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Environmental Life Cycle Assessment of Healthcare Waste Valorisation Alternatives

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Abstract **– Infectious healthcare waste (iHCW), after microbial inactivation treatment, primarily ends up in landfills. Although the morphological composition of iHCW depends on the type of health facility, predominantly HCW consists of plastic and textile waste. Furthermore, after the treatment iHCW is cleaner from a microbiological contamination perspective than household waste, making it a highly valuable resource. Recycling iHCW has environmental and economic benefits and by valorising iHCW, it would be possible to reduce the amount of landfilled waste and use it as a resource. The aim of the research is to understand the environmental consequences and potential benefits of treated iHCW valorisation scenarios through the 'gate-to-gate' (from iHCW generation at medical facilities to end-of-life or recovery) life cycle assessment framework and to compare it with the existing practice – landfilling with functional unit 1 ton of treated iHCW and using ReCiPe 2016 (Midpoint, Hierarchist perspective) method. Valorisation scenarios (VS) analysed the use of treated HCW as a substitute of feedstock for reinforced asphalt, reinforced cement, RDF, syngas, acoustic panel and plastic components used for hydroponics. The results of the LCA demonstrate that from the environmental impact perspective, the best scenarios are syngas production (VS4) with cumulative result −11Pt and −237 kg CO_2 eq for global warming impact category and RDF (VS3) with result −5Pt and −195 kg CO_2 eq for global warming impact category, as the entire iHCW flow is recycled into energy. However, when recycling waste, the most valuable product must be created, and then the best results from plastic recycling are plastic components for hydroponics (VS6) with result 50Pt and 1181 kg CO_2 eq for global warming impact category and reinforced asphalt (VS1) with result 53 Pt and 1246 kg CO_2 eq for global warming impact category. From textile recycling acoustic panels (VS5) with result 55 Pt and 598 kg CO_2 eq for global warming impact category and reinforced cement (VS2) with result 55 Pt and 603 kg CO_2 eq for global warming impact category. Therefore, additional scenario was created where plastic, textile and residual iHCW streams are fully recycled and fully eliminating landfilling. The results show that BAU with result 75 Pt and 1509 kg CO_2 eq for global warming impact category has the greatest environmental impact compared to any of the VS considered in this research. Of the total scenario impacts, the largest impact is caused by waste disposal, followed by transport, which has a similar impact in all scenarios due to assumptions about the distance to be transported, and iHCW treatment also has a similar impact in all scenarios, but the bigger difference is the environmental benefit from recycled waste. Based on the LCA results, recommendations for the stakeholders are developed.**

Keywords **– Chemical treatment; damage; environmental impacts; LCA; medical waste; scenarios; thermal treatment.**

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1. Introduction

The healthcare sector contribution to global warming continues to grow and reaching 4–5 % of the total global greenhouse gas (GHG) emissions [1], [2], which makes it comparable to the effect generated by global food industry [2] and aviation sectors [3]. This statement has finally reached policy-makers reaction at the level of COP28 Declaration on Climate and Health [4]. In addition, the healthcare sector is a significant waste producer [5], originating from a variety of single-use and non-recyclable materials – the problem which was plainly presented during COVID-19 pandemics.

More than 80 % healthcare waste (HCW) is not hazardous waste, and approximately 15 % of HCW is classified as hazardous waste [6]. Hazardous HCW can be infectious, toxic or radioactive [7], thus is obliged to be properly managed avoiding impacts linked with its hazardous nature [8], [9]. To ensure microbial inactivation of infectious HCW (hereinafter iHCW) various thermal (autoclaving, incineration, microwaving) and chemical methods are used and requires different resources such as energy, water, chemical compounds [10]. Once iHCW is treated, from microbiological contamination perspective they are cleaner than household waste [11] giving a strong foundation to be recycled and valorised to added-value products.

Waste valorization, the process of giving value to waste materials, increases environmental, economic and social benefits of waste by advancing circular economy and reduction of environmental impact [12]. Currently, landfilling and incineration of HCW, are the most commonly used technologies due to low capital expenses and well-known technological pathways, while recycling of HCW offers environmental and economic benefits [13]. The valorisation of HCW remains underexplored research field so far [14]–[23] and most studies are mostly focusing on energy recovery from HCW. This trend also fair in regard to life cycle assessment (hereinafter LCA) studies on valorization scenarios [24], [25].

To fill this research gap and to guide the decision makers (policy makers, investors, waste management company operators, grant developers, etc.) the current study is developed. The aim of the research is to understand the environmental impacts generated during the iHCW current management strategy and potential environmental benefits of iHCW valorisation scenarios through the "gate-to-gate" (from HCW generation at medical facilities to end-of-life or recovery) life cycle assessment framework.

2. Methodology

This LCA examines the current situation and potential valorization scenarios for treated iHCW. A total of seven scenarios are analysed in this study: the 'business as usual' (BAU) scenario and seven treated iHCW valorization scenarios (VS). The BAU scenario reflects a linear economy approach, where treated iHCW is disposed of in sanitary landfills. Alongside incineration, landfilling remains one of the most widely used methods for managing treated healthcare waste globally [10]. VS1–VS6 (Table 1) represent circular economy approaches where six distinct products are derived from treated iHCW: reinforced asphalt, reinforced cement, RDF, syngas, acoustic panels and plastic components for hydroponics. These products were selected based on factors such as their added-value potential, the maturity of recovery technologies and their industrial symbiosis potential under Latvian conditions. The materials utilized in the product development (plastics, textiles or all iHCW) and their proportions in the final products vary across scenarios as depicted in Table 1.

TABLE 1. VALORISATION SCENARIOS AND iHCW SHARE IN THE PRODUCT

Scenario	Waste hierarchy approach	iHCW share used	iHCW material type used
VS1: reinforced asphalt	Recycling	34 %	Plastics
VS2: reinforced cement	Recycling	31 %	Textile
VS3: RDF	Energy recovery	100 %	All iHCW
VS4: syngas	Energy recovery	100 %	All iHCW
VS5: acoustic panel	Recycling	31 %	Textile
VS6: plastic components used for hydroponics	Recycling	34 %	Plastics
VS7: combination of products	Max. recycling, min. energy recovery	100 %	All iHCW

A substitution approach is applied in all valorization scenarios, where virgin raw materials are replaced with iHCW-recovered materials. These approaches are based on two waste management strategies: recycling and energy recovery. According to the waste management hierarchy [9], recycling is prioritized after waste prevention and reuse, whereas energy recovery is considered a less favourable option, positioned just above landfill disposal. Consequently, energy recovery should be applied only to non-recyclable or hard-to-recycle waste. Treated iHCW is frequently classified as non-recyclable due to processes like soaking and post-shredding. However, modifications to these processes – such as avoiding shredding – and enhanced segregation practices (e.g., sorting waste into specific fractions or materials at the source) can improve alignment with the waste hierarchy, thereby promoting recycling and material recovery. Building on this framework, an additional scenario (VS7) will be developed as an optimized solution. This scenario aims to maximize the use of recycling strategies with the lowest LCA results while incorporating the energy recovery strategy with the lowest LCA impact for the remaining fractions of treated iHCW (e.g., metals, wood, mixed waste and rubber) – see Table 2.

TABLE 2. RECIPE 2016 MIDPOINT INDICATORS USED WITHIN THE CURRENT STUDY [30], [31]

Impact indicator	Abbreviation and unit	Description of indicator	Damage field
Particulate matter	PM, kg PM2.5 eq	Impact of PM2.5 on health, including lung cancer and cardiovascular risks, using global and region-specific factors.	Human health
Ozone formation (hum)	OFHH, kg NO_x eq	Impact of ground-level ozone on human health, particularly respiratory issues, using global and region-specific characterization factors.	Human health
Ionizing radiation	IR, kBq Co-60 eq	Impact of radiation exposure on human health, considering different types of cancers and using time-horizon-specific characterization factors.	Human health
Stratospheric ozone depletion	SOD, kg CFC11 eq	Impact of ozone layer depletion on human health, particularly focusing on risks like skin cancer and cataracts across various time horizons.	Human health

Impact indicator	**Abbreviation and unit**	**Description of indicator**	**Damage field**
Human cancerogenic toxicity	HCT,kg 1,4-DCB	Impact of chemical exposure on cancer risk in humans, using specific characterization factors for different chemicals.	Human health
Human non-cancerogenic toxicity	HNCT, kg 1,4-DCB	Impact of chemical exposure on non-cancer health effects, using specific characterization factors for various substances.	Human health
Global warming	GW, kg CO_2 eq	Impact of greenhouse gas emissions on climate change, expressed as CO_2 equivalents over various time horizons.	Human health Ecosystems
Water consumption	WC, m^3	Impact of water consumption on human health and ecosystems using region-specific characterization factors.	Human health Ecosystems
Freshwater ecotoxicity	FEc, kg 1,4-DCB	Impact of toxic substances on freshwater ecosystems, using characterization factors that reflect the potential harm to aquatic life.	Ecosystems
Freshwater eutrophication	FE, kg P eq	Impact of nutrient enrichment, particularly phosphorus, on freshwater ecosystems, leading to issues like algal blooms and oxygen depletion.	Ecosystems
ozone formation (eco)	OFE, kg NO_x eq	Impact of ground-level ozone on terrestrial ecosystems, focusing on damage to plant life and overall ecosystem health.	Ecosystems
Terrestrial ecotoxicity	TEC, kg 1,4-DCB	Impact of toxic substances on terrestrial ecosystems, using characterization factors to assess potential harm to soil organisms and plant life.	Ecosystems
Terrestrial acidification	TA, kg SO_2 eq	Impact of acidifying emissions, such as SO_2, on soil quality and plant life, leading to potential ecosystem degradation.	Ecosystems
Land use/transformation	LU, m^2 a crop eq	Impact of land occupation and conversion on biodiversity, focusing on species loss and ecosystem disruption.	Ecosystems
Marine ecotoxicity	MEC, kg 1,4-DCB	Impact of toxic substances on marine ecosystems, using characterization factors to assess potential harm to marine life.	Ecosystems
Marine eutrophication	ME, kg N eq	Impact of nutrient enrichment, particularly nitrogen, on marine ecosystems, leading to issues like algal blooms and oxygen depletion.	Ecosystems
Mineral resources scarcity	MRS, kg Cu eq	Impact of mineral extraction on resource scarcity, expressed in terms of increased future extraction costs.	Resource availability
Fossil resources scarcity	FRS, kg oil eq	Impact of fossil fuel extraction on resource scarcity, focusing on the depletion of reserves and increased future extraction costs.	Resource availability

2.1. Goal and Scope

The goal of this environmental LCA is to define the environmental impacts associated with the management of infectious HCW (hereinafter iHCW) under both linear economy conditions (treatment and landfilling) and circular economy conditions (treatment of iHCW and its subsequent use as a raw material for the development of new products).

2.2. Functional Unit

The study considered two functional units: 1 ton of treated iHCW and the annual amount of treated HCW generated in Latvia. 1 ton of treated iHCW is a well-established unit for measuring waste generation, allowing for comparisons across regions. On the other hand, focusing on the annual quantity of treated HCW generated in Latvia is particularly valuable for policymakers and potential investors at the local scale, as it helps assess the availability and management of such resources on a broader, more practical level.

While both functional units were considered in the study, the focus on 1 ton of treated iHCW was particularly relevant given the variability in waste generation over recent years. This variation is reflected in the data summarized below (see Fig. 1).

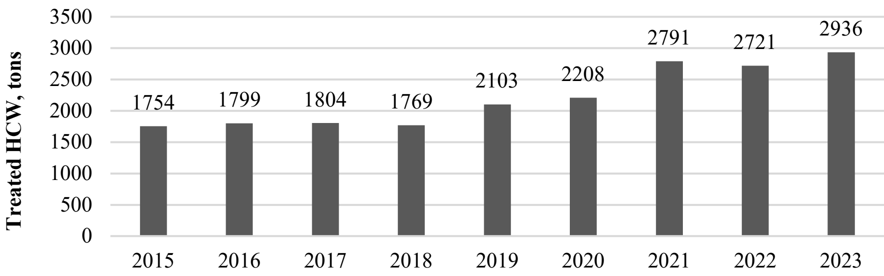

Fig. 1. Annual amount of treated iHCW in Latvia [26].

The data on treated iHCW (180103, 180202, 180207) in Latvia from 2015 to 2022 shows an average of 2209 tons of treated waste per year. Volumes on iHCW have been relatively similar between 2015 and 2019 but have become more variable since the start of the COVID-19 pandemic. All scheduled healthcare services were suspended at the beginning of the pandemic, and therefore there is less treated waste in 2020 than in 2021 and 2022, when planned services were restored. Since iHCW volumes have been so variable in recent years, then in this environmental LCA functional unit (FU) is 1 ton of treated iHCW.

2.3. System Description

The technological system boundaries of the present environmental LCA are ‘gate-to-gate’: from generation of the iHCW in hospitals to end-of-life stage of the iHCW – landfilling or one of the six valorization scenarios (see Fig. 2). The time boundaries of the present LCA are October 2022 – September 2023, a period when the inventory data collection was performed. Geographical boundaries of the LCA cover Latvia.

The definition of the scenarios to be analysed was based on several key considerations. First, the composition of iHCW, which is heterogeneous and varies depending on factors such as seasons, disease outbreaks, location, type of healthcare facility, and the economic and social conditions of a country [27]. Notably, iHCW is predominantly composed of plastic waste (e.g., polypropylene, nylon, polyester), followed by various textiles (e.g., cotton and cellulosic materials) [28]. Second, the mass characterization of iHCW after treatment at iHCW treatment plants was considered. Both technologies involve shredding the treated waste into particles ranging from 13 to 55 mm in size. Third, the presence of symbiotic enterprises in the region – such as energy plants, cement and concrete factories, or asphalt plants – near the iHCW treatment facilities was also considered. A detailed description of the valorization scenarios is provided in the inventory section.

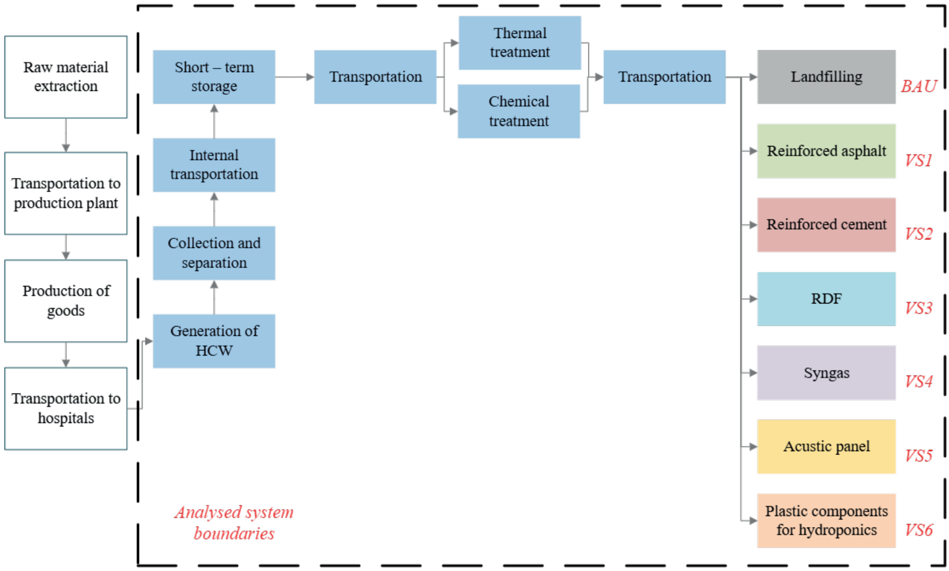

Fig. 2. Technological system boundaries of the analysed scenarios.

2.4. Life Cycle Impact Assessment Method

Life cycle assessment modelling software 'SimaPro' v9.5 [29] was used for the study. ReCiPe 2016 (Midpoint, Hierarchist perspective) was applied as an impact assessment method [30] which includes 18 midpoint indicators (see Table 2) covering three damage fields – damage to human health, damage to ecosystems and damage to resource availability.

The Hierarchist perspective reflects a cultural viewpoint, aiming to achieve consensus while adopting a 100-year timeframe.

2.5. Environmental Life Cycle Inventory

2.5.1. Overall Approach on Data Collection and Limitations

Inventory data required for the survey was collected from Latvian companies involved in the iHCW supply chain, including hospitals, iHCW transportation providers and iHCW treatment companies, as well as a landfill operator. Since none of the analysed valorization scenarios (VS1-VS6) have been implemented in practice, inventory data for the end-of-life stage was sourced from scientific papers (referenced in the corresponding "Results" section) and adjusted to match the analysed supply chain conditions.

In addition, some generalised assumptions are defined:

- The separation of iHCW into fractions (refer to Table 3) is performed at the point of generation, in hospitals, immediately after the product is used. All these fractions are considered infectious and needed to be treated to assure microbial inactivation, as described in Section 2.2.3.

- iHCW is collected from healthcare institutions across Latvia, encompassing both human and veterinary healthcare facilities. While the maximum distance from an iHCW generation point to a treatment plant is 302 km, most healthcare institutions utilizing these services are concentrated within a 60 km radius of the treatment plant. Based on this, the levelized distance from an iHCW generation point to the treatment plant is assumed to be 100 km.
- The valorization scenarios (VS1-VS6) include the transportation of treated iHCW to a production plant. Given the variety of products to be generated from treated iHCW and the varying locations of the associated production sites, a market analysis was conducted to identify the closest feasible options. This analysis prioritized economic considerations, which are a core factor for iHCW treatment companies during the selection process. Consequently, 50 km was established as the assumed distance from the iHCW treatment plant to a production plant.
- Supply chain actors' (hospitals, transportation and treatment companies, landfill management companies) provided data is used as much as possible within the life cycle inventory. However, if no proper qualitative data was able to be submitted by the companies, relevant data was used from 'Ecoinvent' database, specifically related to Latvian parameters. If such data is not available, then data related to RER (Europe) parameters is used. This ensures a hierarchy in data preference, choosing the most relevant and specific information whenever possible.
- Energy (for mechanical separation in fractions) and consumables (additional bins, bags, etc.) used to segregate iHCW streams according to material type are excluded from the inventory. These simplifications are possible because the most proper segregation method for the iHCW is segregation at generation points, i.e. in healthcare facilities, instead of segregation at waste treatment plants or recycling companies.

2.5.2. iHCW Generation at Healthcare Institutions and Transportation

The composition of iHCW generated in healthcare facilities varies and depends on such factors as hospital service profile, segregation practices applied in a specific facility as well as behaviour of medical personnel in the provision of qualitative segregation.

In the current research, a levelized composition of iHCW is utilized for inventory purposes. The compositional data (refer to Table 3) was obtained through experimental testing of mixed iHCW collected from various healthcare institutions across Latvia and delivered to two centralized iHCW treatment facilities in the country. This data was previously reported by Zlaugotne *et al.* [28].

Generated iHCW from healthcare facility rooms is collected in waste bins and subsequently transferred, with both infectious waste and sharps discarded into 1.1 m^3 containers. This mixed iHCW is then transported to treatment plants using specialized trucks owned by iHCW treatment companies. These trucks have a load capacity of 15 tonnes and comply with EURO 6 emission standards, which regulate vehicle emissions by category and engine type.

TABLE 3. LEVELIZED COMPOSITION OF HCW GENERATED IN LATVIAN HEALTHCARE FACILITIES [28]

Fraction	Share in total mass, %
Plastic	34
Cotton	31
Latex, rubber, nitrile	19
Mix of different fraction	12
Aluminium	3
Wood	1

2.5.3. iHCW Treatment

Considering the nature of iHCW, it required to be treated assuring the microbial inactivation reduction of various bacteria, viruses, parasites and other microorganisms present at least at a 6Log10, as well as inactivation of *B. atrophaeus* and *G. stearothermophilus* spores at a 4Log10 reduction or more [32]. In Latvia, treatment of iHCW is provided by two centralised iHCW treatment companies – thermal and chemical treatment companies.

Thermal waste treatment plant uses a thermal treatment technology to treat iHCW from many healthcare facilities in the country (market share based on collected iHCW mass balance is 48 %). The thermal treatment unit is an integrated steam treatment system that uses an inclined horizontal stainless steel pressure vessel with a rotating inner drum containing vanes in the internal surface of the drum. iHCW is piled into 660-litre wheeled red bins. The waste is then loaded into the treatment unit's drum by means of an automatic loader. After the iHCW is introduced into the drum and the vessel door is sealed, a steam jet ejector system is used to pull a vacuum after which steam is introduced to treat the waste. The system is computer controlled. During the treatment process (at proper temperature (up to 132 °C) and pressure levels, the inner drum rotates causing bags and containers to be ruptured and their contents mixed inside the vessel. After a sufficient steam exposure time (from 30 to 60 minutes based on the amount of waste treated), a post-treatment vacuum cycle removes the steam and reduces the moisture content. The vessel door is then opened, and the treated waste is then ejected onto a conveyor which brings the waste into the hopper of a heavy-duty shredder. The finely shredded treated waste (microbial inactivation efficiency of the treatment unit is tested regularly) is then ejected into another series of conveyors into a compactor and roll-off container.

The chemical iHCW treatment plant utilizes a technology that uses ClO_2 to treat iHCW (their market share based on the treated iHCW amount is 52 %). iHCW containers (660 litres) are first lifted and their contents deposited into a hopper. Once waste is dropped into the hopper, shredding of material occurs. During the shredding process, air from the hopper is extracted through a HEPA filtration process. A four-shafted shredder reduces the waste to small particles. This particalized waste falls into a chamber below the shredder which contains a liquid solution of ClO_2 (cold water and ClO_2). A probe monitors the ClO_2 concentration. The entire treatment process is monitored by a control panel that provides the operator with the ClO_2 concentrations as well as a video of the interior of the hopper. If more ClO_2 is required, staff inject the chemical until acceptable levels are reached. After the treatment process (15–25 minutes long) the treated waste is conveyed from this chamber via a screw conveyor to be discharged into a collection bin. The treated waste (microbial inactivation efficiency of the treatment unit is tested regularly) has a moisture content of approximately 50–60 %. As a result, it is stored in specialized containers for several hours to reduce the moisture level to 40–42 % through the passive deliquification process.

Lastly, in both companies, the treated iHCW is transported to the ‘end-of-life’ or recovery site via specialised iHCW treatment companies’ owned trucks (load capacity – 15 tonnes, EURO 6 (emission limits by vehicle category and engine type)).

Considering the shared market of the iHCW treatment activities between two iHCW treatment companies and the selected FU, the mass allocation (52 %:48 %) is performed to demonstrate the proper HCW treatment conditions in Latvia.

2.5.4. *iHCW end-of-life*

The conventional method for managing treated HCW in Latvia is landfilling, which is also applicable to the BAU scenario. The BAU scenario inventory for both Latvian companies managing iHCW is presented in Table 4.

TABLE 4. LIFE CYCLE INVENTORY FOR BAU SCENARIO

Parameter	Unit	Value
Thermal iHCW treatment		
iHCW subjected to chemical treatment	t	0.48
Water	m^3	0.4
Electricity	kWh	0.07
Gas	t	0.02
Transport	tkm	100
Waste scenario – landfill	%	100
Chemical iHCW treatment		
iHCW subjected to chemical treatment	t	0.52
Sodium chloride	t	0.0001
Sodium thiosulfate	t	0.00002
Water	m^3	0.9
Electricity	kWh	18.5
Transport	tkm	100
Waste scenario – landfill	%	100

While the processes of iHCW generation, transportation, treatment, and the transportation of treated iHCW to the end-of-life point are consistent across all analysed scenarios, the end-of-life outcomes for the treated waste varies between the scenarios, as detailed in the description of each scenario below.

<u>*VS1: Feedstock for reinforced asphalt*</u>

Treated iHCW is transported to an asphalt production plant. In the production of asphalt, the raw materials are natural aggregates (gravel), aggregates and asphalt binding agent (bitumen), and after crushing and grinding the raw materials, the asphalt mixture is produced [33]. Different research has examined the use of various plastics in the production of asphalt, the most popular plastics being high-density polyethylene (HDPE), low-density polyethylene (LDPE), polypropylene (PP), polyethylene terephthalate (PET), ethylene-vinyl acetate (EVA), polyvinyl chloride (PVC), polyethylene (PE) and polyethylene terephthalate (PTP)) [34]. Research shows that adding plastic waste improves the strength and stiffness of asphalt, but it is important to understand the morphology of plastic waste because it affects the asphalt production method (dry or wet method) and the performance of the resulting asphalt mixture) [34]. In the research different percentage values are mentioned for the addition of plastic waste to asphalt mixture – 5.7 % of the total asphalt weight [35], 6 % of the bitumen weight [36], [37] and 6.5 % of the bitumen weight [38]. In this scenario, it will be used that 6 % of bitumen is replaced by plastic waste from the treated iHCW, while other iHCW fractions are landfilled. In Table 5 the inventory for VS1 is summarised.

TABLE 5. LIFE CYCLE INVENTORY FOR VS1

Parameter	**Unit**	**Value**
Treatment (chemical: thermal = 52:48) of iHCW[1]	t	1
Transport (healthcare facility – treatment plant – production plant – landfill)	tkm	200
iHCW to recovered product	t	0.34
Substitution of bitumen	t	0.0009
iHCW to be landfilled	t	0.66

[1]inventory of treatment process is given in Table 4

VS2: Feedstock for reinforced cement

Treated iHCW is transported to a concrete production plant, where raw materials such as cement, water, aggregates (sand, gravel, crushed stone and additives) are used [20], [21]. Waste materials, including glass, polypropylene, carbon, polyester and textile fibres, can be incorporated into concrete as reinforcement agents [22]. In VS2, it is assumed that treated iHCW textile waste will partially replace the sand used in concrete, with the previous research [23] noting that replacing 20 % of sand with textile waste yields optimal results. The remaining iHCW fractions are landfilled. The inventory for the value-added product, reinforced concrete, is provided in Table 6.

TABLE 6. LIFE CYCLE INVENTORY FOR VS2

Parameter	**Unit**	**Value**
Treatment (chemical: thermal = 52:48) of iHCW[1]	t	1
Transport (healthcare facility – treatment plant – production plant – landfill)	tkm	200
iHCW to recovered product	t	0.31
Substitution of sand	t	0.02
iHCW to be landfilled	t	0.69

[1]inventory of treatment process is given in Table 4

VS3: Feedstock for RDF

Treated iHCW is transported to an energy generation plant from refuse derived fuel (RDF) generated from treated iHCW. RDF is a specific type of alternative fuel with a high calorific value (on average 16–18 MJ/kg) and uniform particle size [39]. RDF is obtained from non-hazardous waste and is most often composed of 10–75 % high- and low-density plastic waste, 12–85 % paper and cardboard waste, 5–66 % textile waste, 5–30 % organic waste and up to 10 % non-combustible fraction waste [40]. To recover the valuable material, partially homogenize and eliminate water, CO_2 and the non-combustible fraction from waste, the waste are mechanically (crushing, sorting, drying, shredding) or biologically (mechanical treatment with additional biostabilization and biodrying) processed [40]. Within VS3 all treated iHCW is used to produce RDF and replaces natural gas used for heat production. Inventory for VS3 is given in Table 7.

TABLE 7. LIFE CYCLE INVENTORY VS3

Parameter	Unit	Value
Treatment (chemical: thermal = 52:48) of iHCW[1]	t	1
Transport (healthcare facility – treatment plant – production plant)	tkm	150
iHCW to recovered product	t	1
Substitution of heat	MWh	1

[1]inventory of treatment process is given in Table 4

VS4: Feedstock for syngas production

Treated iHCW is transported to a syngas production plant. Syngas can be produced from various carbon sources – fossil fuel (coal gasification, natural gas, oil), but it is also possible to use waste gasification to obtain syngas [41]. Gasification is a process when insignificant materials (including waste) are converted into gaseous products with usable heat capacity and after purification processes, syngas can be used as an alternative fuel to produce thermal energy and electricity [42]. All treated iHCW will be used to produce syngas, which will then be used to generate electricity, and it will replace electricity from the grid. VS4 inventory is in Table 8, value added product produced syngas from the treated iHCW.

TABLE 8. LIFE CYCLE INVENTORY FOR VS4

Parameter	Unit	Value
Treatment (chemical : thermal = 52 % : 48 %) of iHCW[1]	t	1
Transport (healthcare facility – treatment plant – production plant)	tkm	150
iHCW to recovered product	t	1
Substitution of electricity	MWh	0.64

[1]inventory of treatment process is given in Table 4

VS5: Feedstock for acoustic panel

Treated iHCW is transported to an acoustic panel production plant. Sound absorption panels (or acoustic panels) are made from porous synthetic materials such as stone wool, glass wool, polyurethane, polyester and others [43]. The use of waste in the production of sound-absorbing panels is a possible alternative, as they can have good acoustic properties and are like traditionally used materials [43]. It is concluded that the recycled textile waste has good acoustic properties to be used in the production of panels [44]. Research on thermal and acoustic panels from recycled materials, where the main raw materials are wastepaper and textile waste [45]. To produce 1 m^2 of insulation panel, a total of 5.2 kg of raw materials are required – 3.4 kg of wastepaper and 0.4 kg of textile waste, as well as 1.4 kg of glue [45]. All textile waste from the treated iHCW is used to produce acoustic panels, others iHCW fractions are landfilled. Value added product produced acoustic panel from the treated iHCW and inventory data is in Table 9.

TABLE 9. LIFE CYCLE INVENTORY FOR VS5

Parameter	Unit	Value
Treatment (chemical : thermal = 52 % : 48 %) of iHCW[1]	t	1
Transport (healthcare facility – treatment plant – production plant – landfill)	tkm	200
iHCW to recovered product	t	0.31
Substitution of foam glass	t	0.0084
iHCW to be landfilled	t	0.69

[1]inventory of treatment process is given in Table 4

VS6: Feedstock for plastic components in hydroponics

Treated iHCW is transported to hydroponic systems production plant. Hydroponics and aquaponics are closed environments where plant crops and/or aquatic animals are grown under optimized conditions using soilless systems [46]. A vertical farm system combines hydroponics, aeroponics or aquaponics systems [47]. The technological infrastructure of these systems uses many different plastic products, such as different types of containers and connecting tubes [47]. Plastic waste from iHCW can thus be recycled into various plastic products [48]. Plastic products that would be suitable for a vertical farm are various garden items such as growing containers, water system pipes and others. In this scenario, plastic waste from the treated iHCW is replaced by plastic pellets, while remaining iHCW fractions are landfilled. VS6 inventory data is in provided Table 10.

TABLE 10. LIFE CYCLE INVENTORY FOR VS6

Parameter	Unit	Value
Treatment (chemical : thermal = 52 % : 48 %) of iHCW[1]	t	1
Transport (healthcare facility – treatment plant – production plant – landfill)	tkm	200
iHCW to recovered product	t	0.34
Substitution of plastic	t	0.34
iHCW to be landfilled	t	0.66

[1]inventory of treatment process is given in Table 4

3. RESULTS

3.1. Life Cycle Impact Assessment Results

Table 11 shows the results of the life cycle impact assessment using ReCiPe 2016 Midpoint (H) method, where the scenario results indicated in numbers (a positive result indicates that the system influences the given environmental indicator, while a negative result signifies an avoided impact, thereby providing an environmental benefit). The results also are marked with colours on a scale from very low environmental impact (bright green) to very high environmental impact (orange).

As seen from Table 11, the environmental impacts in VS3 and VS4 are entirely negative due to the high share of iHCW being recycled rather than landfilled.

TABLE 11. RECIPE 2016 MIDPOINT (H) RESULTS FOR BAU AND VS1–VS6

	BAU	VS1	VS2	VS3	VS4	VS5	VS6
GW, kg CO_2 eq	1.51E+03	1.25E+03	6.03E+02	−1.95E+02	−2.37E+02	5.98E+02	1.18E+03
SOD, kg CFC11 eq	8.08E−05	8.21E−05	8.89E−05	−2.14E−05	−1.87E−04	8.73E−05	6.02E−05
IR, kBq Co-60 eq	2.77E+00	2.66E+00	2.93E+00	−7.60E−01	−4.33E+01	2.58E+00	1.45E+00
OFHH, kg NO_x eq	2.98E−01	1.96E−01	2.19E−01	−1.65E−01	−5.39E−01	2.07E−01	3.11E−02
PM, kg PM2.5 eq	8.76E−02	7.02E−02	7.71E−02	−2.80E−02	−2.89E−01	6.96E−02	−4.53E−02
OFT, kg NO_x eq	3.13E−01	2.11E−01	2.37E−01	−1.88E−01	−5.71E−01	2.24E−01	4.18E−02
TA, kg SO_2 eq	1.91E−01	1.49E−01	1.64E−01	−7.37E−02	−5.68E−01	1.51E−01	−2.22E−02
FE, kg P eq	9.86E+00	4.62E+00	6.56E+00	−3.33E−03	−4.94E−02	6.55E+00	4.57E+00
ME, kg N eq	2.06E+00	6.10E−01	1.81E+00	−2.35E−03	−5.31E−03	1.80E+00	6.06E−01
TEC, kg 1,4-DCB	9.98E+02	1.20E+03	1.30E+03	−4.02E+02	−3.82E+03	1.27E+03	9.56E+02
FE_C, kg 1,4-DCB	5.18E+02	3.58E+02	4.59E+02	−4.49E−01	−6.52E+00	4.59E+02	3.51E+02
MEC, kg 1,4-DCB	6.87E+02	4.73E+02	6.12E+02	−1.16E+00	−1.20E+01	6.12E+02	4.63E+02
HCT, kg 1,4-DCB	2.04E+01	1.89E+01	2.17E+01	−8.87E+00	−3.23E+01	2.10E+01	1.10E+01
HNCT, kg 1,4-DCB	1.23E+04	8.07E+03	1.12E+04	−2.50E+00	−1.22E+02	1.12E+04	7.97E+03
LU, m^2a crop eq	5.72E+00	4.81E+00	4.70E+00	−2.56E−01	−2.52E+01	4.48E+00	3.68E+00
MRS, kg Cu eq	1.50E−01	1.57E−01	1.79E−01	−1.05E−01	−4.58E−01	1.62E−01	5.76E−02
FRS, kg oil eq	2.09E+01	2.09E+01	2.43E+01	−7.43E+01	−7.48E+01	2.29E+01	6.74E+00
WC, m^3	−5.67E+00	−3.11E+00	−6.07E+00	−1.58E−01	−2.06E+00	−6.09E+00	−3.35E+00

Colour scale	Very low	Low	High	Very high

Overall, the lower environmental impact results were achieved in the VSs, where the entire iHCW stream was recycled for energy recovery (VS3 and VS4), but this does not properly align with the circularity principles where the focus needs to be given on re-use, recycling and recovery. To keep the focus on circularity, VS7 was created: it represents an integrated recycling and energy recovery process – plastic and textile fractions of iHCW are recycled, the remaining fraction (rubber, metals, wood and mix of fines), which cannot be yet recycled to any of the analysed recycling scenario, is transferred to energy recovery. Based on the LCA results (see Table 11), this includes plastics recovery via VS5, textiles recovery via VS7 and the remaining treated iHCW directed to syngas production through VS4. The impact of transportation is similar in all considered scenarios (from 0.4 Pt to 1.5 Pt) due to the distance assumptions made, and the impact of the iHCW treatment process as well as – being in the range from 0.29 Pt to 0.44 Pt.

For better representation of BAU and VS results, Fig. 3 provides the results in single score manner and the values are expressed in EcoPoints (Pt). The single-point results are formed from three main groups: iHCW treatment, transportation and end-of-life. As can be seen, the greatest impact is caused by landfilling iHCW, while the impact of transport and iHCW treatment has similar Pt values in all scenarios.

Fig. 3. Single score results for BAU and VS1–VS7 (ReCiPe 2016 Midpoint (H)) method.

4. DISCUSSION AND CONCLUSIONS

The annual generated amount of treated iHCW in Latvia accounting for close to 3000 tonnes and comprising such fractions as textiles, plastics, metals, wood and other. Despite the high microbiological cleanness and relatively stable annual quantities of treated iHCW, the recovery of it to new materials and products is still underdeveloped nationally and regionally. To guide the potential waste management companies, investors and policymakers in this direction, along the economic benefits, the environmental benefits need to be highlighted particularly considering the EU circular economy and decarbonization targets. This study provided the LCA based ('gate-to-gate' analysis) comparison of end-of-life stages between one BAU scenario (landfilling) and seven VSs for the iHCW generated in Latvian healthcare sector.

The results of the LCA specifies the following recommendations:

- Landfilling of treated iHCW should be minimized as much as possible as it creates a double-negative effect: spending (1) resources and generating environmental impacts related to iHCW microbial inactivation and (2) afterwards again generating environmental impacts through landfilling of treated iHCW.
- The analysis of VSs with varying proportions of iHCW integrated into the production of new products shows that valorizing the majority of the treated iHCW fractions is advantageous.
- While energy recovery valorization strategies properly ensure recovery of all treated iHCW fractions and, as indicated in the results of the study, can even generate the negative environmental impact, this approach does not fully align with the core objective of the EU circular economy framework – recovering the waste into materials rather than energy. From the business perspective, the energy recovery from treated iHCW may become risky in long-term due to future stricter EU regulations in circular economy field. When generating a VS, along the environmental performance results, a special attention should be also put on generation of high-added value products.

– Following the circular economy targets, the healthcare sector is also starting to be oriented on even the higher concepts of waste hierarchy beyond recovery, i.e. waste minimisation and re-use. This shift has been properly addressed by leading healthcare organisation, such as, for example, World Health Organisation and Health Care without Harm [49]–[52] implementing strategies for effective waste separation at source, monitoring waste volumes, integrating sustainability of products and services into procurement processes, reduce unnecessary use of medical consumables, replacing single use materials with reusable ones, and others. These strategies effectively reduce the environmental impacts from the HCW sector. While, from the business perspective, this also eliminates the amount of potential waste recovered resources for entrepreneurs. Therefore, when planning the HCW-derived businesses, high level of flexibility in regards to alternative feedstocks, aside HCW, should be integrated to ensure long-term economical viability.

As far as for recommendations to the future research, the authors recommend to extend the next LCA to broader system boundaries – as a minimum 'gate to grave' and as a best – 'cradle to grave'. This broader perspective would encompass additional life cycle stages and potentially reveal different insights about the environmental benefits and burdens of iHCW valorisation.

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References

[1] Janik-Karpinska E. *et al.* Healthcare Waste – A Serious Problem for Global Health. *Healthcare* 2023:11(2):242. https://doi.org/10.3390/healthcare11020242

[2] Pichler P. P., Jaccard I. S., Weisz U., Weisz H. International comparison of health care carbon footprints. *Environmental Research Letters* 2019:14(6). https://doi.org/10.1088/1748-9326/ab19e1

[3] Dutchen S. Confronting Health Care's Carbon Footprint. 2023. [Online]. [Accessed 16.01.2025]. Available: https://magazine.hms.harvard.edu/articles/confronting-health-cares-carbon-footprint

[4] Abbasi K. *et al.* COP28 climate change conference: time to treat the climate and nature crisis as one indivisible global health emergency. *Vet Anaesth Analg* 2024:51(2):e1–e4. https://doi.org/10.1016/j.vaa.2023.11.006

[5] Mol M. P. G. *et al.* Healthcare waste generation in hospitals per continent: a systematic review. *Environmental Science and Pollution Research* 2022:29(28):42466–42475. https://doi.org/10.1007/s11356-022-19995-1

[6] Bannour R. *et al*. Impact of an educational training about healthcare waste management on practices skills of healthcare workers: a prexperimental study in a tertiary Tunisian hospital. *Antimicrob Resist Infect Control* 2024:13(1):122. https://doi.org/10.1186/s13756-024-01446-w

[7] Kenny C., Priyadarshini A. Review of current healthcare waste management methods and their effect on global health. *Healthcare* 2021:9(3):284. https://doi.org/10.3390/healthcare9030284

[8] European Parliament. Directive 1999/31/EC on the landfill of waste. *Official Journal of the European Union* 1999/31: L 182.

[9] European Parliament. Directive 2008/98/EC on waste and repealing certain Directives. *Official Journal of the European Union* 2008: L 312/3.

[10] Zikhathile T., Atagana H., Bwapwa J., Sawtell D. A Review of the Impact That Healthcare Risk Waste Treatment Technologies Have on the Environment. *Int J Environ Res Public Health* 2022:19(19). https://doi.org/10.3390/ijerph191911967

[11] United Nations Environment Programme. Compendium of Technologies for the Treatment/Destruction of Healthcare Waste. 2012. [Online]. [Accessed 11.12.2023]. Available: https://wedocs.unep.org/20.500.11822/8628

[12] Wang X. *et al.* Emerging waste valorisation techniques to moderate the hazardous impacts, and their path towards sustainability. *J Hazard Mater* 2022:423:127023. https://doi.org/10.1016/j.jhazmat.2021.127023

[13] Mushtaq M. H. *et al.* Environmental Performance of Alternative Hospital Waste Management Strategies Using Life Cycle Assessment (LCA) Approach. *Sustainability* 2022:14(22). https://doi.org/10.3390/su142214942
[14] Haque M. A. *et al.* Sustainable management and valorization of antibiotic waste. *Chemical Engineering Journal* 2024:498:155372. https://doi.org/10.1016/j.cej.2024.155372
[15] Zhou J., Ayub Y., Shi T., Ren J., He C. Sustainable co-valorization of medical waste and biomass waste: Innovative process design, optimization and assessment. *Energy* 2024:288:129803. https://doi.org/10.1016/j.energy.2023.129803
[16] Chu Y. T., Zhou J., Ren J., Shen W., He C. Conversion of medical waste into value-added products using a novel integrated system with tail gas treatment: Process design, optimization, and thermodynamic analysis. *J Hazard Mater* 2023:455:131551. https://doi.org/10.1016/j.jhazmat.2023.131551
[17] Zhao X., You F. Waste respirator processing system for public health protection and climate change mitigation under COVID-19 pandemic: Novel process design and energy, environmental, and techno-economic perspectives. *Applied Energy* 2021:283:116129. https://doi.org/10.1016/j.apenergy.2020.116129
[18] Su G., Ong H. C., Ibrahim S., Fattah I. M. R., Mofijur M., Chong C. T. Valorisation of medical waste through pyrolysis for a cleaner environment: Progress and challenges. *Environmental Pollution* 2021:279:116934. https://doi.org/10.1016/j.envpol.2021.116934
[19] Chu Y. T., Zhou J., Wang Y., Liu Y., Ren J. Current State, Development and Future Directions of Medical Waste Valorization. *Energies* 2023:16(3). https://doi.org/10.3390/en16031074
[20] Chu Y. T., Moktadir M. A., Ren J. Constructing an environmental, social, and governance (ESG) metrics framework for assessing medical waste valorization alternatives: A novel integrated MCDM model under decomposed fuzzy environment. *J Environ Manage* 2025:373:123457. https://doi.org/10.1016/j.jenvman.2024.123457
[21] Asim N., Badiei M., Sopian K. Review of the valorization options for the proper disposal of face masks during the COVID-19 pandemic. *Environ Technol Innov* 2021:23:101797. https://doi.org/10.1016/j.eti.2021.101797
[22] Mushtaq M. H. *et al.* Environmental Performance of Alternative Hospital Waste Management Strategies Using Life Cycle Assessment (LCA) Approach. *Sustainability* 2022:14(22):14942. https://doi.org/10.3390/su142214942
[23] Rachmawati S., Syafrudin, Budiyono, Chairani E., Suryadi I. Life cycle analysis and environmental cost-benefit assessment of utilizing hospital medical waste into heavy metal safe paving blocks. *AIMS Environ Sci* 2024:11(5):665–681. https://doi.org/10.3934/environsci.2024033
[24] Nematollahi H., Ghasemzadeh R., Tuysserkani M., Aziminezhad M., Pazoki M. Comparative life cycle assessment of hospital waste management scenarios in Isfahan, Iran: Evaluating environmental impacts and strategies for improved healthcare sustainability. *Results in Engineering* 2024:24:102912. https://doi.org/10.1016/j.rineng.2024.102912
[25] Ün Ç. Examining the environmental and economic dimensions of producing fuel from medical waste plastics. *Nigde Omer Halisdemir University Journal of Engineering Sciences* 2024:13(1):279–293. https://doi.org/10.28948/ngumuh.1367080
[26] Latvian Center for Environment, Geology and Meteorology. Public access to the State Environmental Protection Statistical Reports '2-Air', '2-Water' and '3-Waste.' [Online]. [Accessed 10.12.2024]. Available: https://parissrv.lvgmc.lv/#viewType=home_view
[27] Su G., Ong H. C., Ibrahim S., Fattah I. M. R., Mofijur M., Chong C. T. Valorisation of medical waste through pyrolysis for a cleaner environment: Progress and challenges. *Environmental Pollution* 2021:279:116934. https://doi.org/10.1016/j.envpol.2021.116934
[28] Zlaugotne B., Pubule J., Gusca J., Kalnins S. N. Quantitative and qualitative assessment of healthcare waste and resource potential assessment. *Environmental and Climate Technologies* 2022:26(1):64–74. https://doi.org/10.2478/rtuect-2022-0006
[29] Goedkoop M., Oele M., Leijting J., Ponsioen T., Meijer E. Introduction to LCA with SimaPro. January, 2016.
[30] Huijbregts M. A. J. *et al.* ReCiPe2016: a harmonised life cycle impact assessment method at midpoint and endpoint level. *Int J Life Cycle Assess* 2017:22(2):138–147. https://doi.org/10.1007/s11367-016-1246-y
[31] Romagnoli F. *et al. Furcellaria lumbricalis* macroalgae cascade biorefinery: a Life Cycle Assessment study in the Baltic Sea Region. *J Clean Prod* 2024:478:143861. https://doi.org/10.1016/j.jclepro.2024.143861
[32] International Society of Analytical Assessment of Treatment Technologies. State and Territorial Association on Alternative Treatment Technologies (STAATT) III. 2005. [Online]. [Accessed 10.12.2024]. Available: https://www.istaatt.org/index.php?option=com_docman&task=doc_download&gid=5&Itemid=2
[33] Yue Y., Abdelsalam M., Khater A., Ghazy M. A comparative life cycle assessment of asphalt mixtures modified with a novel composite of diatomite powder and lignin fiber. *Constr Build Mater* 2022:323:126608. https://doi.org/10.1016/j.conbuildmat.2022.126608
[34] Heydari S., Hajimohammadi A., Haji Seyed Javadi N., Khalili N. The use of plastic waste in asphalt: A critical review on asphalt mix design and Marshall properties. *Constr Build Mater* 2021:309:125185. https://doi.org/10.1016/j.conbuildmat.2021.125185
[35] Machsus M., Chen J. H., Hayati D. W., Khoiri M., Mawardi A. F., Basuki R. Improvement for asphalt mixture performance using plastic bottle waste. *International Journal of GEOMATE* 2021:20(79):139–146. https://doi.org/10.21660/2021.79.j2035

[36] Kovács R., Lukáčová E., Czímerová A., Csölle M., Mandula J. Use of Recycled Polyethylene in Asphalt Mixture. *Selected Scientific Papers – Journal of Civil Engineering* 2023:18(1). https://doi.org/10.2478/sspjce-2023-0001

[37] Ahmadinia E., Zargar M., Karim M. R., Abdelaziz M., Shafigh P. Using waste plastic bottles as additive for stone mastic asphalt. *Mater Des* 2011:32(10):4844–4849. https://doi.org/10.1016/j.matdes.2011.06.016

[38] Genet M. B., Sendekie Z. B., Jembere A. L. Investigation and optimization of waste LDPE plastic as a modifier of asphalt mix for highway asphalt: Case of Ethiopian roads. *Case Studies in Chemical and Environmental Engineering* 2021:4:100150. https://doi.org/10.1016/j.cscee.2021.100150

[39] Rajca P. *et al.* Technological and economic aspect of Refuse Derived Fuel pyrolysis. *Renewable Energy* 2020:161:482–494. https://doi.org/10.1016/j.renene.2020.07.104

[40] García R., González-Vázquez M. P., Rubiera F., Pevida C., Gil M. V. Co-pelletization of pine sawdust and refused derived fuel (RDF) to high-quality waste-derived pellets. *J Clean Prod* 2021:328:129635. https://doi.org/10.1016/j.jclepro.2021.129635

[41] Centi G., Perathoner S. Chemistry and energy beyond fossil fuels. A perspective view on the role of syngas from waste sources. *Catalysis Today* 2020:342:4–12. https://doi.org/10.1016/j.cattod.2019.04.003

[42] Segneri V., Ferrasse J. H., Trinca A., Vilardi G. An Overview of Waste Gasification and Syngas Upgrading Processes. *Energies* 2022:15(17):6391. https://doi.org/10.3390/en15176391

[43] Buratti C., Belloni E., Lascaro E., Lopez G. A., Ricciardi P. Sustainable Panels with Recycled Materials for Building Applications: Environmental and Acoustic Characterization. *Energy Procedia* 2016:101:972–979. https://doi.org/10.1016/j.egypro.2016.11.123

[44] Badida M. *et al.* Analysis and Research on the Use of Bulk Recycled Materials for Sound Insulation Applications. *Sustainability* 2022:14(18). https://doi.org/10.3390/su141811539

[45] Ricciardi P., Belloni E., Cotana F. Innovative panels with recycled materials: Thermal and acoustic performance and Life Cycle Assessment. *Applied Energy* 2014:134:150–162. https://doi.org/10.1016/j.apenergy.2014.07.112

[46] Chen P., Zhu G., Kim H.-J., Brown P. B., Huang J.-Y. Comparative life cycle assessment of aquaponics and hydroponics in the Midwestern United States. *J Clean Prod* 2020:275:122888. https://doi.org/10.1016/j.jclepro.2020.122888

[47] Parkes M. G., Cubillos J. P. T, Dourado F., Domingos T., Teixeira R. F. M. Life Cycle Assessment of a Prospective Technology for Building-Integrated Production of Broccoli Microgreens. *Atmosphere (Basel)* 2022:13(8). https://doi.org/10.3390/atmos13081317

[48] Joseph B., James J., Kalarikkal N., Thomas S. Recycling of medical plastics. *Advanced Industrial and Engineering Polymer Research* 2021:4(3):199–208. https://doi.org/10.1016/j.aiepr.2021.06.003

[49] Health Care Without Harm Europe. Sustainable healthcare waste management in the EU Circular Economy model. 2020. [Online]. [Accessed 10.12.2024]. Available: https://europe.noharm.org/sites/default/files/documents-files/6608/2020-11_HCWH-Europe-position-paper-waste.pdf

[50] Health Care Without Harm. Measuring and reducing plastics in the healthcare sector. 2021. [Online]. [Accessed 10.12.2024]. Available: https://europe.noharm.org/sites/default/files/documents-files/6886/2021-09-23-measuring-and-reducing-plastics-in-the-healthcare-sector.pdf

[51] Health Care Without Harm. New sustainability criteria for examination and surgical gloves. Why choose gloves? 2022. [Online]. [Accessed: 15.01.2025]. Available: https://global.noharm.org/media/4607/download?inline=1

[52] Health Care Without Harm. Plastics and health. An urgent environmental, climate, and health issue. 2022. [Online]. [Accessed 10.12.2024]. Available: https://global.noharm.org/resources/plastics-and-health-urgent-environmental-climate-and-health-issue