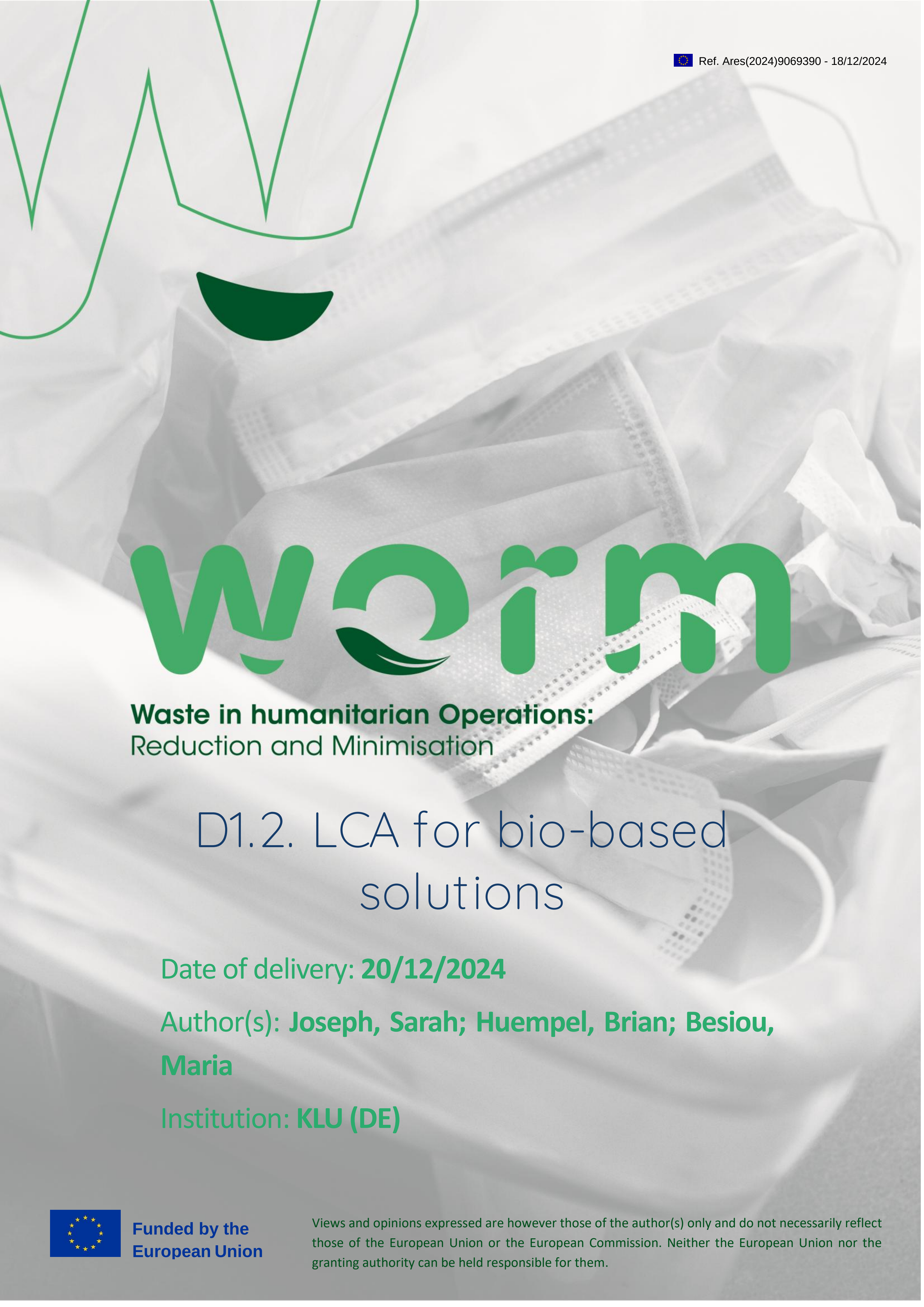

worm

Waste in humanitarian Operations:
Reduction and Minimisation

D1.2. LCA for bio-based solutions

Date of delivery: **20/12/2024**

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V0.2	Brian Huempel (KLU)	29/11/2024	Updated draft internally reviewed
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LIST OF ACRONYMS

ACRONYM	FULL NAME
ACF	Action Against Hunger
CO	Carbon monoxide
CRS	Catholic Relief Services
EC	European Commission
FRC	Finnish Red Cross
GHG	Greenhouse gas
GWP	Global warming potential
HOs	Humanitarian organisations
H_2S	Hydrogen sulfide
ICRC	International Committee of the Red Cross
IMC	International Medical Corps.
JI	Joint Initiative on Sustainable Humanitarian Packaging and Waste Management
KLU	Kuehne Logistics University
kWh	Kilo Watt hours
LCA	Life Cycle Assessment
NH_3	Ammonia

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NRC	Norwegian Refugee Council
PPE	Personal Protective Equipment
PE	Polyethylene
PET	Polyethylene terephthalate
PEVA	Polyethylene vinyl acetate
PLA	Polylactide
PP	Polypropylene
PVC	Polyvinylchloride
PUR	Polyurethane
RMIT	Royal Melbourne Institute of Technology (Vietnam)
VNRC	Viet Nam Red Cross Society
VOCs	Volatile organic compounds
WASH	Water, sanitation, and health
WM	Waste management
WORM	Waste in humanitarian Operations: Reduction and Minimization
WPs	Work Packages
WREC	Waste management & measuring, Reverse logistics, Environmentally sustainable procurement & transport, and Circular economy

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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 KLU's Life Cycle Assessment (LCA) comparing the environmental impacts of bio-based and conventional materials during production and waste management (WM). To do this, we model the production and WM of eight priority products identified in D1.1 which are crucial to humanitarian field hospital settings – facemasks, gloves, surgical gowns, protective boots, syringes and needles, sharps containers, body bags, and temporary water/sludge bladders – based on conventional (e.g., fossil-based plastic) and bio-based (e.g., starch-based plastic) materials. The data for production was gathered directly with manufacturers or through relevant LCA studies in the scientific literature.

The general findings show that bio-based materials have the potential to reduce the environmental impact of production in comparison to conventional materials, but there are several factors to consider. The bio-based product generally outperforms the conventional version in terms of climate change and fossil resource use. This is mainly due to the use of fossil-based plastics. However, the bio-based alternative typically results in higher emissions that drive freshwater ecotoxicity and eutrophication. This is mainly resulting from the agricultural production phase and the need for synthetic fertilizers and pesticides. At the end of the life cycle, the bio-based option almost always outperformed the conventional product, especially when the WM process is incineration or open burning. Open burning should be avoided, while alternatives to incineration of plastics should be explored in future research. Perhaps unexpectedly, open dumping biodegradable biowaste also produces notable GHG emissions, in addition to potential runoff to ground and waterways. Thus, open dumping and open burning should be last resort options for WM.

NON-TECHNICAL SUMMARY

This study summarizes KLU's research to measure the environmental footprint of producing and disposing several key items for humanitarian field hospital settings. We also look at the potential for bio-based materials (e.g., plastics produced from maize) to reduce emissions in comparison to materials typically used today (e.g., plastics produced from fossil fuels).

The results of the study show that bio-based materials may be better for the environment than conventional materials, especially in terms of GHG emissions and the use of fossil-based resources. During waste treatment, bio-based materials almost always perform better than conventional materials. However, open burning waste should be avoided at all costs because it often results in the highest amount of GHG emissions and pollution in comparison to incineration, landfill, or open dump.

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INTRODUCTION

Climate change and environmental degradation are top drivers of humanitarian needs and human suffering (UN, 2021). In response, humanitarian organisations (HOs) aim to reduce the environmental impact of their operations (ICRC & IFRC, 2021; Logistics Cluster, 2023). Production and waste management (WM) have been identified as two key levers for change (Anjomshoae et al., 2023; Corbett et al., 2022; Joseph et al., 2024; Moshtari et al., 2021). Producing the relief items significantly contributes to the overall environmental footprint of the life cycle of the product (Logistics Cluster, 2024; Moshtari et al., 2021). For example, the extensive use of fossil-based materials (e.g., single-use plastics) creates significant environmental challenges such as pollution, unsustainable resource use, waste, and greenhouse gas (GHG) emissions (Siracusa & Blanco, 2020). Decisions made upstream also have notable influence on downstream supply chain operations and WM. This is particularly relevant considering WM in humanitarian operations, where there is often limited or non-existent WM infrastructure in place (Corbett et al., 2022). This challenge is made more complex when considering hazardous waste, such as those generated at field hospital settings, which requires special treatment to limit risks to human and environmental health (Lowe et al., 2021).

Against this backdrop, we explore the potential to reduce the environmental impact of both the procurement and WM phases of selected priority products (D1.1) under different production and WM scenarios using Life Cycle Assessment (LCA). Here, we refer to "procurement" as the steps taken before the item is purchased by the HO (i.e., raw material production, processing, and manufacturing). 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). First, we compare the environmental impacts of producing the priority products using conventional (e.g., fossil-based plastic) and bio-based (e.g., starch-based plastic) materials. Bio-based materials imply the material is wholly or partly comprised of biological origin. This may include plants, animals, or microorganisms (e.g., fungi), which may be virgin or by-products/waste from other processes. Sources for bio-based materials are also typically considered renewable resources that may grow back naturally and/or within a relatively short period (e.g., ten years), implying the potential for enhanced environmental sustainability in comparison to conventional materials such as plastics. We gathered data to model the production of the conventional and bio-based priority products from suppliers and/or manufacturers, D1.5, as well as the scientific and grey literature.

Next, we measure the environmental impacts of disposing of each of the priority products according to common WM practices in humanitarian field hospital settings (e.g., open dump, open burn, landfill, and incineration), as described in D1.1 and D4.1. Here, we also compare how different materials react to different WM processes, and thus test the role of bio-based materials to reduce the environmental impact of WM in comparison to conventional materials. The rest of the document is structured as follows: in the next section we introduce the priority products and their potential for bio-based alternatives. Then, we describe the commonly used WM processes used in humanitarian field hospital settings. This is followed by an introduction to LCA methodology and how we apply it to this research; a presentation of the results; a discussion of results; and finally, the main conclusions, assumptions, limitations and next steps.

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1. DESCRIPTION OF PRIORITY PRODUCTS

As part of D1.1, five priority product categories were selected: Personal Protective Equipment (PPE), including facemasks, gloves, and surgical gowns, as well as protective boots (for waste pickers), syringes and needles, sharps containers (bins), plastic body bags, and temporary water/sludge bladders. WORM defined the priority products through an iterative process, described in D1.1, involving WORM end users (Viet Nam Red Cross Society (VNRC), Action Against Hunger (ACF), Catholic Relief Services (CRS), the Finnish Red Cross (FRC), International Medical Corps. (IMC), the International Committee of the Red Cross (ICRC), and the Norwegian Refugee Council (NRC)), larger stakeholder groups (e.g., HULO and Waste management & measuring, Reverse logistics, Environmentally sustainable procurement & transport, and Circular economy (WREC)), and academic partners (Kuehne Logistics University (KLU), Hanken, and Royal Melbourne Institute of Technology (Vietnam) (RMIT)). The priority products were selected due to their critical role in humanitarian field hospital settings, potential for bio-based alternatives, and/or potential for circularity.

Several studies have examined the potential to use bio-based materials to lower environmental impacts (Batten et al., 2021; Kumari et al., 2023; Singh et al., 2022; Siracusa & Blanco, 2020), as well as for medical products (H. et al., 2021; Honkoop, 2022; Lyu et al., 2023). The authors find that bio-based alternatives have the potential to reduce environmental impacts in comparison to conventional materials, but there are several factors to consider, such as availability and cost. Some examples of bio-based materials commonly used to produce the priority products include bio-based plastics made from starch, microorganisms, or cellulose; bio-based textiles made from cotton; as well as bio-based containers made from wood or paper. Bio-based does not necessarily mean “biodegradable”, although bio-based products may also be biodegradable. Biodegradable materials are designed to break down in the environment through natural processes such as anaerobic digestion or composting. This characteristic may be especially beneficial in settings with limited or non-existent WM infrastructure. In the following sections, we describe each of the priority product groups, why they have been selected, the current environmental challenges associated with their use, as well as the potential to use bio-based materials for production.

1.1. PPE (facemasks, gloves, surgical gowns, and protective boots)

PPE plays an essential role in protecting patients and healthcare workers from infectious agents and significantly reduces the risk of healthcare workers contracting infections when caring for patients (Rizan et al., 2021; WHO, 2024a). Within the humanitarian context, PPE such as facemasks, gloves, and surgical gowns are a critical component to response. This is especially in field hospital settings, where the risk of infection is high within a challenging and resource-limited environment (Lowe et al., 2021). However, PPE is often single use and made from materials such as polypropylene (PP) and polyethylene (PE) that break down into microplastics over time, leading to adverse environmental effects. There have been several studies which examine the potential for bio-based plastics for PPE (H. et al., 2021; Klemeš et al., 2020; Lyu et al., 2023). Some examples of bio-based materials to produce PPE include polylactide (PLA) plastic, made from fermented plant starch such as maize or sugarcane or bio-polyisoprene rubber.

Protective boots were selected as one of the priority products for field hospital settings. However, as requested by the end-users, we model the protective boots worn by waste pickers. These boots can be considered as part of an essential PPE for the waste pickers to protect them from stepping on sharp objects or slips (Omosimua et al., 2021). There have been several studies that assessed the environmental sustainability of boots and other footwear, finding that the leather used to produce boots can be a significant contributor to the overall footprint (Bianchi et al., 2022; Bodoga et al., 2024; Herva et al., 2011), however none have examined bio-based alternatives. Furthermore, most of the other priority items are single use, while boots are intended for multi-use. Thus, we also wanted to consider more durable materials and selected a lightweight leather safety boot with a steel toe to represent the protective boots.

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Potential bio-based alternatives include bio-based leather made from plants or biological sources (e.g., maize or hemp).

1.2. Syringes and needles

Syringes and needles, categorized as sharps, pose a high risk of injury and are considered highly hazardous waste (WHO, 2024b). However, they are also an essential part of field hospitals to safely administer medicine and vaccines and are key to saving lives (Quronfuleh et al., 2024). This is particularly relevant during outbreaks and emergencies, where a rapid response is necessary. While syringes and needles were historically made from reusable materials such as glass, there has been a shift to single-use plastic syringes for economic, safety, and convenience. This has led to increased environmental impacts (Honkoop, 2022; Quronfuleh et al., 2024). We found limited information in the scientific and grey literature about bio-based syringes; however one study examined the environmental impact of syringes, including those made of glass or bio-based materials such as bio-based PP (Honkoop, 2022).

1.3. Sharps containers

Sharps containers are key to support the safe disposal of syringes and needles, however, they are typically made of fossil-based plastic and contribute to significant pollution when disposed of (Grimmond & Reiner, 2012). While there has been some research on role of reusable sharps containers to reduce environmental impacts (Grimmond & Reiner, 2012), very limited research has been done on the potential to use bio-based versions. However, in comparison to all other priority products, it was easiest to identify and connect with suppliers of bio-based sharps containers (made of wood or cardboard) who were already offering their product to humanitarian partners.

1.4. Body bags

Body bags are also crucial supplies for field hospital settings, yet they typically are made from fossil-based plastics which remain in the environment, may release harmful chemicals during decomposition, and in many cases end up in damaging the environment. Thus far, there has been no research (to the best of our knowledge) on bio-based body bags, however, several biodegradable body bags are available from medical supply companies, as discussed in D1.3, typically made from materials such as PE, polyvinylchloride (PVC), polyethylene vinyl acetate (PEVA).

1.5. Temporary water/sludge bladders

Water, sanitation, and health (WASH) is a top priority in humanitarian emergency settings, often implying challenges such as lack of access to resources (e.g., water), as well as insufficient waste infrastructure (Alareqi et al., 2024). On one side, access to safe drinking water is necessary for human life and a top priority following crisis (European Commission, 2024). On the other, wastewater treatment is crucial for reducing environmental and public health impacts (Kosonen et al., 2019). A solution employed in the humanitarian sector is a temporary water and/or sludge bladder. “Temporary” in this case implies the bladder is only intended to be used for a specific period during disaster response, rather than installed as a permanent solution. Although they serve different purposes, temporary water and sludge bladders are often made of plastic materials (Emergency Sanitation Project, 2019), contributing to plastic pollution and the contamination of soil and water if improperly managed. We did not find sufficient data on the market or in the scientific literature for bio-based temporary water/sludge bladders, and thus modelled the production based on the data provided from the manufacturer. Both the temporary water and sludge bladders are primarily comprised of three main materials: PVC, PE, and PP.

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2. COMMON WASTE TREATMENT METHODS

It's important to note that most of the priority items are typically single use, which implies not only increased demand production (as more items are needed to treat patients), but also more waste generated at the end-of-life (since they can only be used once). The challenge of waste is also often exacerbated in humanitarian field settings with limited waste infrastructure, especially for hazardous waste. Thus, this deliverable (D1.2) also explores the current waste treatment methods in typical humanitarian field hospital settings based on the literature and findings from D4.1. The sections below describe four common WM treatments – open burn, open dump, landfill, and incineration – commonly practiced in humanitarian field hospitals. It is important to note that landfill and incineration are the most common WM strategies, but in some cases open dump and open burn are also practiced.

2.1. Open dump

Open dump refers to disposing of waste in areas not designed to handle such materials such as open pits or dump sites. It is a cheap and easily available option for waste management (UNEP, 2024a). However, disposing of untreated waste in open dumps, especially hazardous waste, poses serious risks for environmental and human health (Siddiqua et al., 2022). At a minimum, open dumps require significant amounts of uninhabited land and can release strong odours in the nearby environment. Typically, however, untreated waste can lead to the release of toxic gases, chemicals, or pathogens to air, land, and water (Siddiqua et al., 2022). Although open dumping various by region, it is still a common practice in many countries where HOs are most active (Kaza et al., 2018; Siddiqua et al., 2022; UNEP, 2024b). This is especially relevant for hazardous waste, which results in exacerbated environmental and health consequences for the local community.

2.2. Open burn

Similar to open dumping, open burning is often a result of inadequate WM systems and still commonly practiced in many regions (UNEP, 2024a). Often, when a large amount of waste has accumulated in a dump site, it will be subsequently openly burned to free up space, as described in D4.1. Open burning is a significant source of dangerous toxins in the air and contributes to climate change (Pathak et al., 2024). Polluted air can be inhaled by humans and animals, as well as return to the soil and surface waterways. Dangerous chemicals may also be released when burning certain types of waste (e.g., plastics) which pose serious risks to humans and environment (Pathak et al., 2024).

2.3. Landfill

Landfill refers to the placement of waste into or on the land in a controlled way. It is one of the most common methods of WM,but also can result in environmental risks such as the contamination of (ground)water and soil (Shen et al., 2023; Siddiqua et al., 2022). Controlled landfill sites require large amounts of land, fencing, and security to prevent informal waste picking or other safety breaches. While hazardous waste is typically incinerated, in some cases it also ends up in a landfill, resulting in the mixing of hazardous and non-hazardous waste (El-Saadony et al., 2023).

2.4. Incineration

Incineration is based on a high-temperature combustion range between 800 °C to 1200 °C to eliminate all pathogens and burn up to 90% of organic matter (Datta et al., 2018; Wang et al., 2020). It is the most widely practiced method of hazardous waste disposal and relevant for the field hospital setting. Incineration can also be done locally for both hazardous and non-hazardous waste. However, according to D4.1, the incineration systems at the local level are oftentimes poorly designed and do not reach

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complete waste combustion, resulting in the production of large amounts of ash and dangerous dioxin emissions.

3. 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 (EC, 2021) – 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. It is thus a comprehensive methodology. LCA can also be used to model a specific phase in the life cycle, such as production and 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 (distribution and use).

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. WORM uses LCA to quantify the environmental impacts of the priority products based on different production and waste treatment scenarios. Specifically, we compare the environmental impacts of producing the priority products using conventional (e.g., fossil-based plastic) and bio-based (e.g., starch-based plastic) materials.

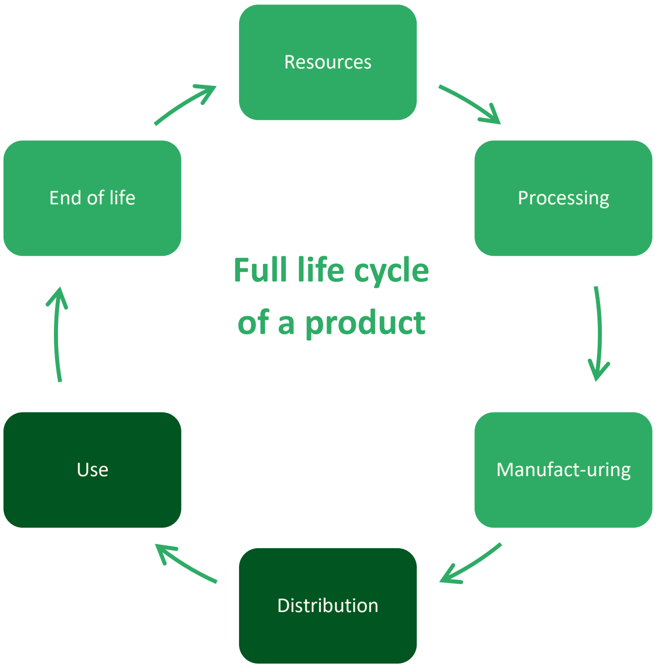

Figure 1 Product life cycle steps that can be considered as part of an LCA. The steps shown in dark green are not included in the study.

Additionally, we also model the end-of-life of each of these items based on the four commonly practiced WM processes as outlined above – open dump, open burn, landfill, and incineration – for both the conventional and the bio-based product. In the next subsections, we describe each step in theory and then apply it to the priority products modelled in this study.

3.1. LCA step 1: Goal and scope definition

3.1.1. 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., the production of one bio-based facemask). The system boundaries define which steps of the life cycle to be considered (e.g., raw material extraction, processing, and manufacturing), as well as the enabling inputs (e.g., starch-based plastic or electricity).

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3.1.2. Step 1 applied to T1.2

The goal of T1.2 is to measure the environmental impacts resulting from the production of the priority products and their waste treatment processes, as well as the environmental trade-offs of conventional vs. bio-based materials. The first step of defining the goal was to select the priority products (MS1.1) and WM practices (MS1.2). Next, we identified potential bio-based alternatives from practice (i.e., as identified by end users or their suppliers) and research (H. et al., 2021; Lyu et al., 2023; Rizan et al., 2023) and combined this with the findings presented in D1.1. Consequently, we defined the functional unit as the production and WM of a single unit of each of the priority items, which will be used in humanitarian field hospital settings, based on different production and WM scenarios.

The system boundaries are defined as the raw material extraction, processing, manufacturing, and end-of-life of each of the priority items, including the enabling inputs. The system boundaries for T1.2 are illustrated in **Erreur ! Source du renvoi introuvable.**. We did not include the environmental impact of t ransport from raw material to manufacturers and/or suppliers for two reasons: 1) the goal of the study is to assess hotspots in production and the difference between conventional and bio-based materials, however, the results may be influenced if the raw materials are sourced from further distances; and 2) we want to produce more general findings and thus concentrating on the transport related to a specific supplier may make the results less generalizable. However, it is important to note that sourcing of raw materials is also relevant to discuss, as international transport, especially by air, can lead to significant environmental consequences (Joseph et al., 2024). By not including transport, we assume the raw materials travel the same distances, although this would typically vary in practice.

3.2. LCA step 2: Inventory analysis

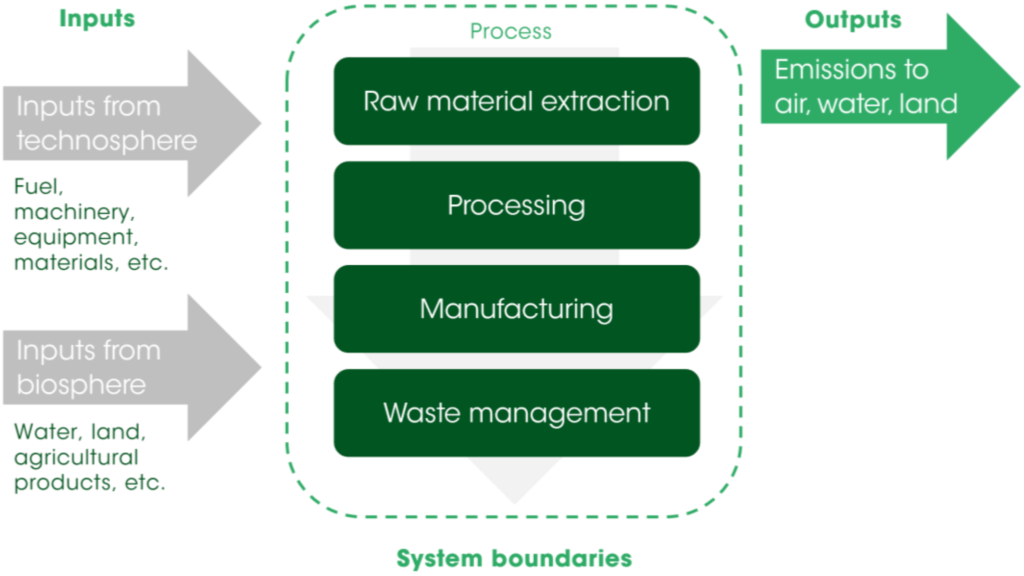

Figure 2 System boundaries for T1.2

3.2.1. 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,

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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 from the relevant actors (e.g., supplier or manufacturer). Background data refers to generic processes (e.g., *x* kWh electricity use in Belgium) and comes from specialized databases (checked for quality and accuracy) embedded into the LCA software. Foreground data is often used to describe the specific step in relation to the study (e.g., how much plastic is used to produce a syringe), which is then combined with background data from the database for the generic use of that input (e.g., the production of *x* grams of plastic). 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). Input data is used to build the model in the LCA software, which then converts this into output data (e.g., *y* kg GHG emissions) based on a corresponding emission factor, as defined in the impact assessment methodology (Step 3).

3.2.2. Step 2 applied to T1.2

We used the LCA software Simapro, combined with the EcoInvent database, and collected both foreground and background data to model the production and WM of the priority products, as illustrated in Figure 3. For some products, foreground data was collected directly with manufacturers of the products on the raw materials used and manufacturing processes. In some cases, the end-users were able to connect us with suppliers who provided data. In other cases, no manufacturer was willing to share production data with us, and therefore we needed to model the production of the product based on the scientific literature and/or industry reports. To model WM, we used the insights on the most common WM processes outlined in D1.1 and D4.1 to define which WM treatment processes to select. This was supplemented with the generic practice (e.g., incineration of 1 kg of PP plastic) from the background database.

This includes data on:

- The types of raw materials used for production
- The quantities of raw materials used for production
- Quantity of electricity, water, or other resources used to produce the item
- Common WM practices at the end-of-life

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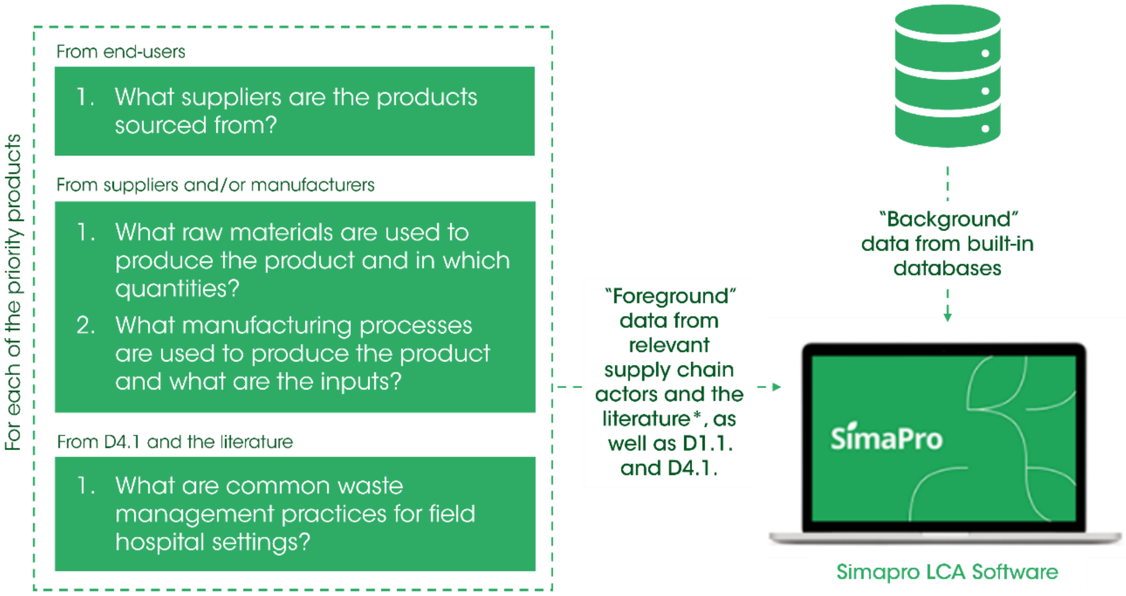

Figure 3 Illustration of data collection process.
**Literature refers to scientific literature as well as industry reports.*

We were not able to connect with a manufacturer of bio-based body bags (which is also very limited on the market). Furthermore, we also did not find any bio-based options for the temporary water/sludge bladders. Thus, only the conventional version for body bags and temporary water/sludge bladders are included in the study. The data sources for each of the priority items is described in *Table 1*. In most cases, suppliers and/or manufacturer wanted to remain anonymous. Thus, we indicate if data was collected directly from a supplier and/or manufacturer in the table as such, without indicating the name of the company.

Table 1 Description of data sources to model priority products.

PRODUCT	TYPE	SOURCE(S)
Facemask	Conventional	Supplier/manufacturer, Ajaj et al. (2023), Atılgan Türkmen (2022), Lyu et al. (2023) Rizan et al. (2021), Rodriguez et al. (2021)
	Bio-based	Lyu et al. (2023)
Gloves	Conventional	H. et al. (2021), Rizan et al. (2021), Jamal et al. (2021)
	Bio-based	H. et al. (2021)
Surgical gowns	Conventional	Rizan et al. (2021), Vozzola et al. (2020)
	Bio-based	Rizan et al. (2021)
Protective boots	Conventional	Bodoga et al., (2024), Bianchi et al., (2021), Herva et al., (2011)
	Bio-based	Muthu & Ramchandani (2024)
Syringes and needles	Conventional	Honkoop (2022), Rizan et al. (2023)
	Bio-based	Honkoop (2022)
Sharps containers	Conventional	Sharpsafe (2023)

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	Bio-based	Supplier/manufacturer
Body bags	Conventional	Supplier/manufacturer
	Bio-based	n.a.
Temporary water/sludge bladders	Conventional	Supplier/manufacturer
	Bio-based	n.a.

In most cases, except for the bio-based sharps containers, we needed to use the scientific literature to model the production of bio-based materials. It’s also important to note that in some cases the bio-based product is not fully comprised of bio-based materials. This may be due to practicality or lack of data for modelling a bio-based alternative. The materials used to model both the conventional product and the bio-based alternative are described in Table 2.

Table 2 Materials used to model conventional and bio-based alternatives.

PRODUCT	CONVENTIONAL MATERIALS	BIO-BASED MATERIALS
Bio-based facemask	• Aluminium (metal)	• Polylactide (PLA) (bioplastic) • Cotton (textile)
Conventional facemask	• Polypropelene (PP) (plastic) • Polyester (textile) • Aluminium (metal)	• Cotton (textile)
Bio-based gloves	n.a.	• Polyisoprene (bio-based rubber)
Conventional gloves	• Synthetic rubber	n.a.
Bio-based surgical gown	n.a.	• PLA • Polyisoprene
Conventional surgical gown	• PP • Synthetic rubber	n.a.
Bio-based protective boots	• PVC (plastic) • PUR (plastic) • Latex • Wax • Solvent • Zinc • Polycarbonate or steel	• Chromium-tanned vegan leather (hemp-based) • Hemp leather • Cotton • PLA
Conventional protective boots	• Chromium-tanned leather • Polyester • Leather • PVR • PUR • Latex • Wax • Solvent • Zinc • Polycarbonate or steel	• Cotton
Bio-based needle and syringe	• Stainless steel	• PLA • Polyisoprene

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Conventional needle and syringe	• PP • Synthetic rubber • Stainless steel	n.a.
Bio-based sharps container	Wood: • Adhesive Cardboard: • n.a.	Wood: • Woodchips • PLA • Kraft paper • Paper, woodfree Cardboard: • Waste paperboard • Waste paper
Conventional sharps container	• PP	n.a.
Conventional body bag	• PE • PP	• Cotton
Conventional temporary water bladder	• PVC • PE • Stainless steel • Aluminium • PP	n.a.

Additionally, we also modelled the WM processes once the priority products reached their end-of-life phase with a twofold objective: (1) to compare common WM strategies for humanitarian field hospital settings, including open dump, open burn, landfill, and incineration for each of the priority items; and (2) to analyse if treating the conventional (e.g., fossil-based products) generated different results than the bio-based alternatives.

We modelled the WM processes using the background database (Ecoinvent) in the Simpro LCA software. A key component of the waste scenario is to define how different waste streams are treated as different materials are expected to have different reactions and resultant emissions depending on the waste treatment process (i.e., PP would imply different emissions than biowaste when incinerated). To model this, we classified each of the input materials by waste type and then selected the suitable waste treatment option for each of the waste types.

For most materials, we were able to find a waste treatment option that was specific to the material (e.g., aluminium incineration). However, for the bio-based options, there were no specific waste treatment options for those materials (e.g., starch-based plastic). Thus, for the bio-based inputs we selected the general waste treatment category of "biowaste", referring to general waste of biological origin that is also suitable for anaerobic digestion. This generalization may influence the results as the bio-based materials for the priority products are in a more processed form and may not biodegrade in the same way as typical biowaste, or at all. The alternative, however, would be to model the WM of the bio-based materials the same as the conventional versions due to lack of suitable data to model the characteristics of the bio-based material. Due to these limitations, we assume that the bio-based material is also biodegradable and model the WM processes under the category of biowaste.

Furthermore, there was no option to model open burning or landfill of biowaste in the background database and we could not find a suitable source of information elsewhere (e.g., scientific studies). Therefore, we modelled open dumping and incineration of bio-based products, while open burning and

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landfill products have been excluded. WM of the bio-based materials is described further in the assumptions and limitations. A description of the type of waste and waste treatment process is described in Table 3.

Table 3 Description of WM process, waste type, waste material, and waste treatment for the different WM scenarios.

WM PROCESS	WASTE TYPE	WASTE MATERIAL	WASTE TREATEMENT
Open dump	Biowaste	PLA Bio-rubber Leather Vegan leather	Open dump, biowaste
	Textiles	PUR PP PE Cotton	Waste yarn and textile, unsanitary landfill Waste polyurethane, open dump
	Metals	Aluminium Steel	Waste Aluminium, market Municipal solid waste, open dump
	Plastics	PVC Latex PP	Polyvinylchloride, open dump Waste plastic, open dump
Open burn	Textiles	PUR PP PE Cotton	Waste Polypropylene, open burning Waste Polyurethane, open burning Waste Polyethylene, open burning Waste textile, incineration
	Metals	Aluminium Steel	Scrab Aluminium, municipal incineration Scrab Steel, municipal incineration
	Plastics	PVC Latex PP	Waste Polyvinylchloride, Waste plastic Waste polypropylene
Incineration	Biowaste	PLA Bio-rubber Leather Vegan leather	Biowaste, municipal incineration
	Textiles	PUR PP PE Cotton	Waste textile, municipal incineration
	Metals	Aluminium Steel	Scrab Aluminium, municipal incineration

			- Scrab Steel, municipal incineration
	Plastics	- PVC - Latex - PP	- Waste Polyvinylchloride, municipal incineration - Waste plastics, municipal incineration - Waste Polypropylene, municipal incineration
Landfill	Textiles	- PUR - PP - PE - Cotton	- Waste yarn and textile, unsanitary landfill
	Metals	- Aluminium - Steel	- Municipal solid waste, unsanitary landfill
	Plastics	- PVC - Latex - PP	- Waste Polyvinylchloride, unsanitary landfill - Waste plastic, unsanitary landfill

3.3. LCA step 3: Impact assessment

3.3.1. Step 3 in theory

The third step is to translate output data (e.g., emissions) to environmental impact categories. The impact assessment methodology defines which environmental challenges (i.e., 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.

3.3.2. Step 3 applied to T1.2

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). These categories help quantify the long-term effects of human activities on the environment. 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 in the case of environmental impacts or depletion of reserves in terms of resources) (Richardson et al., 2023). For example, this may be the earth’s ability to absorb GHG emissions in the atmosphere to reduce GWP that leads to climate change. The normalized results can be interpreted as the relative contribution of the operation or supply chain per capita to the specific planetary boundary allotment per capita. As some of the priority items are intended to serve more than one person (e.g., sharps containers or temporary water/sludge bladders), we do not compare the products to each other. To simplify the results, we report only the results for the damage categories with the highest normalized environmental impact. An overview of the damage categories, units, and normalization values we report is presented in Table 4 based on De Laurentiis et al. (2023).

Table 4 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
Mineral resource use	MRD	kg Sb eq.	Abiotic resource depletion – ultimate reserves	2.74E-02

3.3.3. Description of selected damage categories

3.3.3.1. Climate change

Climate change addresses the contribution of 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.

3.3.3.2. 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.

3.3.3.3. 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

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damage. This category considers the impact of particulate pollution from sources like transportation, industry, agriculture, and WM on human health and the environment.

3.3.3.4. Freshwater eutrophication

Freshwater eutrophication assesses the excess enrichment of freshwater bodies (e.g., 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.

3.3.3.5. 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 resource scarcity.

3.3.3.6. Mineral resource use

Mineral resource use evaluates the depletion of non-renewable mineral resources, such as metals (e.g., iron, copper, aluminum) and non-metallic minerals (e.g., sand, gravel). This category assesses the consumption and extraction of these resources, considering their long-term availability and the environmental impacts associated with their depletion, such as habitat destruction and mining processes.

3.4. LCA Step 4: Results interpretation

3.4.1. 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. 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 affect the results. Furthermore, it is often the case that a small percentage of processes contribute to most environmental impacts. 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.

3.4.2. Step 4 applied to T1.2

We conducted each of these tests to ensure proper results interpretation. Firstly, for the foreground data on production, we discussed the processes in detail with suppliers and/or manufacturers to safeguard quality and accuracy. The rest of the production data was collected from scientific studies which have been peer-reviewed. 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).

Next, for the sensitivity analysis, we test for different materials and inputs to see the impact of changing assumptions. We also expand on the sensitivity analysis to also include further scenarios for WM to test

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for the impact of moisture on landfilling (i.e., to account for seasonal changes) as well as agricultural production processes for the bio-based materials. The contribution analysis feeds into the identification of "hotspots" in the production and WM scenarios. During this step, we also check the network behind the processes which result in the highest environmental impacts, which is also referenced in reporting the results below. Finally, we examined the inventory result table to assess if there any discrepancies in the environmental impact assessment results.

4. LCA RESULTS: PRODUCTION AND WM

The results of the LCA are presented in the sections below. First, we report the environmental impacts (i.e., damage categories) of the production and WM phases for each of the priority products considering conventional and bio-based materials. Here, we refer to "conventional" products as ones that are commonly used today, typically comprised of fossil-based plastics or other synthetic materials. 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. In some cases, this value may be very small (e.g. 0.0016%), especially for items which are very small themselves (e.g., facemasks weighing 3.5 g per unit) which are single use. The value itself is an important note to keep in mind, especially considering that many of these items are used in significant quantities (e.g., PPE for COVID-19).

However, the goal of this research was to compare materials and WM processes to each other, and thus we frame our results and discussion on the differences between the conventional and bio-based scenarios for each of the priority products. To simplify the results, we present the categories which are the top contributors across several or all the products. Furthermore, it is also relevant to identify to overall contribution of the life cycle steps to the total footprint of the item and thus we report the contribution of production in comparison to WM for each of the items and WM scenarios. The results of each of the LCAs for all products and environmental impact categories are presented in Annex 1.

4.1. Facemasks

4.1.1. Production: conventional vs. bio-based

The results for the environmental impacts associated with producing the conventional and bio-based facemasks is presented in Figure 4. For climate change, particulate matter, and fossil and mineral resource use, the conventional facemask results in higher environmental impacts. However, the bio-based alternative implies a relatively greater environmental impact regarding freshwater ecotoxicity and eutrophication. The main drivers for both options are the primary material(s) used to produce the textile, specifically PP and polyester for the conventional facemask (produced from fossil fuels) or the PLA for the bio-based mask (produced from maize). Regarding the conventional facemask, the use of polyester implies greater emissions contributing to climate change, freshwater eutrophication, particulate matter, and mineral resource use than the PP. For freshwater ecotoxicity and fossil resource use, both materials have a similar contribution. Polyester is produced using polyethylene terephthalate (PET), the main contributor to environmental impacts. For the bio-based facemask, the top drivers were the production of the maize itself (e.g., use of synthetic pesticides for ecotoxicity) as well as the electricity required to manufacture the product.

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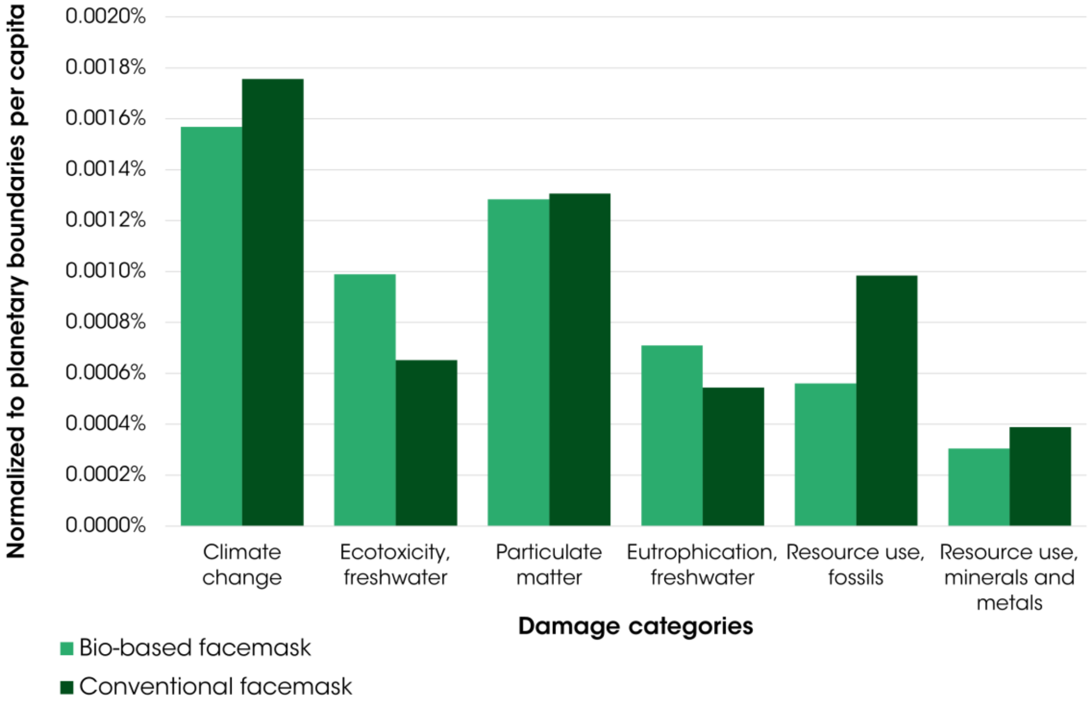

Figure 4 LCA results to produce the conventional and bio-based facemask based on selected damage categories.

4.1.2. End-of-life: common WM practices

At the end of their life cycle, the facemasks can face various WM scenarios. The results of the environmental impacts resulting from end-of-life phase of the conventional and bio-based facemasks according to common WM practices at humanitarian field hospital settings is presented in Figure 5. As previously mentioned, open burning and landfill of the bio-based products are excluded from the results. The results illustrate that disposing of the conventional facemask almost always imply increased environmental impacts in comparison to the bio-based alternative. This is due to the treatment of the PP, which is highest for open burning, followed by incineration for climate change, and freshwater ecotoxicity. In terms of ecotoxicity, open burning and open dumping of the conventional facemask, as well as open dumping of the bio-based facemask, play a significantly larger role than landfill or incineration. This is due to the highest potential for pollution and contamination in uncontrolled WM sites. The WM phase of the bio-based facemasks tell a different story, however. Namely, open dumping implies a much higher contribution to all environmental impact categories on comparison to incineration. This is partly due to the relatively very low impact of incinerating biowaste in a controlled setting in comparison to other materials. The main driver for climate change, however, is the release of methane (CH_4) as the biowaste starts to degrade. Methane is particularly problematic as it has global warming potential of more than twenty times that of carbon dioxide (CO_2) (Bakkaloglu et al., 2022). For ecotoxicity, the main driver is the release of ammonia (NH_3) and hydrogen sulfide (H_2S) to water as the biowaste decomposes.

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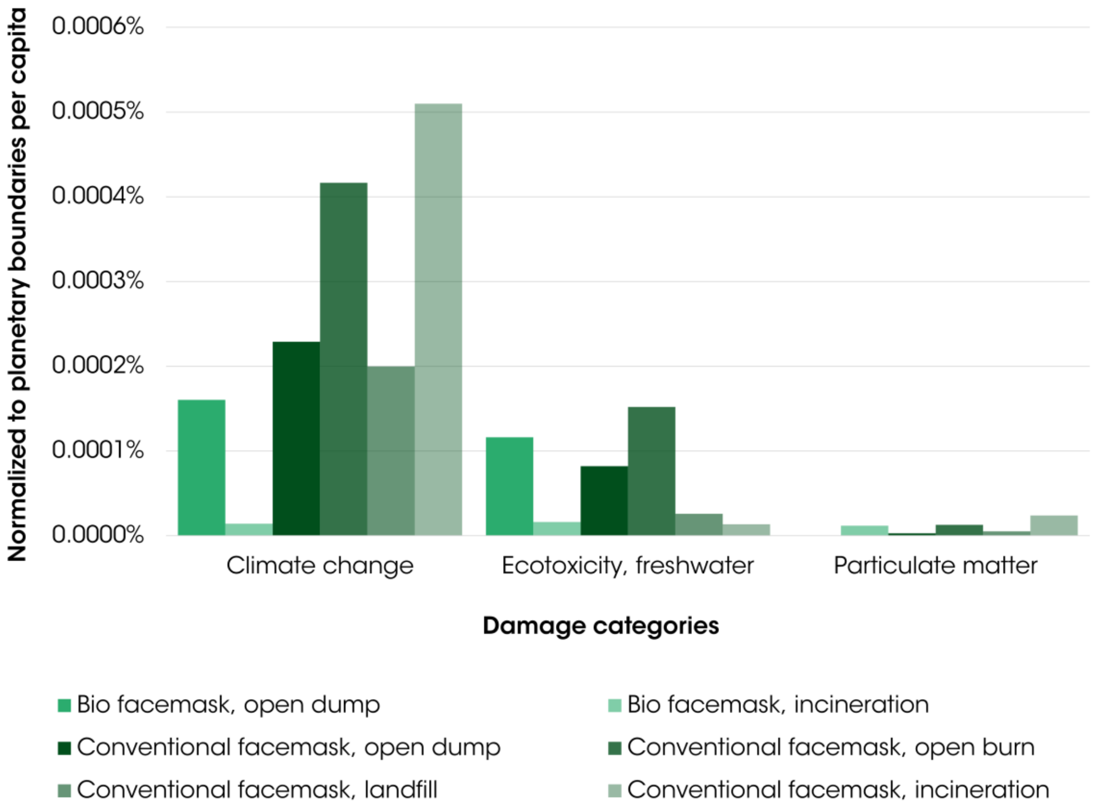

Figure 5 LCA results to relating to common WM practices for the conventional and bio-based facemask based on selected damage categories.

4.1.3. Comparison of life cycle steps

Lastly, it's important to note the relative contribution of production and WM for the life cycle of the product. This does not give the full picture of the life cycle (as the distribution and use phase are not included) but can be used as a valuable tool facilitate improved understanding of the results. For the bio-based facemask, production is the top driver for environmental impacts relative to WM, as illustrated Table 5. At most, disposing of the facemask via open dump contributes to 9% and 10% of total impacts related to climate change and freshwater ecotoxicity, respectively. WM plays a smaller role in relation to particulate matter, freshwater eutrophication, and fossil and mineral resource use.

For the conventional version, however, WM plays a more significant role, as shown in Table 6. Namely, disposing of the fossil-based facemasks via open burn and incineration contributes to 19% and 22% of climate change consequences, respectively. Open burning also contributes to 19% of total emissions related to freshwater ecotoxicity. However, for the rest of the impact categories (particulate matter, freshwater eutrophication, and fossil and mineral resource use), production is the key driver.

Table 5 Resultant emissions from production (unit value) and relative contribution of WM in comparison to production (%) for the bio-based facemask.

DAMAGE CATEGORY	UNIT	PRODUCTION	OPEN DUMP	INCIN.
Climate change	kg CO_2 eq	1.34E-02	9%	1%
Freshwater ecotoxicity	CTUe	1.62E-01	10%	2%

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Particulate matter	disease inc.	8.28E-10	0%	1%
Freshwater eutrophication	kg P eq	5.15E-06	4%	2%
Fossil resource use	MJ	1.57E-01	0%	0%
Mineral resource use	kg Sb eq	8.33E-08	0%	0%

Table 6 Resultant emissions from (unit value) and relative contribution of WM in comparison to production (%) for the conventional facemask.

DAMAGE CATEGORY	UNIT	PRODUCTION	OPEN DUMP	OPEN BURN	LANDFILL	INCIN.
Climate change	kg CO_2 eq	1.50E-02	12%	19%	10%	22%
Freshwater ecotoxicity	CTUe	1.07E-01	11%	19%	4%	2%
Particulate matter	disease inc.	8.43E-10	0%	1%	0%	2%
Freshwater eutrophication	kg P eq	3.96E-06	3%	2%	2%	1%
Fossil resource use	MJ	2.76E-01	0%	0%	0%	1%
Mineral resource use	kg Sb eq	1.06E-07	0%	0%	0%	0%

4.2. Gloves

4.2.1. Production: conventional vs. bio-based

The production results for conventional and bio-based gloves are presented in Figure 6. Synthetic rubber is the primary material for the conventional gloves. For the bio-based option, bio-polyisoprene (a natural rubber derived from agricultural byproducts such as maize stover) is the main material. Both options imply a similar environmental impact for climate change, however the bio-based version results in greater impact than the conventional in terms of freshwater ecotoxicity, particulate matter, and freshwater eutrophication. Regarding fossil and mineral resource use, the bio-based version outperforms the conventional one. Unlike the facemasks, the main driver for climate change, freshwater eutrophication, particulate matter, and fossil resource use is the electricity used to produce both the conventional and bio-based gloves. In this case, the air leakage test is a high contributor to ensure sterility during use phase. On the other hand, the synthetic rubber plays a very small role in terms of freshwater ecotoxicity. However, the bio-polyisoprene, specifically insecticides used to produce the maize, is a relatively greater contributor to freshwater ecotoxicity, alongside electricity use.

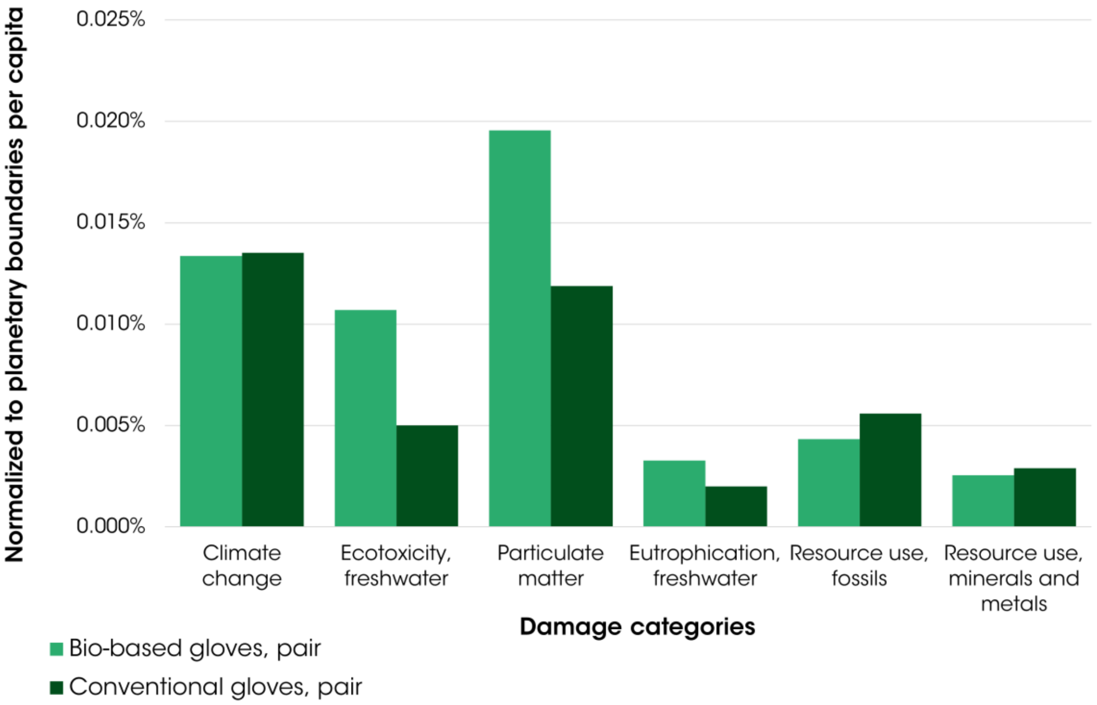

Figure 6 LCA results to produce the conventional and bio-based gloves based on selected damage categories.

4.2.2. End-of-life: common WM practices

WM of the gloves presents a similar picture to the facemasks, with some exceptions. As presented in Figure 7, open dumping of the bio-based version results in higher environmental impacts across all categories than incineration. This is again due to the decomposing process of the biowaste, namely CH_4 (climate change) and the NH_3 and H_2S (freshwater ecotoxicity). However, for the conventional gloves, open burning and incineration result in significantly higher impacts across all categories than open dump and landfill. This is due to the reaction of the synthetic rubber when burned.

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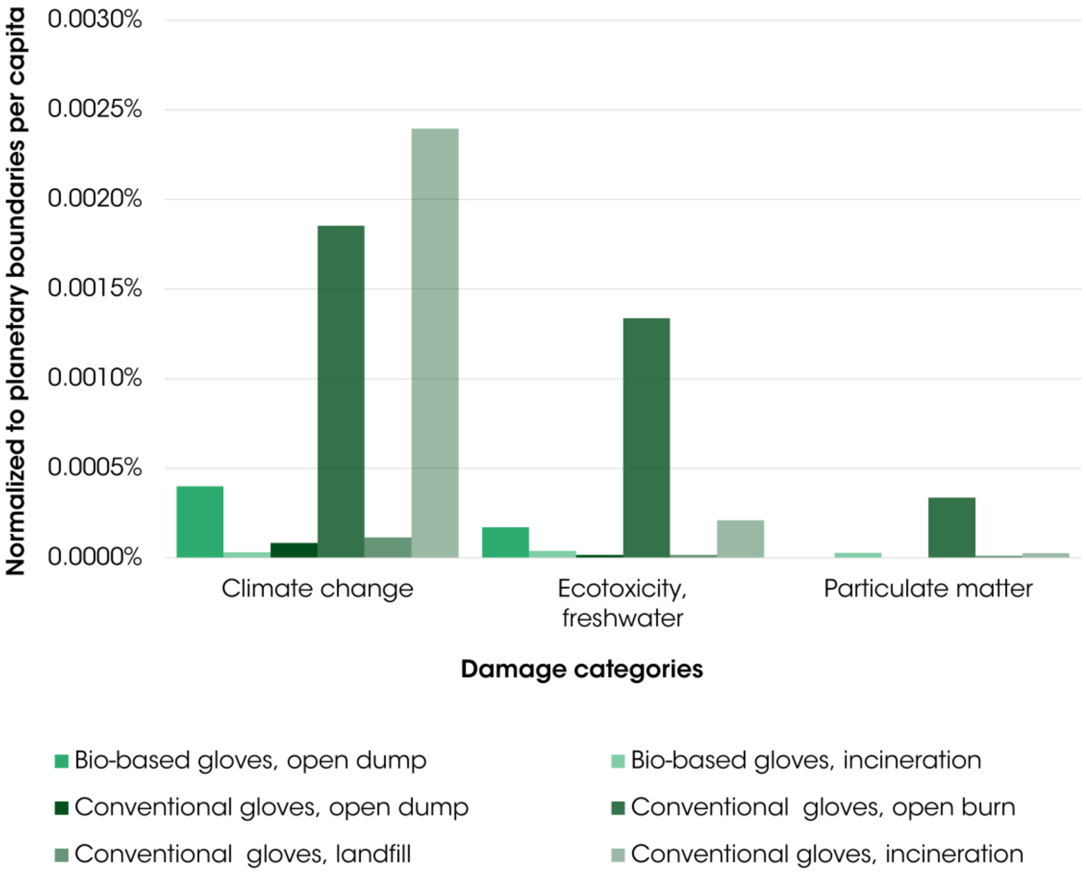

Figure 7 LCA results to relating to common WM practices for the conventional and bio-based gloves based on selected damage categories.

4.2.3. Comparison of life cycle steps

Similar to the facemasks, WM of the bio-based gloves creates a very small contribution to environmental impacts in comparison to production, as illustrated in Table 7. At most, open dump disposal of the bio-based gloves results in a 3% contribution to climate change and 2% to freshwater ecotoxicity, in comparison to production. For the conventional gloves, open burning and incineration contribute 12% and 15% to climate change in comparison to production, respectively. Again, like the facemasks, open burning also plays a larger role in the total environmental impacts related to freshwater ecotoxicity. The results for the conventional gloves are shown in Table 8.

Table 7 Resultant emissions from production (unit value) and relative contribution of WM in comparison to production (%) for the bio-based gloves.

DAMAGE CATEGORY	UNIT	PRODUCTION	OPEN DUMP	INCIN.
Climate change	kg CO_2 eq	1.14E-01	3%	0%
Freshwater ecotoxicity	CTUe	1.75E+00	2%	0%
Particulate matter	disease inc.	1.26E-08	0%	0%
Freshwater eutrophication	kg P eq	2.38E-05	2%	1%
Fossil resource use	MJ	1.21E+00	0%	0%
Mineral resource use	kg Sb eq	6.99E-07	0%	0%

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Table 8 Resultant emissions from production (unit value) and relative contribution of WM in comparison to production (%) for the conventional gloves.

DAMAGE CATEGORY	UNIT	PRODUCTION	OPEN DUMP	OPEN BURN	LANDFILL	INCIN.
Climate change	kg CO_2 eq	1.15E-01	1%	12%	1%	15%
Freshwater ecotoxicity	CTUe	8.21E-01	0%	21%	0%	4%
Particulate matter	disease inc.	7.66E-09	0%	3%	0%	0%
Freshwater eutrophication	kg P eq	1.45E-05	0%	0%	0%	0%
Fossil resource use	MJ	1.57E+00	0%	0%	0%	0%
Mineral resource use	kg Sb eq	7.95E-07	0%	0%	0%	0%

4.3. Surgical gowns

4.3.1. Production: conventional vs. bio-based

As presented in Figure 8, the production of the bio-based surgical gown outperforms the conventional version in terms of contribution to climate change, and fossil and mineral resource use. It scores lower than the conventional gowns for environmental impacts related to freshwater ecotoxicity and eutrophication, as well as particulate matter. The main drivers for the bio-based gowns across all impact categories is the use of PLA (the same bio-based textile in the facemasks), polyisoprene (the same bio-based rubber used for the gloves), and the electricity used to manufacture the item. The PLA, however, implies a much larger contribution to all impact categories, namely due to the production of maize. For the conventional gowns, the PP-based textile is the most significant contributor across all environmental impact categories.

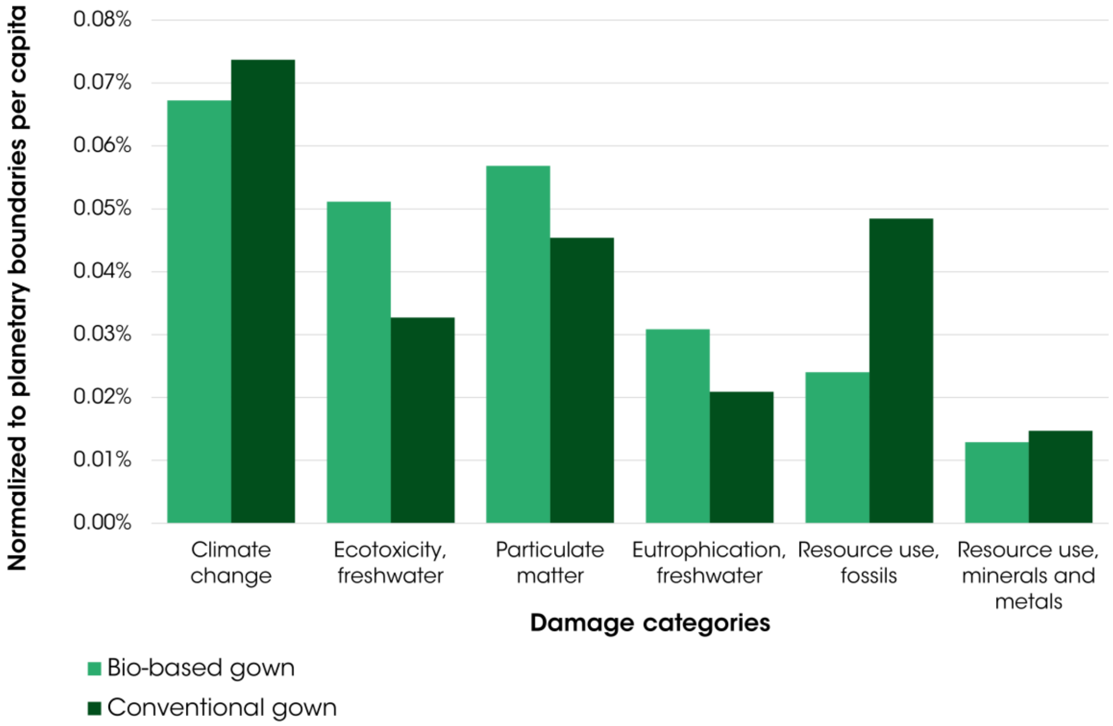

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Figure 8 LCA results to produce the conventional and bio-based surgical gown based on selected damage categories.

4.3.2. End-of-life: common WM practices

The results for WM of the bio-based and conventional surgical gowns are presented in Figure 9. They reiterate the findings of the previous products, in which the WM of the bio-based products significantly outperforms the conventional versions. This is due to the lower emissions associated with waste treatment of biowaste in comparison to materials such as fossil-based plastics or synthetic rubber. Open dumping results in much greater impacts than incineration of the bio-based gown, again, due to the breakdown of the biowaste. Also like the previous results, incineration and open burning of the conventional version implies a significantly larger contribution to climate change, than open dump or landfill. Again, this is due to the CO_2 and CH_4 emitted when burning fossil-based plastic (PP). Open burning also results in higher result for freshwater ecotoxicity as it implies uncontrolled emissions to soil when burning the PP.

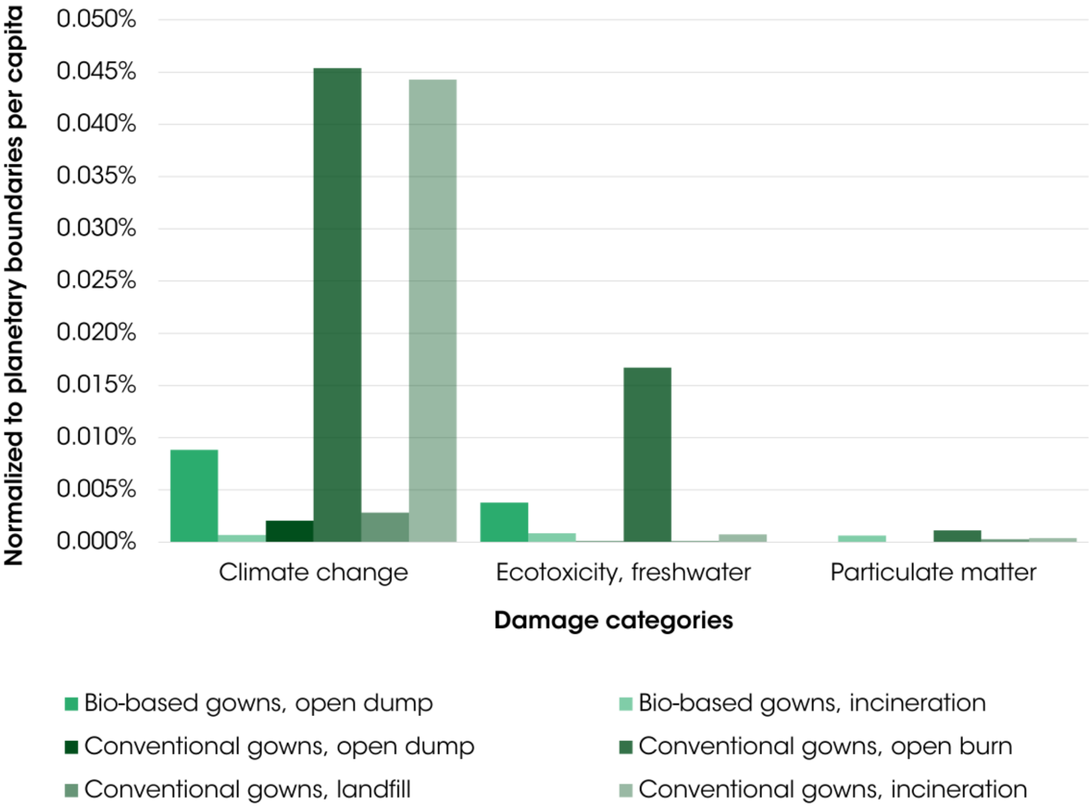

Figure 9 LCA results to relating to common WM practices for the conventional and bio-based gowns based on selected damage categories.

4.3.3. Comparison of life cycle steps

Further aligned to the previous findings, production remains the significant contributor to overall environmental impacts in comparison to WM of the gowns. As illustrated in Table 9, open dumping contributes to 12% of total climate change emissions, 7% of freshwater ecotoxicity, and 5% of freshwater eutrophication. Incineration of the bio-based gowns, however, only accounts for a 1%, 2%, and 3%

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contribution to climate change, freshwater ecotoxicity, and freshwater eutrophication, respectively, in comparison to production. For the conventional gown, open burning and incineration imply a significantly larger contribution to environmental impacts in comparison to landfill or open dump. This is illustrated in

Table 10.

Table 9 Resultant emissions from production (unit value) and relative contribution of WM in comparison to production (%) for the bio-based gown.

DAMAGE CATEGORY	UNIT	PRODUCTION	OPEN DUMP	INCIN.
Climate change	kg CO_2 eq	5.73E-01	12%	1%
Freshwater ecotoxicity	CTUe	8.37E+00	7%	2%
Particulate matter	disease inc.	3.67E-08	0%	1%
Freshwater eutrophication	kg P eq	2.24E-04	5%	3%
Fossil resource use	MJ	6.73E+00	0%	1%
Mineral resource use	kg Sb eq	3.53E-06	0%	0%

Table 10 Resultant emissions from production (unit value) and relative contribution of WM in comparison to production (%) for the conventional gown.

DAMAGE CATEGORY	UNIT	PRODUCTION	OPEN DUMP	OPEN BURN	LANDFILL	INCIN.
Climate change	kg CO_2 eq	1.15E-01	1%	12%	1%	15%
Freshwater ecotoxicity	CTUe	8.21E-01	0%	21%	0%	4%
Particulate matter	disease inc.	7.66E-09	0%	3%	0%	0%
Freshwater eutrophication	kg P eq	1.45E-05	0%	0%	0%	0%
Fossil resource use	MJ	1.57E+00	0%	0%	0%	0%
Mineral resource use	kg Sb eq	7.95E-07	0%	0%	0%	0%

4.4. Protective boots

4.4.1. Production: conventional vs. bio-based

There are several options for protective boots. In our case, as previously described, the protective boots are intended to be those used by waste pickers and we selected a lightweight safety boot made of leather to represent the conventional version. As a bio-based alternative, we model hemp-based vegan leather. As illustrated in Figure 10, the bio-based boots significantly outperform the conventional boots across all environmental impact categories. Most emissions associated with producing the conventional boot are associated with the leather. This is due to the nature of leather production, which requires an input of many raw hides to produce a comparatively much smaller output of usable leather (Minh & Ngan, 2021; Navarro et al., 2020).

For the bio-based version however, the bio-based vegan leather plays a smaller role in the contribution to environmental impacts in comparison to other materials used to produce the boots, such as polyurethane (PUR), a fossil-based material also included in the production of the bio-based boots. We could not find a suitable alternative in the literature and thus this was included for the bio-based boots.

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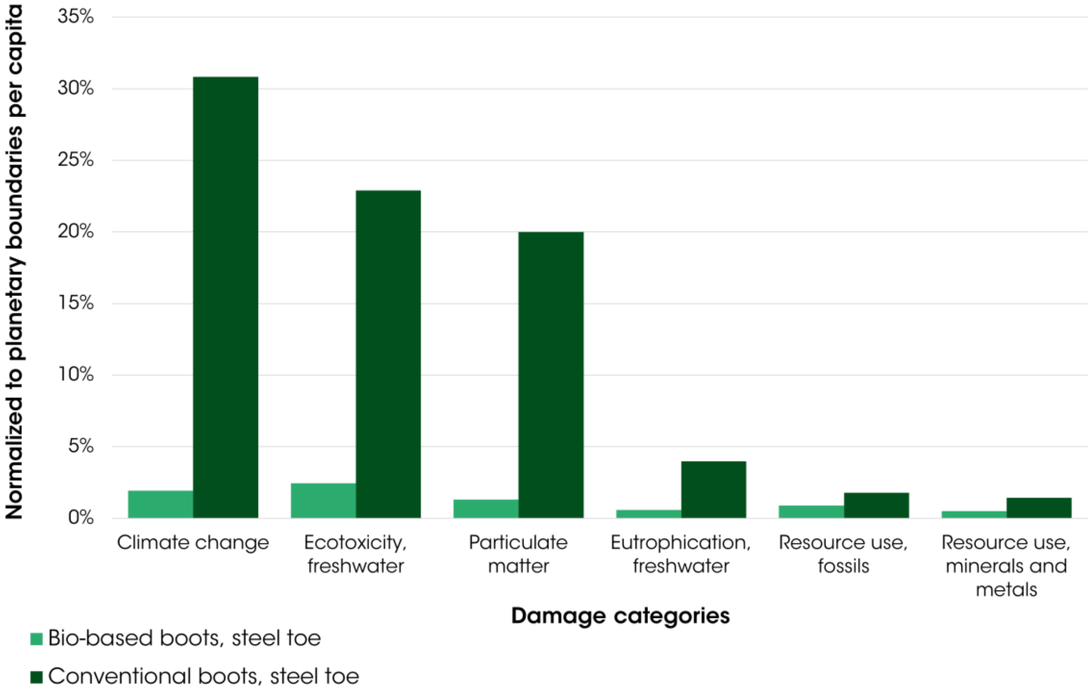

Figure 10 LCA results to produce the conventional and bio-based protective boots based on selected damage categories.

4.4.2. End-of-life: common WM practices

Once the boots reach their end of life, they are disposed of via various methods. Unlike the previous products, open burning and incineration result in the highest impacts across all categories for both the conventional bio-based version, as illustrated in Figure 11. For the conventional leather boots, the open burning represents the greatest emitter in terms of freshwater ecotoxicity and particulate matter, while incineration is slightly worse for climate change. The main driver for both open burning and incineration is treatment of the PUR. For open dump and landfill of the conventional boots, a combination of processes contributes to the impacts, namely the PVC, as well as the waste treatment for textiles.

For the bio-based vegan leather option, incineration results in significantly larger impacts in comparison to open dump for climate change, freshwater ecotoxicity, and particulate matter. As opposed to the previous products, the bio-based boots also include some fossil-based materials such as PUR. The incineration of these materials, particularly PUR, is worse for the environment than biowaste. However, for climate change, the decomposition of the biowaste component (i.e., bio-based vegan leather) is the largest driver.

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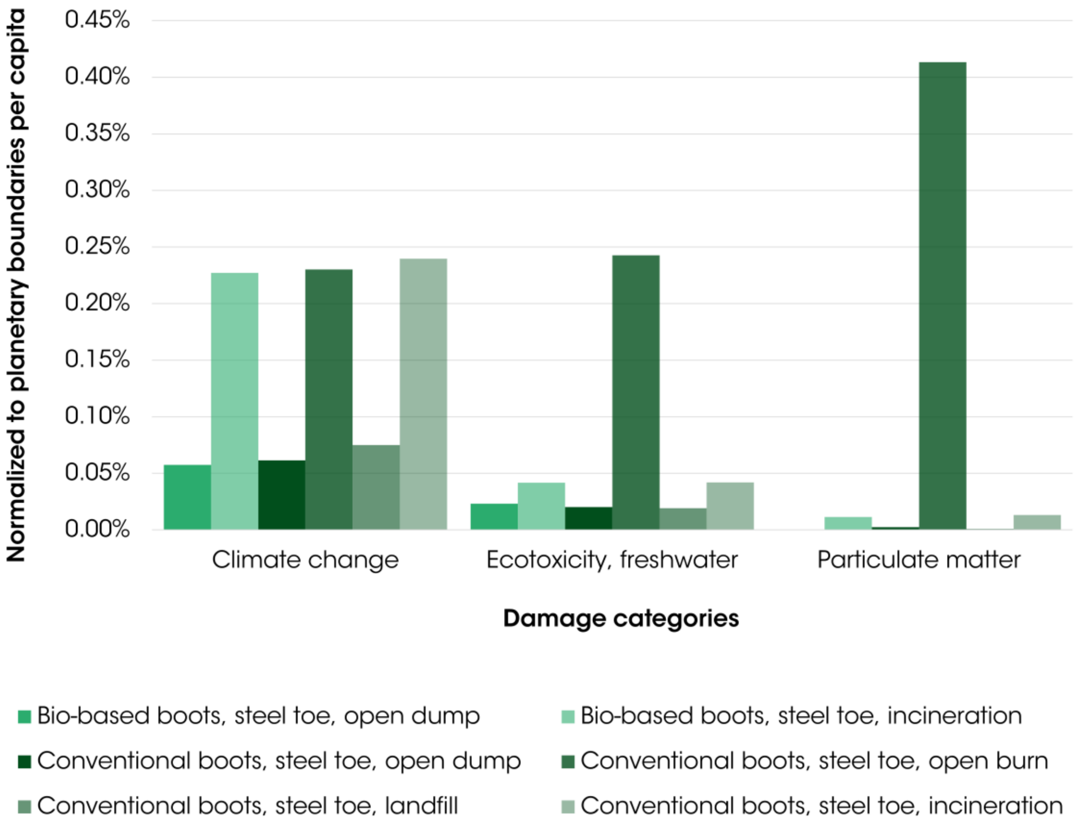

Figure 11 LCA results to relating to common WM practices for the conventional and bio-based protective boots based on selected damage categories.

4.4.3. Comparison of life cycle steps

When comparing the production and WM phases of the protective boots, the results are different than the previous products. As presented in *Table* 11, incinerating the bio-based boots implies greater contributions to climate change, freshwater ecotoxicity and eutrophication, as well as fossil resource use than open dumping. However, for the conventional boots, the impact of WM is starkly limited in comparison to production, as shown in Table 12. This is because the production of the leather for the conventional boots implies significantly more environmental impacts than the bio-based version.

Table 11 Resultant emissions from production (unit value) and relative contribution of WM in comparison to production (%) for the bio-based boots.

DAMAGE CATEGORY	UNIT	PRODUCTION	OPEN DUMP	INCIN.
Climate change	kg CO_2 eq	1.64E+01	3%	11%
Freshwater ecotoxicity	CTUe	4.01E+02	1%	2%
Particulate matter	disease inc.	8.37E-07	0%	1%
Freshwater eutrophication	kg P eq	4.24E-03	3%	1%
Fossil resource use	MJ	2.49E+02	0%	1%
Mineral resource use	kg Sb eq	1.35E-04	0%	0%

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Table 12 Resultant emissions from production (unit value) and relative contribution of WM in comparison to production (%) for the conventional boots.

DAMAGE CATEGORY	UNIT	PRODUCTION	OPEN DUMP	OPEN BURN	LANDFILL	INCIN.
Climate change	kg CO_2 eq	2.62E+02	0%	1%	0%	1%
Freshwater ecotoxicity	CTUe	3.75E+03	0%	1%	0%	0%
Particulate matter	disease inc.	1.29E-05	0%	2%	0%	0%
Freshwater eutrophication	kg P eq	2.89E-02	0%	0%	0%	0%
Fossil resource use	MJ	5.01E+02	0%	0%	0%	0%
Mineral resource use	kg Sb eq	3.90E-04	0%	0%	0%	0%

4.5. Syringes and needles

4.5.1. Production: conventional vs. bio-based

The results for the syringe and needle are presented in Figure 12. In this case, the conventional syringe is made of PP and synthetic rubber, while the bio-based version is comprised of PLA and polyisoprene. However, for both cases, the needle is made from steel, as there we were not able to identify a suitable bio-based alternative. The bio-based version outperforms the conventional one in terms of climate change, and fossil and mineral resource use, while the conventional scores better than the bio-based option in relation to freshwater ecotoxicity and eutrophication, and particulate matter. The main contributor to freshwater ecotoxicity, and fossil and mineral resource use for the conventional syringe and needle is the use of PP to produce the syringe. For other categories, such as climate change, freshwater eutrophication, and particulate matter, the injection moulding process during manufacturing also plays a role. The story is similar for the bio-based version, where the primary materials (PLA and polyisoprene) are the main drivers for freshwater ecotoxicity, as well mineral resource use. For climate change, particulate matter, freshwater eutrophication, and fossil resource use, the injecting moulding process is also a top contributor.

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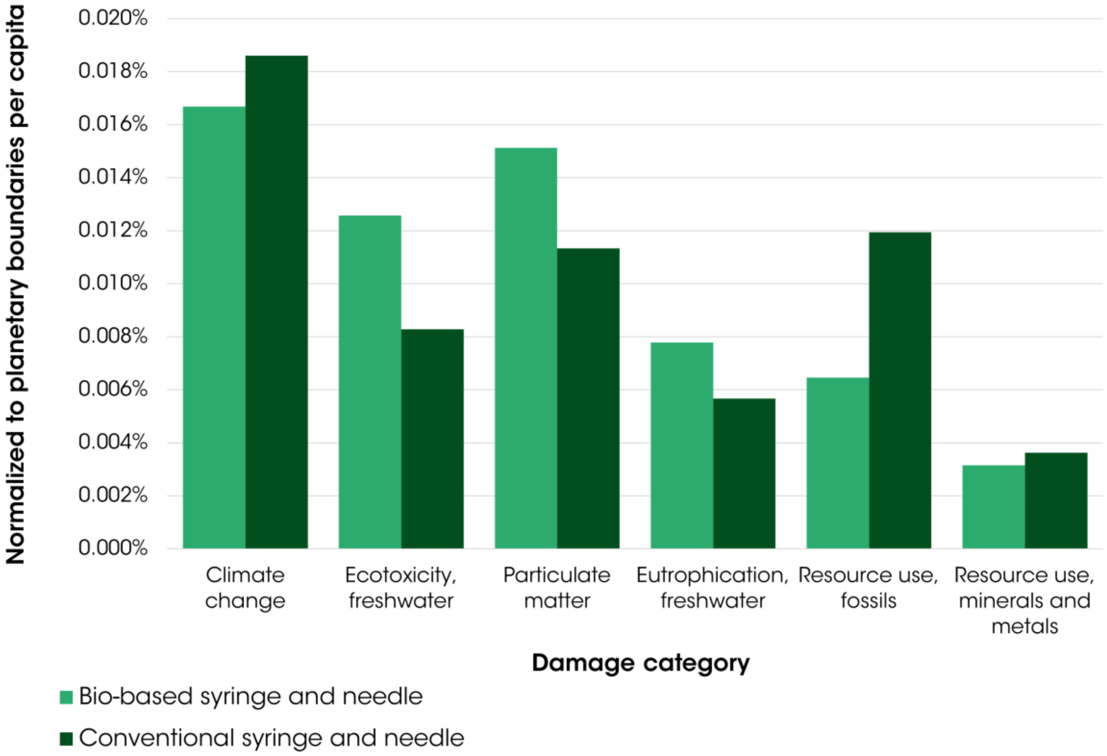

Figure 12 LCA results to produce the conventional and bio-based syringe and needle based on selected damage categories.

4.5.2. End-of-life: common WM practices

The results for WM of the bio-based and conventional syringe and needle are presented in Figure 13. As with the previous results, open burning and incineration imply the largest emissions regarding climate change for the conventional option. Furthermore, open burning results in the largest emissions for freshwater ecotoxicity, as it results in uncontrolled treatment of emissions to soil. For the bio-based syringe and needle, open dumping implies the greatest contribution to climate change and freshwater ecotoxicity in comparison to incineration. This is again driven by the emissions resulting from the decomposition process. However, similarly to the boots, incineration of the bio-based syringe and needle does have a relatively large contribution. This is due to the disposal of the metal and rubber used in the syringe, rather than the biowaste.

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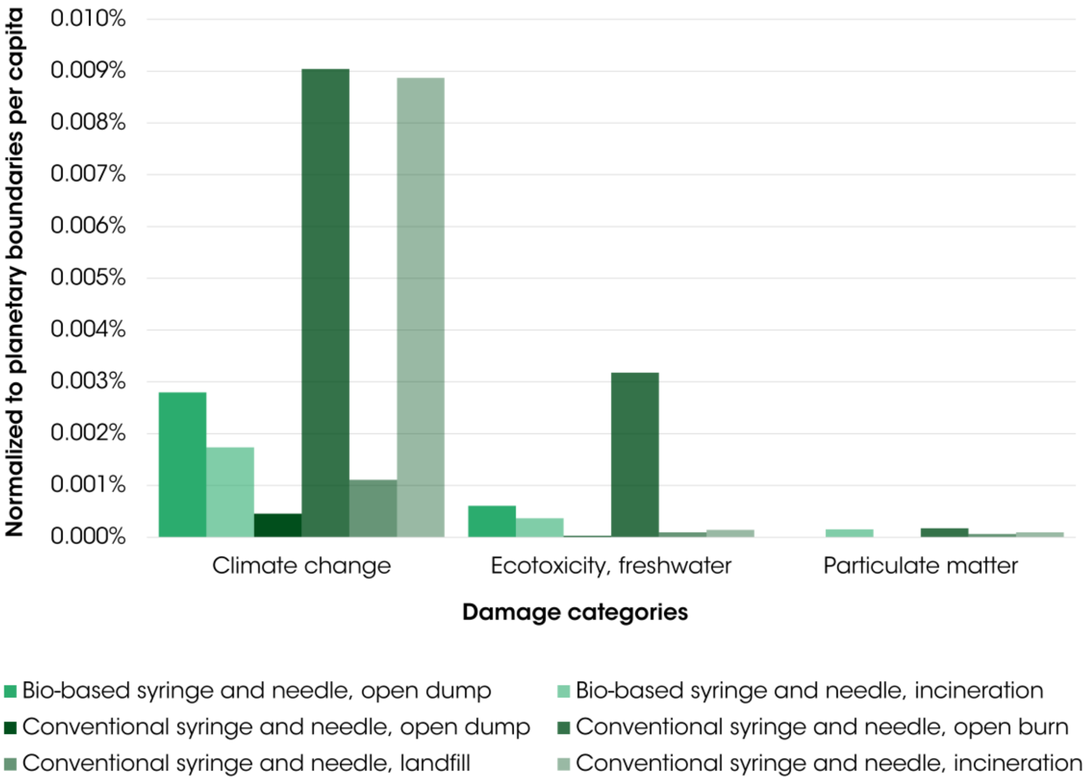

Figure 13 LCA results to relating to common WM practices for the conventional and bio-based syringe and needle based on selected damage categories.

4.5.3. Comparison of life cycle steps

Table 13 presents the environmental emissions associated with producing the bio-based syringe and needle as well as the relative contribution of WM to the life cycle of the product (in comparison to production). In terms of climate change, open dump implies the largest share, with a relative contribution of 19%. Incineration, in comparison, is 9% of the total footprint. Open dump and incineration are similar for freshwater ecotoxicity and eutrophication, while the contribution to particulate matter and fossil and mineral resource use is minimal. As shown in Table 14, open burning and incineration of the conventional syringe and needle result in a significantly larger contribution to climate change (33% and 32%, respectively), in comparison to landfill or open dump. As with previous products, open burning also implies notable emissions to freshwater ecotoxicity.

Table 13 Resultant emissions from production (unit value) and relative contribution of WM in comparison to production (%) for the bio-based syringe and needle.

DAMAGE CATEGORY	UNIT	PRODUCTION	OPEN DUMP	INCIN.
Climate change	kg CO_2 eq	1.42E-01	19%	9%
Freshwater ecotoxicity	CTUe	2.06E+00	5%	3%
Particulate matter	disease inc.	9.76E-09	0%	1%
Freshwater eutrophication	kg P eq	5.66E-05	4%	3%
Fossil resource use	MJ	1.81E+00	0%	1%
Mineral resource use	kg Sb eq	8.62E-07	0%	0%

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Table 14 Resultant emissions from production (unit value) and relative contribution of WM in comparison to production (%) for the conventional syringe and needle.

DAMAGE CATEGORY	UNIT	PRODUCTION	OPEN DUMP	OPEN BURN	LANDFILL	INCIN.
Climate change	kg CO_2 eq	1.58E-01	2%	33%	6%	32%
Freshwater ecotoxicity	CTUe	1.36E+00	0%	28%	1%	2%
Particulate matter	disease inc.	7.31E-09	0%	1%	1%	1%
Freshwater eutrophication	kg P eq	4.12E-05	0%	0%	1%	1%
Fossil resource use	MJ	3.35E+00	0%	0%	0%	0%
Mineral resource use	kg Sb eq	9.94E-07	0%	0%	0%	0%

4.6. Sharps containers

4.6.1. Production: conventional vs. bio-based

We were able to collect data from manufacturers on two types of bio-based sharps containers; one produced with wood and the other with cardboard. The results of these options are compared with a conventional sharps container comprised predominantly of PP is presented in Figure 14. An obvious observation in the graph is that the bio-based container made of cardboard results in a significantly lower environmental footprint than the bio-based wood container or the conventional PP version. Secondly, the wood-based sharps container also outperforms the fossil-based PP option across all categories. The top contributor to all categories for the conventional version is the use of PP, and in some cases (climate change, particulate matter, and freshwater eutrophication) the electricity used for the injection moulding process during manufacturing also plays a role. While the bio-based wood sharps container is primarily comprised of wood, it also includes some bio-based plastic (PLA), which is the main driver for the environmental impacts across all categories for this option. The bio-based cardboard sharps container is made only of cardboardand thus has a relatively small environmental footprint.

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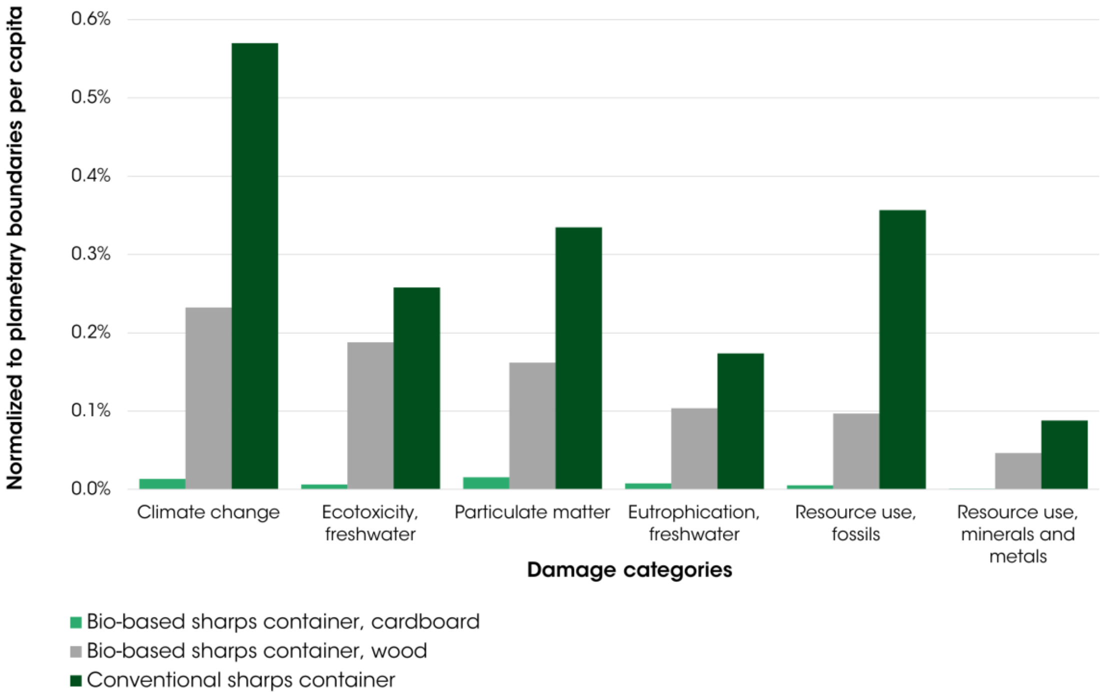

Figure 14 LCA results to produce the conventional and bio-based sharps container based on selected damage categories.

4.6.2. End-of-life: common WM practices

The results for WM of the bio-based (cardboard and wood) and conventional sharps container are shown in Figure 15. Regarding the conventional sharps container, open burning and incineration result in the highest contribution to climate change. Like the previous findings, this is due to the harmful emissions to air because of burning plastic (in this case PP). Open burning the PP-based sharps container also results in the largest contribution to freshwater ecotoxicity. Disposing of the cardboard-based sharps container aligns with similar findings for WM, where open dump implies greater emissions than incineration. This is again due to the CH_4 being released as the product decomposes. Here, we did not model "biowaste" but rather waste "paperboard". For the wood-based sharps container, however, incineration implies greater impact than open dump. This is because wood decomposes much slower than cardboard and thus results in lower climate change emissions (Ximenes et al., 2018).

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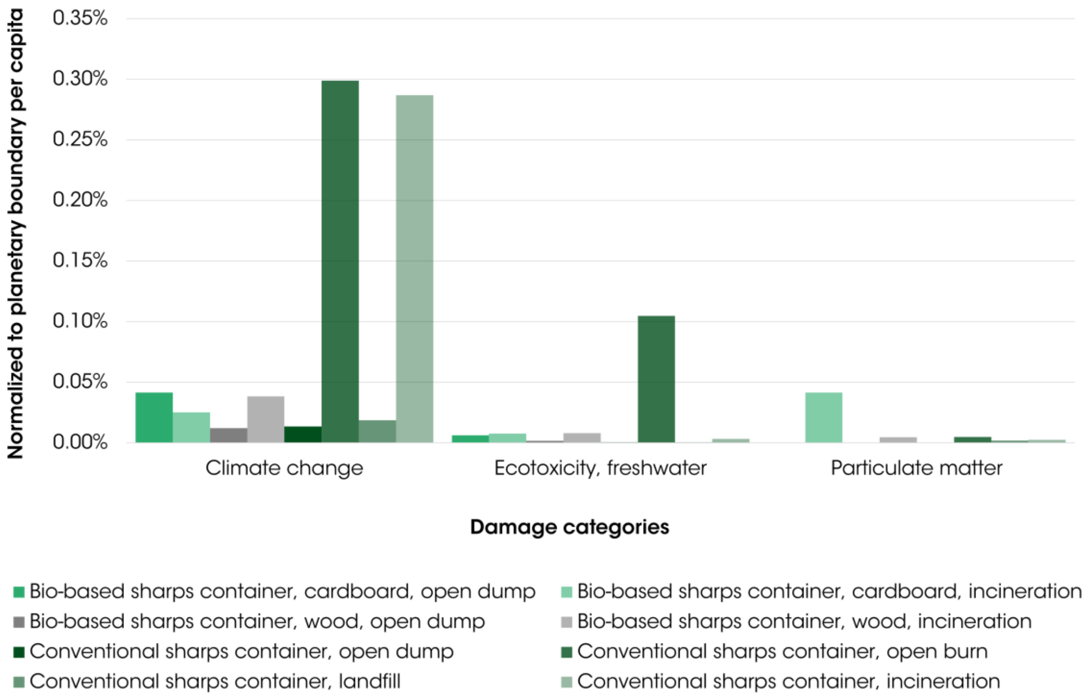

Figure 15 LCA results to relating to common WM practices for the conventional and bio-based sharps container based on selected damage categories.

4.6.3. Comparison of life cycle steps

As with the previous products, production is a main driver for environmental impacts for the sharps containers. However, it plays a much larger role for the bio-based sharps container produced from wood and the conventional sharps container produced with PP. For the bio-based sharps container made from cardboard, however, the impacts of production are relatively lower than the other versions. Simultaneously, the footprint of WM for the cardboard container is higher than the wood-based version. Thus, WM plays a significantly larger role in comparison to production, as shown in Table 15. Open dumping and incineration contribute to 18% and 12% of climate change impacts, respectively. Incinerating the cardboard sharps container implies a 68% contribution to particulate matter. This is partly due to the impacts associated with burning cardboard, but more significantly to the fact that producing the container implies very low emissions related to particulate matter. For the bio-based sharps container made of wood, incineration also implies a larger contribution for all impact categories in comparison to open dump, as discussed in the previous section. For the conventional sharps container made of PP, open burn and incineration contribute 34% and 33% to climate change impacts, respectively. Again, open burning the PP also implies large emissions that result in particulate matter.

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Table 15 Resultant emissions from production (unit value) and relative contribution of WM in comparison to production (%) for the bio-based sharps container (cardboard and wood).

DAMAGE CATEGORY	UNIT	CARDBOARD			WOOD		
		PROD.	OPEN DUMP	INCIN.	PROD.	OPEN DUMP	INCIN.
Climate change	kg CO_2 eq	1.15E-01	18%	12%	1.98E+00	5%	14%
Freshwater ecotoxicity	CTUe	1.05E+00	4%	5%	3.08E+01	1%	4%
Particulate matter	disease inc.	1.01E-08	0%	68%	1.05E-07	0%	3%
Freshwater eutrophication	kg P eq	5.66E-05	8%	4%	7.54E-04	0%	4%
Fossil resource use	MJ	1.45E+00	0%	0%	2.71E+01	0%	1%
Mineral resource use	kg Sb eq	3.15E-07	0%	0%	1.27E-05	0%	0%

Table 16 Resultant emissions from production (unit value) and relative contribution of WM in comparison to production (%) for the conventional sharps container.

DAMAGE CATEGORY	UNIT	PRODUCTION	OPEN DUMP	OPEN BURN	LANDFILL	INCIN.
Climate change	kg CO_2 eq	4.85E+00	2%	34%	3%	33%
Freshwater ecotoxicity	CTUe	4.22E+01	0%	29%	0%	1%
Particulate matter	disease inc.	2.16E-07	0%	1%	1%	1%
Freshwater eutrophication	kg P eq	1.26E-03	0%	0%	0%	0%
Fossil resource use	MJ	9.99E+01	0%	0%	0%	0%
Mineral resource use	kg Sb eq	2.41E-05	0%	0%	0%	0%

4.7. Body bags

4.7.1. Production: conventional vs. biodegradable

As shown in Figure 16, producing the conventional body bag, primarily composed of PE and PP, results in emissions across all the top categories. Furthermore, the main driver across all categories is the use of PE. In some cases, such as freshwater ecotoxicity and eutrophication, the electricity required for the extrusion process to manufacture the body bag also results in a larger portion of the total emissions.

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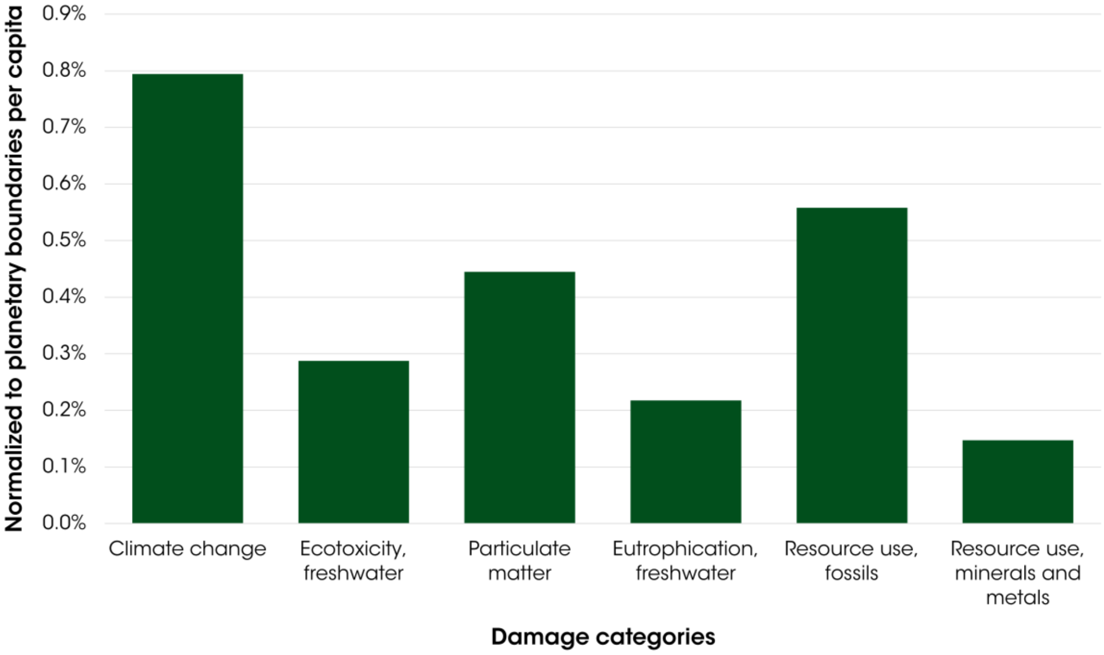

Figure 16 LCA results to produce the conventional body bag based on selected damage categories.

4.7.2. End-of-life: common WM practices

At the end of life, the body bag can face different waste scenarios. Here, we are measuring only the environmental impacts associated with disposing of a body bag itself and do not account for methods of handling a body bag which includes human remains. In this case, we it could be assumed that the body bag was not used or damaged. The results for the end-of-life assessment are shown in Figure 17. Climate change is the top environmental impact category related to WM, and especially high for incineration and open burning. In both cases, treating the PE is the main contributor to emissions and environmental impacts. Additionally, the use of the PE also has a strong influence on the emissions related to freshwater ecotoxicity resulting from open burning.

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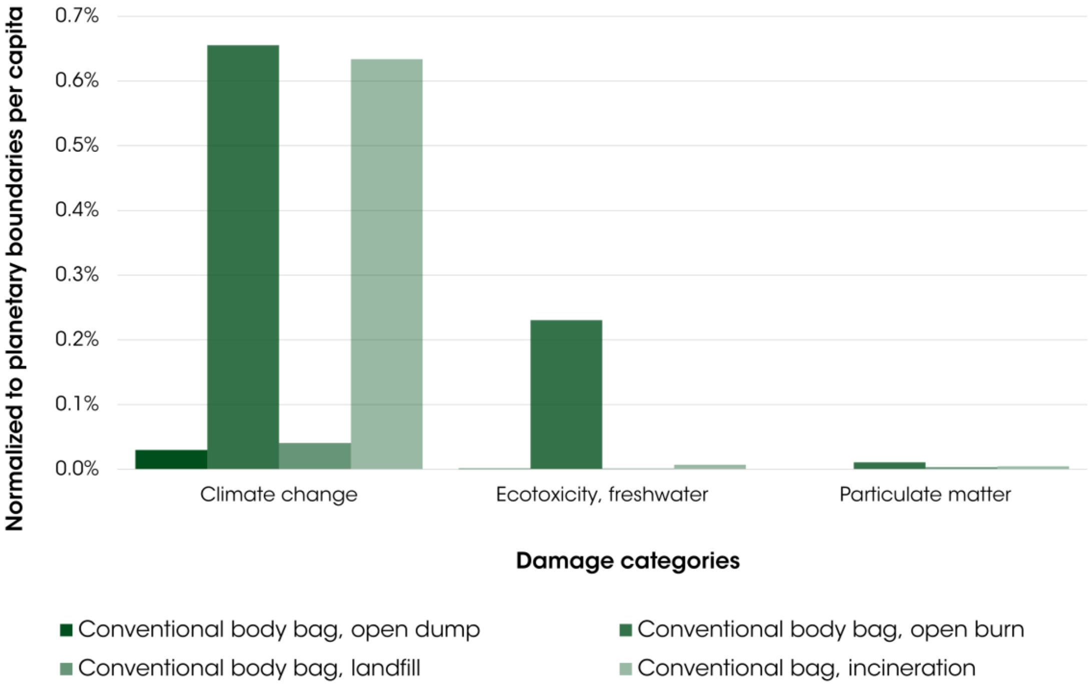

Figure 17 LCA results to relating to common WM practices for the conventional body bag based on selected damage categories.

4.7.3. Comparison of life cycle steps

Similar to the previous conventional products, WM plays a significant role in comparison for production, especially if this is done via open burning or incineration. In terms of climate change, these WM methods account for 45% and 44% of GHG emissions, respectively, in comparison to production of the body bag. This is shown in Table 17. Again, open burning waste also results in high emissions that drive freshwater ecotoxicity. Finally, as with the other conventional products, WM plays a very small role in overall environmental impacts related to particulate matter, freshwater eutrophication, and fossil and mineral resource use in comparison to production.

Table 17 Resultant emissions from production (unit value) and relative contribution of WM in comparison to production (%) for the conventional body bag.

DAMAGE CATEGORY	UNIT	PRODUCTION	OPEN DUMP	OPEN BURN	LANDFILL	INCIN.
Climate change	kg CO_2 eq	6.76E+00	4%	45%	5%	44%
Freshwater ecotoxicity	CTUe	4.70E+01	0%	45%	0%	2%
Particulate matter	disease inc.	2.87E-07	0%	0%	1%	1%
Freshwater eutrophication	kg P eq	1.58E-03	0%	0%	0%	0%
Fossil resource use	MJ	1.56E+02	0%	0%	0%	0%
Mineral resource use	kg Sb eq	4.03E-05	0%	0%	0%	0%

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4.8. Temporary water/sludge bladders

4.8.1. Production: conventional

The results to produce the conventional temporary water bladder are presented in Figure 18. Climate change is the damage category with the relatively largest contribution to planetary boundaries. It should be noted that the normalization value is per capita, whereas the bladder is intended to serve many people. The main materials used to produce the conventional version are PVC, PE, PP, aluminium, and steel. In the case of climate change, however, the use of plastics, specifically the PVC is the top driver. PVC is also the main source of emissions related to freshwater ecotoxicity and eutrophication, particulate matter, and fossil resource use. The use of chemicals (specifically the copper used to produce those chemicals) is also a contributor to mineral resource use, along with PVC.

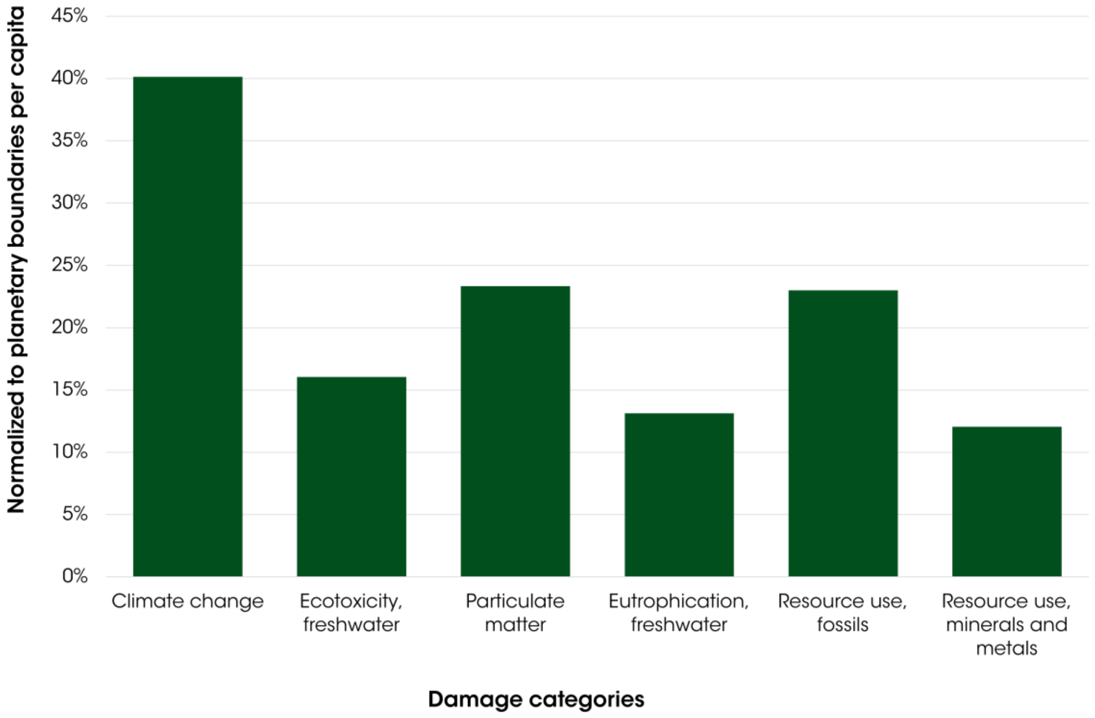

Figure 18 LCA results to produce the conventional temporary water bladder based on selected damage categories.

4.8.2. End-of-life: common WM practices

The results for WM of the conventional temporary water bladder are shown in Figure 19. Incineration and open burning stand out as the WM practices that results in the greatest impacts across all the presented categories. This is due to the harmful emissions released when burning plastics, namely the PVC, which is by far the dominant material used to produce the temporary water bladders. However, particulate matter is the damage category with the highest relative contribution to planetary boundaries. In this case, open burning the temporary water bladder results in significant emissions that drive particulate matter – again driven by the PVC.

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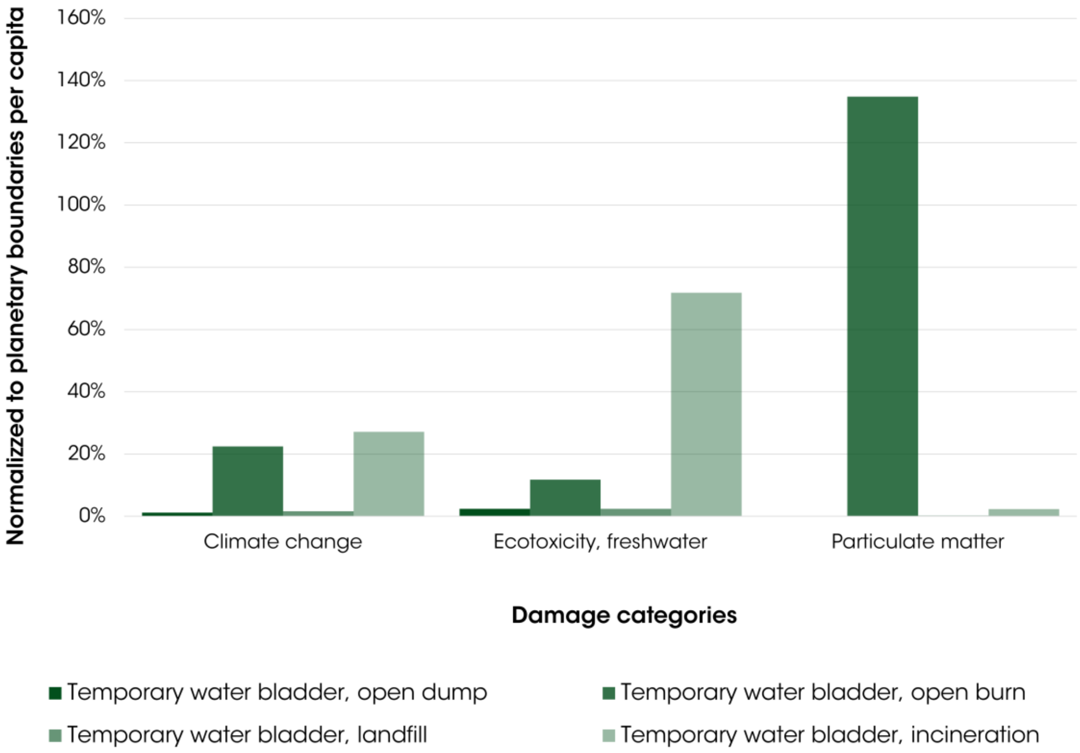

Figure 19 LCA results to relating to common WM practices for the conventional temporary water bladder based on selected damage categories.

4.8.3. Comparison of life cycle steps

Comparing production and end-of-life of the temporary water bladders is in general aligned to the other conventional products, with some exceptions, as illustrated in Table 18. Similar to the previous products, production is a main driver, especially in terms of freshwater eutrophication, and fossil and mineral resource use. However, incineration does have a small contribution to these categories relative to production. In terms of climate change, open burning and incineration contribute almost equally to production, whereas the impact of open dump and landfill remains small. The more notable difference from previous results is in regard to freshwater ecotoxicity and particulate matter. Namely, the incineration of the temporary water bladder contributes to 82% of total impacts on freshwater ecotoxicity. Open burning also implies a challenge for freshwater ecotoxicity. In terms of particulate matter, open burning again performs the worst among all WM strategies, yet in this case the result is 85% of the total impacts for this category. As previously discussed nearly all impacts related to WM are derived from disposing of the PVC.

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Table 18 Resultant emissions from production (unit value) and relative contribution of WM in comparison to production (%) for the conventional temporary water bladder.

DAMAGE CATEGORY	UNIT	PRODUCTION	OPEN DUMP	OPEN BURN	LANDFILL	INCIN.
Climate change	kg CO_2 eq	3.42E+02	3%	36%	4%	40%
Freshwater ecotoxicity	CTUe	2.62E+03	13%	42%	13%	82%
Particulate matter	disease inc.	1.51E-05	0%	85%	1%	9%
Freshwater eutrophication	kg P eq	9.53E-02	0%	0%	0%	10%
Fossil resource use	MJ	6.44E+03	0%	0%	0%	5%
Mineral resource use	kg Sb eq	3.29E-03	0%	0%	0%	5%

4.9. Sensitivity analysis

We also test the sensitivity of the results based on different scenarios for production and WM conditions. This includes testing the change in environmental impacts when switching from non-organic (i.e., average industrialized agricultural practices) to organic agricultural production for the bio-based materials. Additionally, we examine the impact of different moisture conditions on results environmental impacts associated with open dumping and landfill.

4.9.1. Agricultural production for bio-based materials

Several bio-based materials such as starch- or sugar-based plastics also require agricultural production, which has implications on overall environmental impacts. We assume average industrial agricultural production and, as indicated in the results, this can cause the bio-based version to score lower for some environmental categories. Thus, we use the facemasks as an example to compare the impact of different agricultural production systems on the overall environmental impact of production. This includes comparing organic and non-organic (i.e., average industrial standards). Organic agriculture has been identified as a relevant method to reduce the environmental impacts associated with agricultural production (Barbieri et al., 2017; Muller et al., 2017; Ponisio et al., 2015; Reganold & Wachter, 2016; Seufert et al., 2012). We assume the organic bio-based materials do not include synthetic fertilizers or pesticides. The nutrients are supplemented with organic fertilizers and manures but also require more land to produce the same yield as the non-organic version.

Table 19 presents the results for the top damage categories including climate change, particulate matter, freshwater ecotoxicity and eutrophication, fossil and mineral resource use, and land use. We also include land use in the results, expressed as points (Pts). This refers to the use and transformation of land for agricultural or other purposes. This is a composite indicator which measures impact according to four soil properties: biotic production, erosion resistance, groundwater regeneration and mechanical filtration. Organic outperforms all categories except for particulate matter and land use. This is namely due to the use of green manure (e.g., growing plants that are ploughed into the soil to be used as fertilizer) to replace the synthetic fertilizers and pesticides. Land use is higher for the organic option due to the yield gap commonly associated with organic agriculture in comparison to conventional industrialized practices with high inputs of synthetic fertilizers and chemicals. Organic is higher for particulate matter due to the higher particulate matter emissions associated with drying the organic maize. However, organic production

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methods are often highly contextual and intended to adapt to local conditions. Thus, this can be seen as one option for organic production.

Table 19 The influence of non-organic vs. organic production on the LCA results to produce the bio-based facemasks.

DAMAGE CATEGORY	UNIT	BIO FACEMASK, NON-ORGANIC PRODUCTION	BIO FACEMASK, ORGANIC PRODUCTION
Climate change	kg CO_2 eq	1.12E-02	1.08E-02
Freshwater ecotoxicity	CTUe	1.42E-01	4.13E-02
Particulate matter	disease inc.	6.18E-10	9.07E-10
Freshwater eutrophication	kg P eq	4.22E-06	4.08E-06
Fossil resource use	MJ	1.31E-01	1.27E-01
Mineral resource use	kg Sb eq	6.50E-08	5.73E-08
Land use	Pt	2.75E-01	3.24E-01

The largest change, however, is the effect on freshwater ecotoxicity. Figure 20 presents the change in resultant impacts to freshwater ecotoxicity, expressed as comparative toxic units to ecosystems (CTUe), to produce the bio-based facemasks under average industrial agricultural and organic production methods. Switching to organic results a significant decrease in freshwater ecotoxicity.

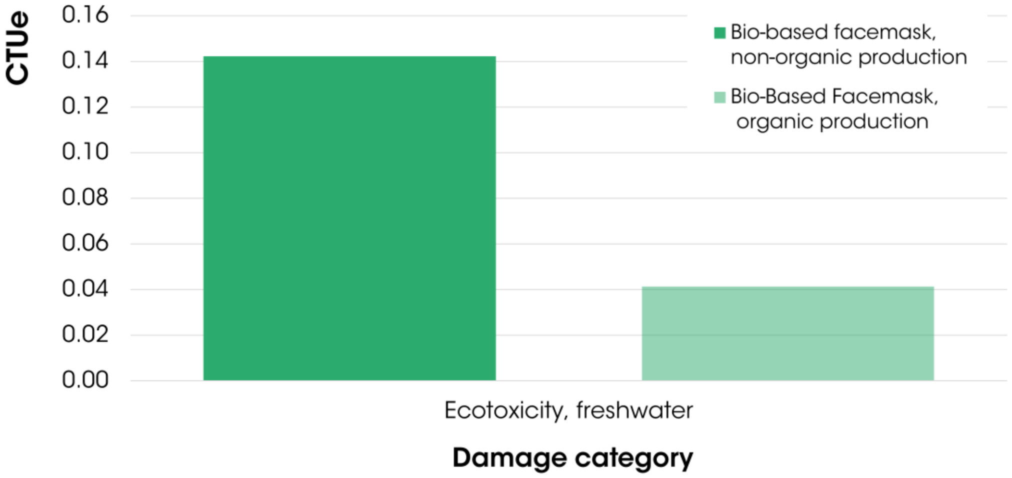

Figure 20 Change in resultant impacts to freshwater ecotoxicity (CTUe) to produce the bio-based facemasks when switching from non-organic to organic production methods.

4.9.2. Moisture levels in open dump and landfill

Furthermore, the open dump and landfill conditions modelled in this study assume a general moist climate. However, due to different seasons, the soil and moisture conditions can differ significantly throughout the year. WORM uses Kenya and Vietnam as focus areas for field hospital settings. For the LCAs presented above, we assume general global averages with a moist soil condition. However, open

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dump and landfill are two processes which can be strongly influenced by the changing seasonal conditions. Thus, we test for sensitivity of the LCA results to moisture levels and modeled disposing of conventional gloves (as an example) under very wet soil conditions (1000mm); moist conditions (300mm); and hyperarid soil conditions (-250mm). Table 20 indicates the average monthly soil conditions in Kenya and Vietnam (World Bank, 2021a, 2021b).

Table 20 Average monthly climate conditions in Kenya and Vietnam.

COUNTRY	SOIL CONDITIONS	NUMBER OF MONTHS	MONTHS
Kenya	Hyperarid/arid	6	Jan., Feb., June, July, August, Sept.
	Moist	2	March, Dec.
	Wet	4	April, May Oct., Nov.
Vietnam	Moist	5	Jan., Feb., March, April, Dec.
	Wet	2	May, Nov.
	Very wet	5	June, July, August, Sept., Oct.

It's important to note that there are regional differences in climate within the country, but we report the averages to provide context to the sensitivity analysis. We test the climate extremes (hyperarid and super wet) to develop upper and lower bounds in comparison to the general moist conditions. For half the year, Kenya is on average classified as hyperarid/arid, while for the other half moisture levels can vary from moist to wetTable 21 The influence of hyperarid, moist, and wet soil conditions on the LCA results of the open dump WM scenario for conventional gloves. Vietnam, on the other hand, is relatively wet throughout the year, with some regional exceptions during the dry season (December to January). For more than half of the year Vietnam experiences wet or very wet conditions.

Table 21 presents the results for the change in environmental impacts related to climate change, freshwater ecotoxicity, and particulate matter for conventional gloves based on different moisture conditions. In terms of climate change, there is no change in environmental impacts under different moisture conditions for both open dumping and landfill. However, for freshwater ecotoxicity, a hyperarid climate implies a significant increase in environmental consequences. This is due to the relative ease that chemical runoff can occur in soils with low moisture. In terms of particulate matter, the footprint in a region with hyperarid soil conditions increases exponentially in comparison to the moist or wet alternative. This is due to the increased number of inhalable particulates emitted to air under hyperarid conditions.

Table 21 The influence of hyperarid, moist, and wet soil conditions on the LCA results of the open dump WM scenario for conventional gloves.

WASTE TREATMENT	DAMAGE CATEGORY	UNIT	HYPERARID	MOIST	VERY WET
Open dump	Climate change	kg CO_2 eq	7.11E-04	7.11E-04	7.11E-04
	Freshwater ecotoxicity	CTUe	1.90E-01	2.74E-03	2.74E-03
	Particulate matter	disease inc.	3.57E-08	1.18E-14	1.18E-14

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Landfill	Climate change	kg CO_2 eq	2.40E-02	2.40E-02	2.40E-02
	Freshwater ecotoxicity	CTUe	2.08E+00	1.68E-02	1.68E-02
	Particulate matter	disease inc.	7.64E-07	1.78E-10	1.78E-10

5. DISCUSSION AND INTERPRETATION

5.1. Conventional vs. bio-based alternatives

Bio-based materials and conventional materials each present distinct trade-offs when evaluated for environmental sustainability. As illustrated in the results, bio-based materials often offer a lower environmental footprint, especially in terms of climate change, and fossil and mineral resource use. When biodegradable, bio-based materials also imply lower emissions during WM and can also reduce accumulation of waste in landfill and dump sites. However, bio-based materials do not always outperform conventional materials, especially in terms of freshwater ecotoxicity and eutrophication. The performance of bio-based materials is also dependent on factors such as fertilizer use, land-use changes, water consumption and runoff, and the impact of large-scale farming. As previously discussed, synthetic fertilizers and pesticides used to produce the raw agricultural material for the bio-based materials (e.g., maize for PLA) are major contributors to freshwater ecotoxicity and eutrophication. Furthermore, increasing the number of crops grown for bio-based materials can compete with food production or lead to deforestation if not managed sustainably.

The results of the sensitivity analysis indicate that switching to more environmentally friendly agricultural production methods such as organic agriculture have the potential to reduce the environmental footprint of producing the bio-based materials derived from plants, especially in relation to freshwater ecotoxicity. However, there are several factors to consider such as land use or availability on the market. While organic products tend to require more land, they also imply less environmental damage with the goal of enhancing or maintaining the quality of the soil. In comparison to industrialized agricultural methods which tend to degrade soil over time, switching to organic may also be a better option when considered using a long-term perspective.

In contrast, conventional materials, particularly those derived from fossil fuels like plastics, metals, and synthetic textiles, generally result in higher GHG emissions and challenges to handle waste. While they may offer superior performance in terms of durability, strength, or cost, their persistence in the environment (e.g., plastic pollution) poses long-term ecological challenges. Furthermore, WM of conventional materials results in greater emissions than bio-based alternatives across nearly all environmental impact categories, as described above. This is especially true for open burning and incineration, which results in significantly higher contributions to climate change than the other WM scenarios. Ultimately, bio-based materials have the potential to be more environmentally sustainable in the long term, but achieving true environmental benefits requires careful consideration of their full life cycle, including resource extraction (e.g., sustainable agricultural production), processing, and end-of-life management.

5.2. WM practices

Waste management processes such as open dumping, open burning, incineration, and landfill vary widely in terms of their environmental impacts and long-term sustainability. Open dumping, which involves the uncontrolled disposal of waste in open spaces, can lead to significant environmental pollution, including

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contamination of soil and groundwater with toxic chemicals and hazardous materials. As shown in the results, open dumping also contributes to the release of GHG emissions as biowaste decomposes anaerobically, producing CH_4, a potent contributor to climate change. Furthermore, as shown in the sensitivity analysis, different soil and moisture conditions can significantly affect the impact on freshwater ecotoxicity and particulate matter, and thus this should also be considered regarding open dumping waste.

Open burning, although a common way to reduce waste volume, results in significant challenges, especially in terms of climate change and freshwater ecotoxicity. Open burning releases a range of pollutants, including carbon monoxide (CO), volatile organic compounds (VOCs), and particulate matter, all of which can have serious health effects when inhaled. Open burning also contributes to smog formation and GHG emissions. Despite its harmful impacts, open burning remains prevalent in some regions due to limited waste management infrastructure and a lack of enforcement of environmental regulations.

In contrast, incineration is a more controlled method of waste disposal that involves burning waste at high temperatures in specialized facilities. This process reduces waste volume significantly and generates energy in the form of heat or electricity, which has the potential to be captured (although not discussed in this study). However, while incineration offers some benefits in terms of reducing waste volume and the potential to recover energy, it still presents environmental challenges. The combustion process can release air pollutants depending on the composition of the waste. Modern incinerators are often equipped with pollution control technologies to minimize emissions, but they still require careful regulation and monitoring to avoid negative environmental and health effects. However, in many cases (as described in D4.1), facilities may not be equipped with the proper infrastructure to sufficiently incinerate waste.

Landfills, which involve the burial of waste in designated areas, are one of the most common methods of general waste disposal. They are more controlled than open dumps, yet still pose several environmental risks. Landfills also take up large amounts of land space, and leachate – liquid that percolates through waste – can contaminate surrounding soil and groundwater if not adequately contained. The results of the sensitivity analysis also indicate that landfill conditions may be more harmful to the environment in drier climates.

In general, open burning and incinerating conventional waste such as plastics results in the highest environmental impacts and should be avoided when possible (especially open burning). This may be particularly challenging regarding hazardous waste, such as medical waste produced in field hospital settings. We address this challenge in D1.3. In terms of biowaste, incineration implies a lower impact than open dumping, but this may vary depending on the type of product and its potential for biodegradation. We discuss the limitations of the results on WM in the conclusions section.

5.3. Production vs. end-of-life

In comparison to WM, production is the primary contributor to all environmental impact categories presented in this study – climate change, freshwater ecotoxicity, particulate matter, freshwater eutrophication, fossil resource use, and mineral resource use – across all priority products, with a few exceptions in the case of temporary water bladder. The efficiency and innovative technology used in production (e.g., bio-based materials) can mitigate some of these impacts, but the current scale of production and reliance on non-renewable resources remain critical issues.

On the other hand, WM plays a pivotal role in limiting environmental harm once an item has reached its end-of-life. Proper disposal - or lack thereof – can significantly affect the environment and is also a critical

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component for humanitarian field hospital settings. Improper treatment of waste not only creates environmental impacts at a local level (e.g., pollution of soil and water) but it also poses risks for human health – directly impacting the local community HOs aim to support. Although the role of WM is smaller in comparison to production, both production and WM should work synergistically to minimize environmental impacts. This may include integrating sustainable procurement criteria that consider the full life cycle of the product, as described in D2.1.

5.4. Circularity of bio-based materials

Although not specifically examined in this study, bio-based materials have significant potential for circularity. One of the key advantages of bio-based materials in a circular system is their potential for compostability and biodegradability. Unlike fossil-based plastics that persist in the environment for hundreds of years, bio-based plastics like PLA can break down naturally when exposed to microbial action. This allows for a more sustainable end-of-life solution, where waste can be composted or degraded without leaving harmful residues. Furthermore, bio-based materials, when properly managed, can be reincorporated into the production system as organic matter, contributing to soil health and reducing the need for synthetic fertilizers.

However, achieving full circularity with bio-based materials requires addressing several challenges. The cultivation of raw materials for bio-based products must be managed sustainably to avoid negative environmental impacts, such as deforestation, monoculture farming, or excessive water usage. Additionally, the infrastructure for collecting, sorting, and processing bio-based materials for recycling or composting is not always in place, which can hinder the potential for circularity. For example, while some bio-based plastics are biodegradable, they may require specific conditions to break down, and their recycling or composting systems must be carefully designed to avoid contamination with conventional plastics or other non-biodegradable materials. A more thorough analysis of the potential for bio-based materials within the circular economy is presented in D3.2. Furthermore, in the context of humanitarian field hospital settings, a portion of waste (regardless of if it is bio- or fossil-based) is considered hazardous and may have encountered pathogens or other harmful substances. Therefore, the potential for circularity is dependent on the potential to disinfect hazardous waste before further treatment, as explored in D4.1 and D1.3.

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6. CONCLUSIONS, ASSUMPTIONS AND LIMITATIONS, AND NEXT STEPS

In this report, we use LCA to compare the environmental impacts associated with producing and disposing of eight priority products – facemasks, gloves, surgical gowns, protective boots, syringes and needles, sharps container, body bags, and temporary water/sludge bladder – critical to humanitarian field hospital settings. We also test the potential to reduce the environmental footprint through bio-based materials. During the production phase, the results indicate that bio-based materials have the potential to significantly reduce the overall environmental footprint of a product (especially in terms of climate change and fossil resource use), but there are several trade-offs to consider. Namely, bio-based alternatives (derived from plants, as shown in this study) often result in higher emissions to freshwater ecotoxicity and eutrophication due to the use of synthetic fertilizers and pesticides during the agricultural production phase. Thus, it is important to also consider how the raw materials that comprise bio-based products are produced to reduce the environmental impact in comparison to fossil-based products.

At the end of the life cycle, bio-based products outperform the conventional version (typically plastic) across nearly all WM scenarios. This is mainly due to the significant amounts of emissions (especially in terms of climate change, freshwater ecotoxicity, and particulate matter) resulting from open burning or incinerating waste. Open burning is especially consequential in regard to freshwater ecotoxicity and should be avoided. Incineration may be necessary to treat hazardous waste. However, the resultant emissions associated with incinerating waste implies a need to address alternative methods to treat hazardous waste, as explored in D1.3.

Nonetheless, in comparison to WM, production is typically the top driver for environmental impacts and thus should be a focus area for improvement. Reducing the need use of fossil-based plastics is a major global challenge, due to their large footprint to produce and persistence in the environment after use. Bio-based materials are a promising alternative but require careful attention to the production of the raw materials to result in improvements across several environmental impact categories (i.e., going beyond GHG emissions). This study illustrates the potential for bio-based materials to help tackle this issue and highlights targeted areas for improvement.

6.1. Assumptions and limitations

We aim to model the production and WM phases of the priority products as close to reality as possible. This includes sourcing data directly from manufacturers and peer-reviewed scientific journals, following the standardized steps to conduct and LCA, and testing the model according to recommendations from the LCA standards. However, in some cases, we faced limitations which require attention.

Firstly, we limited this analysis to only a few bio-based alternatives, mostly made of plant-based materials. For the sharps containers, we were able to collect data directly from manufacturers on which bio-based materials were used, however this was not the case for the rest of the products. We were not able to connect with manufacturers of the other bio-based products and thus modelled bio-based materials based on those from the scientific literature. In this case, we verified if the material was a suitable alternative for the conventional version, but the results may change when modelling data directly gathered at the manufacturer. Furthermore, the results for the bio-based materials may also change considered other sources such as microorganisms or waste, which do not require agricultural production (and thus synthetic fertilizers and pesticides as inputs).

The main limitations, however, were encountered when modelling WM. On one side, we could not find a suitable source to model WM methods for the specific bio-based materials (e.g., PLA or polyisoprene). In the Ecoinvent database, there was an option to model WM of biowaste, which represents general

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biological waste that is also biodegradable. While this is true for many bio-based materials, it is not true of all. We assume in this case that the bio-based products are also biodegradable. Thus, the results for WM of biowaste can be seen as a lower bound as a fully biodegradable bio-based product. Furthermore, there was no option to model open burning or landfill of bio-based products due to data limitations. Thus, we do not include those in this study.

6.2. Next steps

While this research provides a comprehensive overview of the production and WM of bio-based vs. conventional products, it highlights several areas for future research and practical implementation. Firstly, there is a need for improved data availability on bio-based materials. This may include further LCA studies into the production of a variety of bio-based materials as well as exploration on how different bio-based materials react to different WM methods. Additionally, there is a need to understand the market for bio-based materials (D1.4), viability of implementing bio-based materials, especially in local contexts (D1.5), and the potential to integrate bio-based materials in humanitarian procurement policies (D2.2). Furthermore, there is an implicit need to explore the potential to reduce the need for incinerating waste. This starts with understanding the common reasons for incineration, but also requires identifying alternative methods to treat hazardous waste, as explored in D4.1. We expand on this research by also conducting LCAs on less/non-destructive methods for hazardous waste in D1.3.

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ANNEX 1

Table 22 LCA results for environmental impacts associated with the production of conventional and bio-based facemasks.

DAMAGE CATEGORY	UNIT	BIO FACEMASK	CONVENT. FACEMASK
Acidification	mol H+ eq	8.33E-05	7.09E-05
Climate change	kg CO2 eq	1.34E-02	1.50E-02
Ecotoxicity, freshwater	CTUe	1.62E-01	1.07E-01
Particulate matter	disease inc.	8.28E-10	8.43E-10
Eutrophication, marine	kg N eq	2.79E-05	1.63E-05
Eutrophication, freshwater	kg P eq	5.15E-06	3.96E-06
Eutrophication, terrestrial	mol N eq	2.45E-04	1.62E-04
Human toxicity, cancer	CTUh	5.15E-11	5.81E-11
Human toxicity, non-cancer	CTUh	9.99E-11	1.28E-10
Ionising radiation	kBq U-235 eq	9.13E-04	8.10E-04
Land use	Pt	3.11E-01	6.28E-02
Ozone depletion	kg CFC11 eq	1.64E-10	2.05E-08
Photochemical ozone formation	kg NMVOC eq	5.86E-05	6.70E-05
Resource use, fossils	MJ	1.57E-01	2.76E-01
Resource use, minerals and metals	kg Sb eq	8.33E-08	1.06E-07
Water use	m3 depriv.	1.43E-02	6.33E-03

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Table 23 LCA results for environmental impacts associated with the waste management of conventional and bio-based facemasks.

DAMAGE CATEGORY	UNIT	BIO-BASED		CONVENTIONAL			
		INCINERATION	OPEN DUMP	INCINERATION	LANDFILL	OPEN BURN	OPEN DUMP
Acidification	mol H+ eq	7.03E-07	1.67E-07	3.98E-06	1.65E-07	2.07E-06	1.42E-07
Climate change	kg CO2 eq	1.21E-04	1.36E-03	4.34E-03	1.70E-03	3.54E-03	1.95E-03
Ecotoxicity, freshwater	CTUe	2.62E-03	1.90E-02	2.20E-03	4.25E-03	2.49E-02	1.34E-02
Particulate matter	disease inc.	7.65E-12	2.88E-13	1.53E-11	3.28E-12	8.21E-12	1.76E-12
Eutrophication, marine	kg N eq	4.01E-07	2.88E-06	2.83E-06	1.66E-06	9.43E-07	1.48E-06
Eutrophication, freshwater	kg P eq	1.28E-07	2.10E-07	2.50E-08	9.94E-08	6.48E-08	1.06E-07
Eutrophication, terrestrial	mol N eq	3.15E-06	4.83E-08	1.99E-05	5.85E-07	9.78E-06	3.14E-07
Human toxicity, cancer	CTUh	9.61E-13	1.81E-14	1.55E-12	7.95E-14	2.32E-12	3.67E-14
Human toxicity, non-cancer	CTUh	8.94E-12	3.07E-12	5.63E-12	3.43E-12	4.93E-11	3.83E-12
Ionising radiation	kBq U-235 eq	1.17E-06	4.82E-08	2.44E-06	7.47E-08	5.85E-07	8.33E-08
Land use	Pt	4.30E-04	2.45E-03	3.60E-04	1.35E-03	2.26E-04	1.88E-03
Ozone depletion	kg CFC11 eq	1.12E-12	2.89E-14	4.22E-12	1.94E-13	5.47E-13	1.20E-13
Photochemical ozone formation	kg NMVOC eq	8.21E-07	5.33E-07	4.88E-06	7.92E-07	7.43E-06	8.25E-07
Resource use, fossils	MJ	7.44E-04	2.63E-05	2.45E-03	1.66E-04	3.71E-04	1.04E-04
Resource use, minerals and metals	kg Sb eq	1.88E-10	4.52E-12	3.97E-10	4.53E-12	9.47E-11	6.65E-12
Water use	m3 depriv.	5.79E-05	-7.22E-06	8.34E-05	3.59E-07	2.92E-05	-7.05E-06

Table 24 LCA results for environmental impacts associated with the production of conventional and bio-based gloves.

DAMAGE CATEGORY	UNIT	BIO GLOVES	COVENT. GLOVES
Acidification	mol H+ eq	2.61E-03	7.65E-04
Climate change	kg CO2 eq	1.14E-01	1.15E-01
Ecotoxicity, freshwater	CTUe	1.75E+00	8.21E-01
Particulate matter	disease inc.	1.26E-08	7.66E-09
Eutrophication, marine	kg N eq	1.02E-03	1.17E-04
Eutrophication, freshwater	kg P eq	2.38E-05	1.45E-05
Eutrophication, terrestrial	mol N eq	1.15E-02	1.27E-03
Human toxicity, cancer	CTUh	1.05E-09	1.07E-09
Human toxicity, non-cancer	CTUh	1.72E-09	1.01E-09
Ionising radiation	kBq U-235 eq	1.80E-03	2.06E-03
Land use	Pt	2.55E+00	3.06E-01
Ozone depletion	kg CFC11 eq	2.39E-09	1.93E-09
Photochemical ozone formation	kg NMVOC eq	2.46E-03	5.08E-04
Resource use, fossils	MJ	1.21E+00	1.57E+00
Resource use, minerals and metals	kg Sb eq	6.99E-07	7.95E-07
Water use	m3 depriv.	-2.06E-02	-5.71E-02

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Table 25 LCA results for environmental impacts associated with the waste management of conventional and bio-based gloves.

DAMAGE CATEGORY	UNIT	**BIO-BASED**		**CONVENTIONAL**			
		INCINERATION	OPEN DUMP	INCINERATION	LANDFILL	OPEN BURN	OPEN DUMP
Acidification	mol H+ eq	1.61E-06	3.96E-07	3.02E-06	2.99E-07	4.45E-05	1.59E-08
Climate change	kg CO2 eq	2.63E-04	3.41E-03	2.04E-02	9.78E-04	1.58E-02	7.11E-04
Ecotoxicity, freshwater	CTUe	6.39E-03	2.81E-02	3.45E-02	2.81E-03	2.19E-01	2.74E-03
Particulate matter	disease inc.	1.84E-11	2.96E-13	1.75E-11	8.06E-12	2.17E-10	1.18E-14
Eutrophication, marine	kg N eq	9.01E-07	7.20E-06	1.17E-06	1.33E-05	2.07E-05	1.32E-05
Eutrophication, freshwater	kg P eq	3.21E-07	5.24E-07	6.44E-08	9.21E-10	x	x
Eutrophication, terrestrial	mol N eq	7.15E-06	3.56E-08	1.27E-05	1.44E-06	2.27E-04	2.30E-09
Human toxicity, cancer	CTUh	2.35E-12	2.41E-14	2.38E-12	1.28E-13	1.50E-10	4.87E-15
Human toxicity, non-cancer	CTUh	2.25E-11	7.22E-12	6.12E-12	2.05E-12	6.47E-10	1.59E-12
Ionising radiation	kBq U-235 eq	2.82E-06	x	6.26E-06	1.85E-07	x	x
Land use	Pt	1.02E-03	6.05E-03	1.12E-03	3.30E-03	x	6.05E-03
Ozone depletion	kg CFC11 eq	2.62E-12	x	5.62E-12	4.82E-13	x	x
Photochemical ozone formation	kg NMVOC eq	1.87E-06	1.31E-06	3.27E-06	7.30E-07	7.92E-05	2.13E-07
Resource use, fossils	MJ	1.75E-03	x	2.80E-03	4.11E-04	x	x
Resource use, minerals and metals	kg Sb eq	4.55E-10	x	9.41E-10	1.12E-11	x	x
Water use	m3 depriv.	1.42E-04	x	6.53E-04	8.92E-07	x	x

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Table 26 LCA results for environmental impacts associated with the production of conventional and bio-based surgical gowns.

DAMAGE CATEGORY	UNIT	BIO GOWNS	COVENT. GOWNS
Acidification	mol H+ eq	5.66E-03	2.44E-03
Climate change	kg CO2 eq	5.73E-01	6.27E-01
Ecotoxicity, freshwater	CTUe	8.37E+00	5.36E+00
Particulate matter	disease inc.	3.67E-08	2.93E-08
Eutrophication, marine	kg N eq	2.29E-03	4.97E-04
Eutrophication, freshwater	kg P eq	2.24E-04	1.52E-04
Eutrophication, terrestrial	mol N eq	2.24E-02	5.20E-03
Human toxicity, cancer	CTUh	1.43E-09	1.68E-09
Human toxicity, non-cancer	CTUh	5.35E-09	4.59E-09
Ionising radiation	kBq U-235 eq	4.13E-02	3.11E-02
Land use	Pt	1.69E+01	1.73E+00
Ozone depletion	kg CFC11 eq	8.38E-09	1.42E-08
Photochemical ozone formation	kg NMVOC eq	4.57E-03	2.57E-03
Resource use, fossils	MJ	6.73E+00	1.36E+01
Resource use, minerals and metals	kg Sb eq	3.53E-06	4.02E-06
Water use	m3 depriv.	7.44E-01	1.61E-01

Table 27 LCA results for environmental impacts associated with the waste management of conventional and bio-based surgical gowns.

DAMAGE CATEGORY	UNIT	**BIO-BASED**		**CONVENTIONAL**			
		INCINERATION	OPEN DUMP	INCINERATION	LANDFILL	OPEN BURN	OPEN DUMP
Acidification	mol H+ eq	3.56E-05	8.73E-06	4.87E-05	6.36E-06	2.36E-04	1.15E-07
Climate change	kg CO2 eq	5.80E-03	7.52E-02	3.77E-01	2.40E-02	3.86E-01	1.75E-02
Ecotoxicity, freshwater	CTUe	1.41E-01	6.20E-01	1.20E-01	1.68E-02	2.74E+00	1.55E-02
Particulate matter	disease inc.	4.05E-10	6.54E-12	2.54E-10	1.78E-10	7.17E-10	8.60E-14
Eutrophication, marine	kg N eq	1.99E-05	1.59E-04	2.33E-05	4.49E-05	1.04E-04	4.20E-05
Eutrophication, freshwater	kg P eq	7.07E-06	1.16E-05	5.61E-07	2.03E-08	x	x
Eutrophication, terrestrial	mol N eq	1.58E-04	7.84E-07	2.47E-04	3.17E-05	1.14E-03	7.35E-09
Human toxicity, cancer	CTUh	5.17E-11	5.31E-13	5.26E-11	2.75E-12	3.72E-10	3.13E-14
Human toxicity, non-cancer	CTUh	4.96E-10	1.59E-10	5.08E-10	4.43E-11	5.49E-09	3.31E-11
Ionising radiation	kBq U-235 eq	6.21E-05	x	4.71E-05	4.09E-06	x	x
Land use	Pt	2.26E-02	1.33E-01	1.06E-02	7.29E-02	x	1.33E-01
Ozone depletion	kg CFC11 eq	5.77E-11	x	5.53E-11	1.06E-11	x	x
Photochemical ozone formation	kg NMVOC eq	4.13E-05	2.88E-05	6.13E-05	1.68E-05	8.36E-04	5.21E-06
Resource use, fossils	MJ	3.86E-02	x	3.82E-02	9.06E-03	x	x
Resource use, minerals and metals	kg Sb eq	1.00E-08	x	8.56E-09	2.48E-10	x	x
Water use	m3 depriv.	3.14E-03	x	2.77E-03	1.97E-05	x	x

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Table 28 LCA results for environmental impacts associated with the production of conventional and bio-based surgical gowns.

DAMAGE CATEGORY	UNIT	BIO BOOTS	COVENT. BOOTS
Acidification	mol H+ eq	7.84E-02	1.78E+00
Climate change	kg CO2 eq	1.64E+01	2.62E+02
Ecotoxicity, freshwater	CTUe	4.01E+02	3.75E+03
Particulate matter	disease inc.	8.37E-07	1.29E-05
Eutrophication, marine	kg N eq	1.54E-02	1.79E+00
Eutrophication, freshwater	kg P eq	4.24E-03	2.89E-02
Eutrophication, terrestrial	mol N eq	1.46E-01	7.66E+00
Human toxicity, cancer	CTUh	1.47E-07	1.80E-06
Human toxicity, non-cancer	CTUh	1.61E-07	3.31E-04
Ionising radiation	kBq U-235 eq	7.16E-01	1.38E+00
Land use	Pt	6.14E+01	6.14E+04
Ozone depletion	kg CFC11 eq	2.92E-07	3.01E-06
Photochemical ozone formation	kg NMVOC eq	5.23E-02	2.65E-01
Resource use, fossils	MJ	2.49E+02	5.01E+02
Resource use, minerals and metals	kg Sb eq	1.35E-04	3.90E-04
Water use	m3 depriv.	6.85E+00	4.69E+01

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Table 29 LCA results for environmental impacts associated with the waste management of conventional and bio-based boots.

DAMAGE CATEGORY	UNIT	BIO-BASED		CONVENTIONAL			
		INCINERATION	OPEN DUMP	INCINERATION	LANDFILL	OPEN BURN	OPEN DUMP
Acidification	mol H+ eq	1.73E-03	4.67E-05	2.10E-03	4.38E-05	3.86E-02	4.44E-04
Climate change	kg CO2 eq	1.93E+00	4.90E-01	2.04E+00	6.39E-01	1.96E+00	5.24E-01
Ecotoxicity, freshwater	CTUe	6.85E+00	3.80E+00	6.86E+00	3.15E+00	3.97E+01	3.31E+00
Particulate matter	disease inc.	7.46E-09	6.80E-11	8.51E-09	5.23E-10	2.67E-07	1.54E-09
Eutrophication, marine	kg N eq	1.30E-03	1.43E-02	1.58E-03	1.41E-02	2.03E-02	1.44E-02
Eutrophication, freshwater	kg P eq	3.51E-05	5.19E-05	3.00E-05	3.98E-05	2.66E-05	4.21E-05
Eutrophication, terrestrial	mol N eq	9.10E-03	6.28E-05	1.10E-02	9.48E-05	2.21E-01	2.09E-03
Human toxicity, cancer	CTUh	8.99E-10	1.09E-11	9.67E-10	1.47E-11	5.11E-08	1.32E-10
Human toxicity, non-cancer	CTUh	7.25E-09	1.06E-09	6.83E-09	1.29E-09	1.01E-07	9.90E-10
Ionising radiation	kBq U-235 eq	1.43E-03	6.60E-06	1.60E-03	1.16E-05	3.59E-04	2.41E-04
Land use	Pt	3.13E-01	1.26E+00	3.18E-01	1.09E+00	7.26E-02	1.15E+00
Ozone depletion	kg CFC11 eq	2.08E-09	1.21E-11	2.44E-09	3.01E-11	5.51E-10	4.41E-10
Photochemical ozone formation	kg NMVOC eq	2.24E-03	1.93E-04	2.70E-03	2.61E-04	5.53E-02	6.59E-04
Resource use, fossils	MJ	1.28E+00	6.79E-03	1.48E+00	2.57E-02	3.21E-01	2.48E-01
Resource use, minerals and metals	kg Sb eq	2.30E-07	1.04E-09	2.57E-07	7.03E-10	5.72E-08	3.81E-08
Water use	m3 depriv.	1.18E-01	2.07E-04	1.22E-01	5.58E-05	1.35E-02	7.55E-03

Table 30 LCA results for environmental impacts associated with the production of conventional and bio-based syringe and needle.

DAMAGE CATEGORY	UNIT	BIO SYRINGE & NEEDLE	CONVENT. SYRINGE & NEEDLE
Acidification	mol H+ eq	1.71E-03	6.01E-04
Climate change	kg CO2 eq	1.42E-01	1.58E-01
Ecotoxicity, freshwater	CTUe	2.06E+00	1.36E+00
Particulate matter	disease inc.	9.76E-09	7.31E-09
Eutrophication, marine	kg N eq	7.14E-04	1.18E-04
Eutrophication, freshwater	kg P eq	5.66E-05	4.12E-05
Eutrophication, terrestrial	mol N eq	7.33E-03	1.22E-03
Human toxicity, cancer	CTUh	3.51E-10	3.99E-10
Human toxicity, non-cancer	CTUh	1.38E-09	1.05E-09
Ionising radiation	kBq U-235 eq	9.87E-03	7.51E-03
Land use	Pt	4.33E+00	5.97E-01
Ozone depletion	kg CFC11 eq	2.42E-09	3.38E-09
Photochemical ozone formation	kg NMVOC eq	1.52E-03	6.09E-04
Resource use, fossils	MJ	1.81E+00	3.35E+00
Resource use, minerals and metals	kg Sb eq	8.62E-07	9.94E-07
Water use	m3 depriv.	4.75E-01	3.43E-01

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Table 31 LCA results for environmental impacts associated with the waste management of conventional and bio-based syringe and needle.

DAMAGE CATEGORY	UNIT	**BIO-BASED**		**CONVENTIONAL**			
		INCINERATION	OPEN DUMP	INCINERATION	LANDFILL	OPEN BURN	OPEN DUMP
Acidification	mol H+ eq	9.50E-06	1.27E-06	1.05E-05	1.59E-06	3.87E-05	7.22E-08
Climate change	kg CO2 eq	1.48E-02	2.38E-02	7.55E-02	9.45E-03	7.70E-02	3.84E-03
Ecotoxicity, freshwater	CTUe	6.00E-02	9.95E-02	2.32E-02	1.56E-02	5.20E-01	3.94E-03
Particulate matter	disease inc.	9.68E-11	1.92E-12	6.16E-11	4.05E-11	1.10E-10	1.03E-12
Eutrophication, marine	kg N eq	5.10E-06	3.20E-05	5.15E-06	1.04E-05	1.69E-05	1.20E-05
Eutrophication, freshwater	kg P eq	1.47E-06	2.33E-06	2.62E-07	3.14E-07	5.92E-08	5.19E-10
Eutrophication, terrestrial	mol N eq	4.36E-05	3.06E-07	5.34E-05	7.23E-06	1.85E-04	1.86E-07
Human toxicity, cancer	CTUh	1.83E-11	6.67E-13	1.26E-11	7.18E-13	4.16E-11	3.60E-14
Human toxicity, non-cancer	CTUh	1.74E-10	5.16E-11	1.24E-10	1.83E-11	9.87E-10	7.35E-12
Ionising radiation	kBq U-235 eq	1.55E-05	9.78E-08	1.02E-05	9.29E-07	1.32E-06	9.78E-08
Land use	Pt	7.13E-03	2.97E-02	3.00E-03	1.66E-02	1.44E-03	2.97E-02
Ozone depletion	kg CFC11 eq	1.55E-11	1.81E-13	1.21E-11	2.42E-12	1.37E-12	1.81E-13
Photochemical ozone formation	kg NMVOC eq	1.14E-05	8.98E-06	1.33E-05	5.36E-06	1.56E-04	1.21E-06
Resource use, fossils	MJ	1.04E-02	1.53E-04	8.62E-03	2.06E-03	1.24E-03	1.53E-04
Resource use, minerals and metals	kg Sb eq	2.40E-09	9.77E-12	1.85E-09	5.64E-11	2.20E-10	9.77E-12
Water use	m3 depriv.	1.19E-03	6.70E-06	5.50E-04	4.47E-06	3.47E-05	6.70E-06

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Table 32 LCA results for environmental impacts associated with the production of conventional and bio-based sharps container.

DAMAGE CATEGORY	UNIT	BIO SHARPS CONTAINER (WOOD)	BIO SHARPS CONTAINER (CARDBOARD)	CONVENT. SHARPS CONTAINER
Acidification	mol H+ eq	1.28E-02	5.70E-04	1.82E-02
Climate change	kg CO2 eq	1.98E+00	1.15E-01	4.85E+00
Ecotoxicity, freshwater	CTUe	3.08E+01	1.05E+00	4.22E+01
Particulate matter	disease inc.	1.05E-07	1.01E-08	2.16E-07
Eutrophication, marine	kg N eq	4.93E-03	1.46E-04	3.58E-03
Eutrophication, freshwater	kg P eq	7.54E-04	5.66E-05	1.26E-03
Eutrophication, terrestrial	mol N eq	4.01E-02	1.31E-03	3.71E-02
Human toxicity, cancer	CTUh	8.14E-09	2.74E-10	1.18E-08
Human toxicity, non-cancer	CTUh	1.57E-08	9.48E-10	3.13E-08
Ionising radiation	kBq U-235 eq	3.79E-01	7.63E-03	2.23E-01
Land use	Pt	6.46E+01	1.95E+00	1.80E+01
Ozone depletion	kg CFC11 eq	2.94E-08	8.32E-09	1.02E-07
Photochemical ozone formation	kg NMVOC eq	8.15E-03	6.29E-04	1.82E-02
Resource use, fossils	MJ	2.71E+01	1.45E+00	9.99E+01
Resource use, minerals and metals	kg Sb eq	1.27E-05	3.15E-07	2.41E-05
Water use	m3 depriv.	3.06E+00	3.44E-02	1.21E+00

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Table 33 LCA results for environmental impacts associated with the waste management of bio-based sharps container (wood and cardboard).

DAMAGE CATEGORY	UNIT	BIO-BASED (WOOD)		BIO-BASED (CARDBOARD)	
		INCINERATION	OPEN DUMP	INCINERATION	OPEN DUMP
Acidification	mol H+ eq	2.54E-04	1.77E-06	9.05E-05	1.38E-05
Climate change	kg CO2 eq	3.27E-01	1.04E-01	2.14E-01	3.53E-01
Ecotoxicity, freshwater	CTUe	1.32E+00	2.87E-01	1.25E+00	1.03E+00
Particulate matter	disease inc.	2.94E-09	1.32E-12	2.67E-08	1.03E-11
Eutrophication, marine	kg N eq	1.37E-04	1.38E-03	1.60E-04	2.66E-04
Eutrophication, freshwater	kg P eq	3.08E-05	3.08E-06	1.53E-06	3.15E-06
Eutrophication, terrestrial	mol N eq	1.20E-03	2.65E-07	4.24E-04	1.42E-06
Human toxicity, cancer	CTUh	4.80E-10	5.47E-13	5.82E-11	2.18E-11
Human toxicity, non-cancer	CTUh	4.34E-09	2.24E-10	8.94E-10	3.20E-09
Ionising radiation	kBq U-235 eq	3.65E-04	x	5.25E-05	x
Land use	Pt	1.53E-01	9.57E-01	9.32E-02	1.76E-01
Ozone depletion	kg CFC11 eq	3.74E-10	x	5.97E-11	x
Photochemical ozone formation	kg NMVOC eq	3.11E-04	3.39E-05	2.01E-04	1.33E-04
Resource use, fossils	MJ	2.56E-01	x	4.50E-02	x
Resource use, minerals and metals	kg Sb eq	5.71E-08	x	9.53E-09	x
Water use	m3 depriv.	2.67E-02	x	2.15E-03	x

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Table 34 LCA results for environmental impacts associated with the waste management of conventional sharps container.

DAMAGE CATEGORY	UNIT	**CONVENTIONAL**			
		INCINERATION	LANDFILL	OPEN BURN	OPEN DUMP
Acidification	mol H+ eq	3.12E-04	4.16E-05	1.27E-03	6.62E-07
Climate change	kg CO2 eq	2.44E+00	1.58E-01	2.55E+00	1.15E-01
Ecotoxicity, freshwater	CTUe	5.44E-01	9.35E-02	1.71E+01	8.46E-02
Particulate matter	disease inc.	1.61E-09	1.16E-09	3.17E-09	4.98E-13
Eutrophication, marine	kg N eq	1.52E-04	2.01E-04	5.52E-04	1.82E-04
Eutrophication, freshwater	kg P eq	3.35E-06	1.33E-07	x	x
Eutrophication, terrestrial	mol N eq	1.60E-03	2.08E-04	6.05E-03	3.19E-08
Human toxicity, cancer	CTUh	3.45E-10	1.80E-11	1.33E-09	1.77E-13
Human toxicity, non-cancer	CTUh	3.47E-09	2.90E-10	3.27E-08	2.16E-10
Ionising radiation	kBq U-235 eq	2.74E-04	2.68E-05	x	x
Land use	Pt	6.44E-02	4.77E-01	x	8.74E-01
Ozone depletion	kg CFC11 eq	3.36E-10	6.96E-11	x	x
Photochemical ozone formation	kg NMVOC eq	3.98E-04	1.11E-04	5.13E-03	3.43E-05
Resource use, fossils	MJ	2.41E-01	5.93E-02	x	x
Resource use, minerals and metals	kg Sb eq	5.15E-08	1.62E-09	x	x
Water use	m3 depriv.	1.38E-02	1.29E-04	x	x

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Table 35 LCA results for environmental impacts associated with the production of conventional body bag.

DAMAGE CATEGORY	UNIT	CONVENT. BODY BAG
Acidification	mol H+ eq	2.51E-02
Climate change	kg CO2 eq	6.76E+00
Ecotoxicity, freshwater	CTUe	4.70E+01
Particulate matter	disease inc.	2.87E-07
Eutrophication, marine	kg N eq	5.08E-03
Eutrophication, freshwater	kg P eq	1.58E-03
Eutrophication, terrestrial	mol N eq	5.18E-02
Human toxicity, cancer	CTUh	1.94E-08
Human toxicity, non-cancer	CTUh	4.76E-08
Ionising radiation	kBq U-235 eq	2.88E-01
Land use	Pt	3.10E+01
Ozone depletion	kg CFC11 eq	1.61E-07
Photochemical ozone formation	kg NMVOC eq	2.84E-02
Resource use, fossils	MJ	1.56E+02
Resource use, minerals and metals	kg Sb eq	4.03E-05
Water use	m3 depriv.	2.99E+00

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Table 36 LCA results for environmental impacts associated with the waste management of conventional body bag.

DAMAGE CATEGORY	UNIT	CONVENTIONAL			
		INCINERATION	LANDFILL	OPEN BURN	OPEN DUMP
Acidification	mol H+ eq	6.86E-04	7.82E-05	2.61E-03	1.48E-06
Climate change	kg CO2 eq	5.39E+00	3.48E-01	5.58E+00	2.55E-01
Ecotoxicity, freshwater	CTUe	1.18E+00	2.04E-01	3.78E+01	1.87E-01
Particulate matter	disease inc.	3.02E-09	2.18E-09	6.95E-09	1.70E-12
Eutrophication, marine	kg N eq	3.35E-04	4.37E-04	1.12E-03	4.02E-04
Eutrophication, freshwater	kg P eq	7.09E-06	2.50E-07	7.77E-09	6.83E-11
Eutrophication, terrestrial	mol N eq	3.53E-03	3.90E-04	1.23E-02	1.77E-07
Human toxicity, cancer	CTUh	6.90E-10	3.38E-11	2.82E-09	4.00E-13
Human toxicity, non-cancer	CTUh	7.65E-09	6.39E-10	7.20E-08	4.78E-10
Ionising radiation	kBq U-235 eq	5.78E-04	5.02E-05	7.86E-07	1.37E-08
Land use	Pt	1.35E-01	8.95E-01	9.66E-05	1.64E+00
Ozone depletion	kg CFC11 eq	7.34E-10	1.30E-10	1.44E-12	3.57E-14
Photochemical ozone formation	kg NMVOC eq	8.73E-04	2.24E-04	9.85E-03	7.59E-05
Resource use, fossils	MJ	5.19E-01	1.11E-01	8.08E-04	3.04E-05
Resource use, minerals and metals	kg Sb eq	1.10E-07	3.04E-09	1.24E-10	8.33E-13
Water use	m3 depriv.	3.00E-02	2.42E-04	2.46E-05	6.61E-08

Table 37 LCA results for environmental impacts associated with the production of conventional temporary water bladder.

DAMAGE CATEGORY	UNIT	CONVENT. TEMPORARY WATER BLADDER
Acidification	mol H+ eq	1.45E+00
Climate change	kg CO2 eq	3.42E+02
Ecotoxicity, freshwater	CTUe	2.62E+03
Particulate matter	disease inc.	1.51E-05
Eutrophication, marine	kg N eq	2.74E-01
Eutrophication, freshwater	kg P eq	9.53E-02
Eutrophication, terrestrial	mol N eq	2.81E+00
Human toxicity, cancer	CTUh	1.32E-06
Human toxicity, non-cancer	CTUh	3.42E-06
Ionising radiation	kBq U-235 eq	1.63E+01
Land use	Pt	9.04E+02
Ozone depletion	kg CFC11 eq	8.72E-05
Photochemical ozone formation	kg NMVOC eq	1.26E+00
Resource use, fossils	MJ	6.44E+03
Resource use, minerals and metals	kg Sb eq	3.29E-03
Water use	m3 depriv.	1.03E+02

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Table 38 LCA results for environmental impacts associated with the waste management of conventional temporary water bladder.

DAMAGE CATEGORY	UNIT	CONVENTIONAL			
		INCINERATION	LANDFILL	OPEN BURN	OPEN DUMP
Acidification	mol H+ eq	1.65E-01	5.05E-03	2.36E-01	2.60E-04
Climate change	kg CO2 eq	2.31E+02	1.37E+01	1.91E+02	9.82E+00
Ecotoxicity, freshwater	CTUe	1.18E+04	3.93E+02	1.93E+03	3.92E+02
Particulate matter	disease inc.	1.48E-06	1.36E-07	8.70E-05	1.96E-10
Eutrophication, marine	kg N eq	4.95E-02	4.16E-02	9.04E-02	3.94E-02
Eutrophication, freshwater	kg P eq	1.03E-02	1.52E-04	8.21E-05	1.36E-04
Eutrophication, terrestrial	mol N eq	4.56E-01	2.43E-02	9.90E-01	1.34E-05
Human toxicity, cancer	CTUh	1.58E-07	2.20E-09	1.58E-04	1.14E-10
Human toxicity, non-cancer	CTUh	1.06E-06	2.82E-08	8.75E-06	2.15E-08
Ionising radiation	kBq U-235 eq	1.42E+00	3.13E-03	x	x
Land use	Pt	1.75E+02	5.59E+01	x	1.02E+02
Ozone depletion	kg CFC11 eq	1.04E-06	8.14E-09	x	x
Photochemical ozone formation	kg NMVOC eq	1.46E-01	1.16E-02	6.67E-01	3.04E-03
Resource use, fossils	MJ	3.64E+02	6.95E+00	x	x
Resource use, minerals and metals	kg Sb eq	1.65E-04	1.90E-07	x	x
Water use	m3 depriv.	1.80E+02	1.51E-02	x	x

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