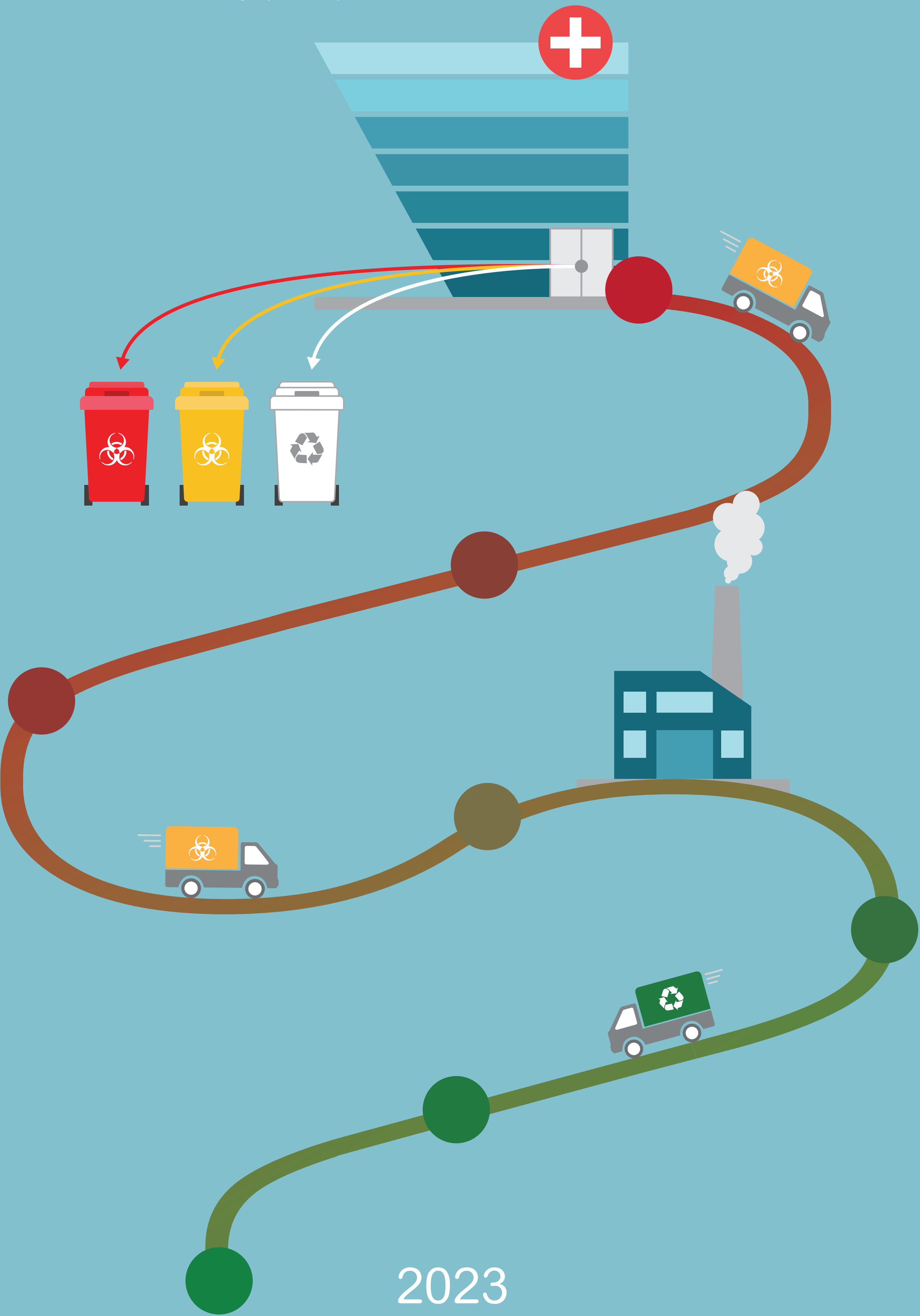
Panacea

Healthcare waste sector roadmap
to circular economy perspective



2023

Introduction

In March 2020, the European Commission adopted the new Circular Economy Action Plan and this is one of the key elements of the European Green Deal, Europe's new (from 2020) sustainable growth agenda. The action plan focuses on how products are produced, promotes circular economy processes, the sustainable consumption of resources and the prevention of waste [50]. Among other sectors prioritised in delivering circular economy targets (biomass and bio-based products, plastics, food waste, critical raw materials, construction and demolition), such a major sector as health care should also be highlighted. According to World Bank data, current health expenditures (% of GDP) are still rising, reaching 10.89% globally in 2020 compared to 8.56% in 2000. According to the definition of the World Health Organization (1), "health care waste is a by-product of health care that includes sharps, non-sharp blood contaminated items, blood, body parts and tissues, chemicals, pharmaceuticals and radioactive materials". The main concerns related to the healthcare waste are linked with its hazardous properties –infectious, containing hazardous chemicals or pharmaceuticals, sharps as physicals hazards, etc. About 85% of all wastes generated by health care institutions are defined as general non-hazardous waste and the potential of their reuse/recovery is high and mainly corresponds to the actions taken with municipal waste[2]. The rest or 15%, however, is considered as hazardous healthcare waste (the largest proportion of hazardous health-care waste generated is potentially infectious, thus needs to be disinfected to minimize the potential for disease transmission) (1). To ensure protection of public health, the management of healthcare waste should primarily be based on the waste-management hierarchy.

Waste management hierarchy (2)**.**

Besides preventive measures (waste minimisation, green procurement, sustainable planning, environmental management systems), healthcare waste treatment methods should also be viewed in the context of the waste-management hierarchy via selection of such technologies which add value via the recycling and recovery of materials and comply with circular economy principles.

Health Care Without Harm (HCWH) Europe has compiled principles for safe and sustainable healthcare waste management in Europe and helps to support the circular economy model which includes how healthcare waste is disposed and what technologies are to be applied for its treatment (3). Sustainability in the healthcare waste sector needs to be led by the Sustainable Development Goals and European Union policy, including the European Green Deal.

- ***Towards zero waste*** **–** the conservation of resources and minimization of waste are parts of the waste hierarchy strategies and can be applied to healthcare waste by first considering the use or need for a product and then by reduce waste through recycling. Any waste reduction/recycling plan shall be based on goals set after consideration of information gained through the monitoring of waste generated in the healthcare facility.

- ***Phase down incineration*** – while incineration is commonly used in the world but it can be replaced or at least the volume of waste incinerated should be reduced with safe disinfection technologies.
- ***Toxic-free future*** – carcinogenic, mutagenic, toxic, or hazardous substances should be excluded from healthcare.
- ***Worker protection*** – workers who are managing waste need to be provided with education on the potential hazards and must be protected from risks.

To ensure proper transition of the healthcare waste sector towards the circular economy and climate neutrality targets, clear and scientific evidence-based national guidelines need to be provided. The developed "Panacea" roadmap is designed for policy and decision makers, healthcare waste management companies and health care institutions as well as potential investors on circular economy oriented actions. The roadmap focused on hazardous healthcare waste (infectious and sharps) and considered recycling and material recovery valorisation scenarios, thus encompassing areas with the most potential and presenting alternatives for incineration due to high risks of dioxin emissions and incompatibility with circular economy principles of safe and clean environment.

This roadmap is developed within the Latvian Council of Science funded project "Public health and environmental pollution prevention through circular economy approaches in health care waste management (Panacea)" (No. LZP-2020/1-0299) implemented from January 2021 – December 2023 by the Institute of Energy Systems and Environment of the Riga Technical University (Latvia).

FLPP FUNDAMENTAL AND APPLIED RESEARCH PROJECTS

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1. Generation of healthcare waste

Healthcare systems continue to evolve: the overall population is rapidly ageing and numbers are expected to rise by 2050 from 901 million to almost 2,1 billion over the age of 60 (4). Population growth is putting pressure on healthcare systems and with increased demand, healthcare waste amounts will also grow. In addition, the healthcare system is becoming more complex (5).

The generation of healthcare waste in healthcare facilities is inevitable. Healthcare waste is generated in hospitals, clinics, healthcare centres, dental centres, laboratories, research centres, mortuary and autopsy centres, animal research and testing facilities, blood banks and collection services, nursing homes, sport schools, prisons, cosmetic saloons and other institutions where healthcare or skin & body care services are provided (6). The waste generation stage is the beginning of potential problems, but also holds potential for opportunities, especially in terms of bringing the healthcare sector closer to the circular economy framework.

Institutions generating waste need to take measures to reduce waste, provided that they do not endanger human health or damage the environment and comply with the requirements of laws and regulations on waste management. Figure 1.1 summarises Figure 1.1. Main waste categories generated in healthcare facilities (7)the main waste categories generated by healthcare institutions.

Hazardous waste or waste treated as hazardous waste (15-20%)	**Non-hazardous municipal waste (80-85%)**
sharps infectious waste anatomical waste waste cytotoxic and cytostatic drugs poor quality or unsuitable medicines chemical waste radioactive waste	biodegradable waste packaging (plastics, glass, paper and cardboard) mixed municipal waste

Figure 1.1. Main waste categories generated in healthcare facilities (7)**.**

Hazardous healthcare waste can be infectious, pathological, sharp, chemical, pharmaceutical, genotoxic and radioactive waste and must be properly treated before disposal (6). Non-hazardous healthcare waste is similar to municipal waste and available for recycling since more than 50% of healthcare waste is paper, cardboard and plastic and the rest of waste is food, metal, glass, textiles and wood (3).

In European Union (EU) countries, healthcare waste is strictly controlled and is defined in subcategories according to Annex III of Directive 2008/98/EC and established a List of Waste by Commission Decision 2014/955/EU – category 18 which is waste from human or animal healthcare and related research – see Table 1.1.

Table 1.1. Wastes from human or animal healthcare or related research (8)

18 01	**Wastes from natal care, diagnosis, treatment or prevention of disease in humans**
18 01 01	sharps (except 18 01 03)
18 01 02	body parts and organs including blood bags and blood preserves (except 18 01 03)
18 01 03*	waste the collection and disposal of which is subject to special requirements in order to prevent infection
18 01 04	wastes the collection and disposal of which is not subject to special requirements in order to prevent infection (for example dressings, plaster casts, linen, disposable clothing, diapers)
18 01 06*	chemicals consisting of or containing hazardous substances

18 01 07	chemicals other than those mentioned in 18 01 06
18 01 08*	cytotoxic and cytostatic medicines
18 01 09	medicines other than those mentioned in 18 01 08
18 01 10*	amalgam waste from dental care
18 02	**Wastes from research, diagnosis, treatment or prevention of disease involving animals**
18 02 01	sharps (except 18 02 02)
18 02 02*	waste the collection and disposal of which is subject to special requirements in order to prevent infection
18 02 03	waste the collection and disposal of which is not subject to special requirements in order to prevent infection
18 02 05*	chemicals consisting of or containing hazardous substances
18 02 06	chemicals other than those mentioned in 18 02 05
18 02 07*	cytotoxic and cytostatic medicines
18 02 08	medicines other than those mentioned in 18 02 07

*hazardous waste

Safe and correct sorting and management of healthcare waste ensures safe and quality care for patients and staff so that the generated healthcare waste reduces the spread of infections. Since healthcare waste is heterogeneous waste, its amount and composition depend on various factors such as season, healthcare facility type, population changes, the prevalence of different diseases, different types of accidents and natural disasters and other factors. The amount and composition of healthcare waste in each country can vary considerably, and so the methods chosen to manage it can also vary, as can be observed by the lack of common medical waste management systems among countries (9).

Figure 1.2 summarises the data on hazardous and non-hazardous healthcare and biological waste generated in Europe. Waste generation varies cyclically over the years, but with a continuing upward trend in recent years.

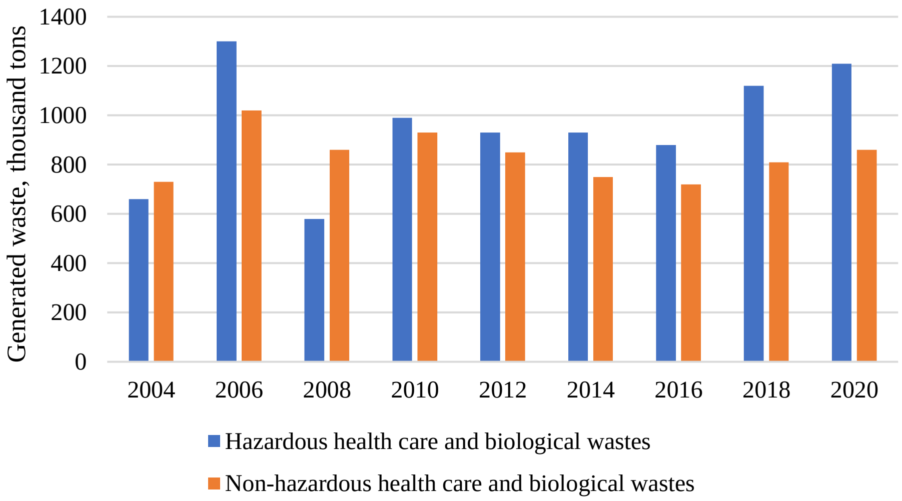

Figure 1.2. Generation of hazardous and non-hazardous healthcare and biological wastes in European Union - 27 countries (10)**.**

Given that each country's level of development and the provision of health services is different, it is not advisable to carry out a comparative analysis between countries. The most accurate assessment of the amount of waste generated will be the aggregation of data within a country.

In the Republic of Latvia, the circulation and classification of medical waste is regulated by the Waste Management Law and the Cabinet of Ministers Regulation No. 353 “Requirements for the Management of Waste Generated in Medical Institutions”. These documents regulate how waste is categorised, how it is collected, in what packaging and how it must be closed, as well as storage conditions(11,12). All facilities providing healthcare services must be certified, and to meet these requirements it is also necessary to ensure proper and efficient waste management. The facility may establish a contract with a waste management company that has obtained the relevant permits on waste management services. An institution, if it has the capacity, may carry out its own pre-treatment, which changes the characteristics of the waste, such as reducing its hazardousness or its appearance, and thus its subsequent treatment. In order to carry out such activities, the institution must obtain a pollution permit for the relevant category of waste (13,14).

Based on the above mentioned, the medical waste generators can be divided into two broad groups according to the volume of waste they produce:

- large waste generators, which are large and small hospitals, laboratories and research institutes, polyclinics, morgues and autopsy centres, health centres, military clinics, blood donation centres;
- small, isolated points where the amount of medical waste generated is relatively small, rarely containing radioactive or cytotoxic waste, mostly non-human parts, and of sharps, most often only hypodermic needles; among such establishments are small private medical practices, dental clinics, acupuncture surgeries, cosmetic surgeries, specialised nursing low-waste surgeries, funeral parlours and homecare.

The amount of hazardous healthcare waste generated in Latvia is provided in Figure 1.3.

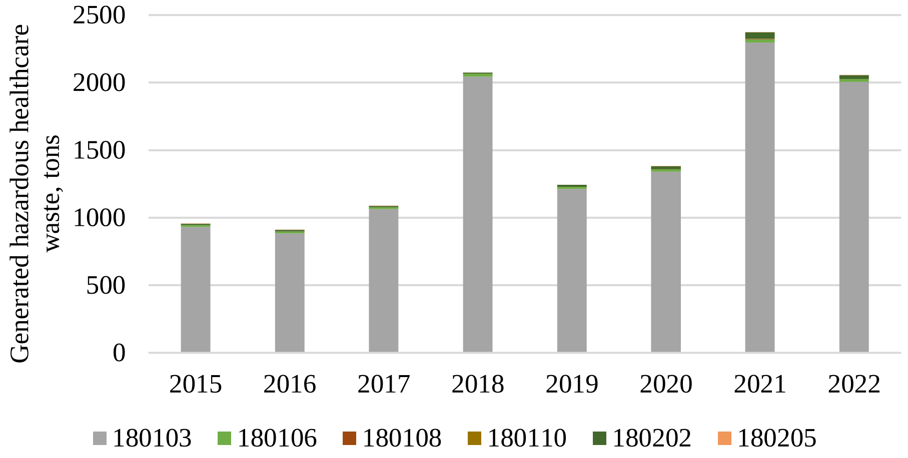

Figure 1.3. Generated hazardous healthcare waste in Latvia in the period 2015-2022 (15)**.**

The global medical waste management market was valued at €6361.5 million in 2020 and is forecast to be worth €11 299.7 million in 2030 (16) [xx]. The European medical waste management market is forecast to reach a value of €6 977 million in 2029 (17). Market growth is attributed to the increasing volume of medical waste, stricter regulatory frameworks for waste management, and infrastructure development in the health sector, while changes in dynamics at the country level, such as a decrease in population, may directly influence these trends. When analysed by type of waste, non-hazardous waste dominated in 2020 and will continue to do so in the future, but hazardous waste is projected to increase due to the rise in chronic and infectious diseases, the growth of the pharmaceutical and biotechnology industries, and R&D activities in the healthcare sector (17).

According to the forecast done in "Panacea" on healthcare waste generation in Latvia, the amount of generated healthcare waste would decrease by 2035 by 7-10 % which is linked to a projected population decline to 1670460 persons in 2035. Another reason for this decrease in generated healthcare waste is planned increase of re-use practises. While this will result in lower environmental pollution generated by the healthcare waste sector, it will negatively affect the competitiveness and cost models of healthcare waste treatment companies.

2. Segregation and transportation of waste

Mixing of municipal, hazardous, industrial and radioactive waste is prohibited in healthcare facilities, as is the mixing of different types of hazardous waste (7). It is important to separate these wastes to deter at least two consequences:

1. mixing non-hazardous waste with hazardous waste increases the amount of hazardous waste
2. management costs of hazardous healthcare waste are 2-4 times higher than municipal waste.

Appropriate bins should be available on site where healthcare waste is generated, indicating the type of waste it is destined for, and the sorting of healthcare waste should be standardized throughout the country, based on uniform colour containers that visually indicate the potential risk of infection waste arising from the waste, as well as facilitating storage and further waste treatment processes (7). Hazardous healthcare waste from home treatment procedures needs to be collected in specific packages and destroyed.

It is recommended for healthcare waste management to use different colour containers or bags with labels as described in Table 2.1.

Table 2.1. Recommendations for healthcare waste management (18,19)

Waste category	Colour of container and markings	Type of container	Collection frequency
Infectious waste	Yellow with biohazard symbol and highly infectious waste marked as "highly infectious"	Strong, leak-proof plastic bag, or container capable of being autoclaved	When three quarters of container is filled or at least once a day
Sharp waste	Yellow with biohazard symbol and marked as “sharp”	Puncture-proof container	When filled to the line or three-quarters full
Pathological waste	Yellow with biohazard symbol	Strong and leak-proof plastic bag placed in container	When three quarters of container is filled or at least once a day
Chemical and pharmaceutical waste	Brown and labelled with appropriate hazard symbol	Plastic bag or rigid container	On demand
Radioactive waste	Labelled with radioactive symbol	Lead box, labelled with the radioactive symbol	On demand
General health-care waste	Black	Plastic bag inside container or container which is disinfected after it is used	When three quarters of container is filled or at least once a day

However, the segregation practices at healthcare facilities may and should vary based on the treatment technology applied and the circular economy approach selected by the healthcare institution and other partners involved in the valorisation of waste. The following aspects should be properly analysed when applying the segregation approaches:

- What type/specific material of healthcare waste is planned to be used for valorisation?
- Are there any additional types of waste /materials proper for valorisation with similar pre-treatment procedure required? Can this waste be collected together?
- Should it be a special attention paid to segregation of this type of waste due to its physical, chemical or other hazards?
- Is a special treatment (disinfection) required for this type of material?

Hazardous and non-hazardous healthcare waste needs to be transported separately and routes for waste transportation also need to be separated and should follow the principle from “clean to dirty” (18). It is important to separate hazardous and non-hazardous waste because if it is mixed together, a larger volume of hazardous waste is created which will need to be treated appropriately. Waste from healthcare facilities needs to be treated according to Directive 2008/98/EC about hazardous waste and national law of infectious waste treatment. For healthcare facilities waste generated during the cleaning process needs to be treated like it is infectious and for non-healthcare facilities this waste needs to be disposed in a separate bag because it is needed to be treated as infections waste with the possibility of being infectious.

3. Treatment of waste

Healthcare waste is a group of waste generated during provision of healthcare services and can potentially contain harmful microorganisms that can infect hospital patients, health workers and the general public. Due to potential hazards to humans and animals, infectious healthcare waste should be treated prior the landfilling, processing, recycling and recovery to avoid the spread of disease. Technologies used for inactivation of microbial activity (pathogens) existing in infectious healthcare waste flow are called healthcare waste pre-treatment or treatment technologies. After healthcare waste disinfection, the treated waste is cleaner than domestic waste from the biological standpoint (20). Hazardous waste can be treated in thermal, chemical, irradiative or biological processes. However, the correspondence of a specific healthcare waste treatment technology or a combination of technologies to the required healthcare institution or waste management facility needs should be evaluated properly via designated indicators.

An indicator is a parameter that, as a data element or combination of data, displays information about the relevant situation and can be used to make situational assessments, as well as help to make a decision against a reference point or benchmark, and can be used as an evaluation function and assess objectives (21). The indicators not only show current conditions or trends, but also provide an understanding of how activities affect different dimensions of sustainability - economic, environmental and social (22). The indicators chosen for waste management must relate to consumption, production, use of resources and their recycling, as well as environmental impact (23). Literature suggests considering the following indicators when selecting the optimal technology (24): correspondence to national and international rules and requirements, environmental and occupational safety factors, waste characteristics and quantity, technology capabilities and requirements, cost considerations, operation and maintenance requirements.

Within "Panacea" project, a multi-criteria decision-making analysis (MCDA) tool was developed for proper selection of healthcare waste treatment technologies. MCDA is used to solve problems and evaluate the best solution. It consists of goal, decision-makers' choice, alternatives, criteria and outcomes (25). At first define the problem with alternatives, then find criteria which describes the alternatives. After that, find values for the criteria (indicators) and weights and use the MCDA method to find the best alternative for the problem.

In "Panacea" three types of criteria (environmental, technical and economic) and 12 quantitative and qualitative criteria (indicators) were selected demonstrating the healthcare waste treatment technology. The number of indicators vary based on the needs of users and include such indicators as installation and/or maintenance requirements (time, personnel qualifications), operational safety level, number of persons involved in operation, etc. In our case, we focused on indicators having an effect of waste recovered resource valorisation potential.

Table 3.1. Selected criteria and its weights for ranking of healthcare waste treatment technologies

	Criteria	Weight	Description	Type of indicator	Unit
Environmental	Energy consumption	0.1	Energy consumption (electricity, heat) required to disinfect healthcare waste (recalculated per 1 tonne of untreated waste)	quantitative	kWh/t waste
	Water consumption	0.1	Water consumption required to disinfect healthcare waste (recalculated per 1 tonne of untreated waste)	quantitative	m^3/t waste
	Wastewater generated	0.02	Amount of wastewater generated after treatment of healthcare waste (recalculated per 1 tonne of untreated waste)	quantitative	m^3/t waste
	Hazardous emissions	0.09	Hazardous emissions (e.g. dioxins, furans, and particulate matter, chlorine dioxide, etc.) generated during the treatment process	quantitative	t/t waste
	Hazardous residues	0.09	Hazardous residues/waste (e.g. ash) generated during the treatment process	quantitative	t/t waste
Technical	Load per cycle	0.08	Maximum amount of waste treated during one operational cycle (recalculated per 1 hour)	quantitative	t/h
	Disinfection efficiency	0.09	Level of destruction of pathogenic and other types of microorganisms present in healthcare waste by treatment technology	qualitative	high/low
	Operating temperature	0.08	Average temperature in which the waste treatment is performed	quantitative	°C
	Potential for post-treatment waste sorting	0.12	Possibility to sort the treated waste to specific material fractions (plastics, metals, textiles) after the treatment process	qualitative	Yes/No
	Diversity of waste treated	0.03	Diversity of waste (e.g. sharps, textiles, pathologic waste, etc.) that can be treated in a treatment technology	qualitative	High/low
Economic	Investment cost	0.1	Cost of equipment and its one-time installation (recalculated per 1 tonne of untreated waste)	quantitative	Euro/t waste
	Operating cost	0.1	Ongoing expenses arising from daily operation of technology (incl. personnel costs, electricity costs, etc.)	quantitative	Euro/t waste

Expert-based weighting procedure was selected for the research needs assigning relative importance or weights to various criteria based on the expertise and judgment of individual experts knowledgeable about the decision context. The number of experts involved in the MCDA process varies depending on factors such as the complexity of the decision, the diversity of perspectives needed, however ensuring a comprehensive consideration of relevant viewpoints and enhancing the robustness and credibility of the decision-making process.

MCDA method TOPSIS (Technique for Order of Preference by Similarity to Ideal Solution) method was applied for calculation of the ideal solution. TOPSIS method solves problems by ranking alternatives from their distance from the positive ideal solution and negative ideal solution (26). The advantages of the TOPSIS method include the small amount of data and the result reflects closeness to the ideal solution (27).

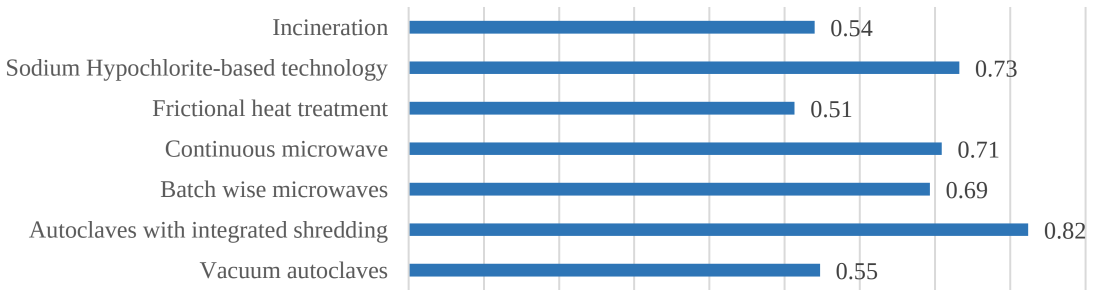

Figure 3.1. Ranking of healthcare waste treatment technologies (score equal to 1 is an ideal solution).

It should be noted, that the presented results are sensitive to the decision question defined and the indicators framework built and can be interpreted within the defined conditions/boundaries.

4. Quality performance for the healthcare waste recovered resources

Quality performance for the healthcare waste recovered resources includes several steps:

- Ensuring the microbiological safety of healthcare waste recovered resources.
- New product/material defined quality criteria (e.g., composition and presence of specific substances, physical and chemical properties).

4.1. Microbial inactivation testing

Due to the fact that healthcare waste may contain pathogenic agents that can adversely affect public health by causing the spread of infections, and also potentially affecting the environment, it is essential to ensure the inactivation of such potential pathogens.

Strict international and national regulations are defined to ensure proper management of contaminated healthcare waste.

"**Sterilization** is defined as the destruction of all microbial life. Since the complete destruction of all microorganisms is difficult to establish, sterilization of medical and surgical instruments is generally expressed as a 6 log10 reduction of a specified microorganism, corresponding to a one millionth (0.000001) survival probability of the microbial population."

"**Disinfection** can be defined as the reduction or removal of disease-causing microorganisms (pathogens) in order to minimize the potential for disease transmission." (28,29)

The primary objective of disinfection is to decrease the concentration of specific microorganisms to levels considered safe for the public. While various microorganisms demonstrate different levels of resistance to disinfection methods, proper disinfection protocols aim to effectively eliminate or inhibit the growth of harmful pathogens, thereby safeguarding public health.

Microbial inactivation levels and the procedure of inactivation of microbial contamination is stated in the State and Territorial Association on Alternate Treatment Technologies (STAATT). According to this (30), four levels are defined:

- Level I – Inactivation of vegetative bacteria, fungi, and lipophilic virus
- Level II – Inactivation of vegetative bacteria, fungi, all viruses, and mycobacteria.
- Level III – Inactivation of vegetative bacteria, fungi, all viruses, mycobacteria, and *stearothermophilus* spores at 4 $\log_{10}$ or greater; or *B. subtilis* spores at 4 $\log_{10}$ or greater with chemical treatment. (*Note: in the updated version of STAAT III, B. subtilis spores were replaced with B. atrophaeus spores*).
- Level IV – Inactivation of vegetative bacteria, fungi, all viruses, and mycobacteria and *stearothermophilus* spores at 6 $\log_{10}$ or greater. This level could also be defined as sterilization.

Microbial inactivation procedure for healthcare waste treatment is also based on the STAATT criteria Level III (28): Level III Inactivation of vegetative bacteria, fungi, lipophilic/hydrophilic viruses, parasites, and mycobacteria at a 6 $\log_{10}$ reduction or greater; and inactivation of *G. stearothermophilus* spores and *B. atrophaeus* spores at a 4 Log_{10} reduction or greater.

In addition to the STAAT method, specific ISO standards can be applied to test the microbial inactivation efficiency of treatment technologies (for example, ISO 19458: 2006 or ISO 11138-7:2019).

4.2. Morphological analysis

The typology of generated healthcare waste in a health care institution depends on several factors: type of healthcare services provided, amount of patients treated, nature of medical procedures performed, healthcare facility size and specialization, healthcare waste segregation practices defined, etc.

To understand the composition (material types of waste, dominating waste flows, amounts, etc.) of infectious healthcare waste, a morphological analysis of healthcare waste generated in the healthcare facilities of Latvia was performed in September 2022. The institutions included in the research are:

- Private general practitioner's office;
- Regional multi-purpose hospital;
- Polyclinics;
- Hospital specialised in traumatology and orthopaedics;
- University multi-purpose hospital;
- Children's University hospital;
- Clinical laboratory;
- Clinical laboratory specialised in phlebotomy.

To ensure an in-depth analysis of the material types dominating the disinfected healthcare waste flow, instrumental differential scanning calorimetry was performed. At this stage, the type of healthcare facility was neglected and the mixed disinfected healthcare waste was analysed. Results of the instrumental compositional analysis is summarised in Figure 4.1.

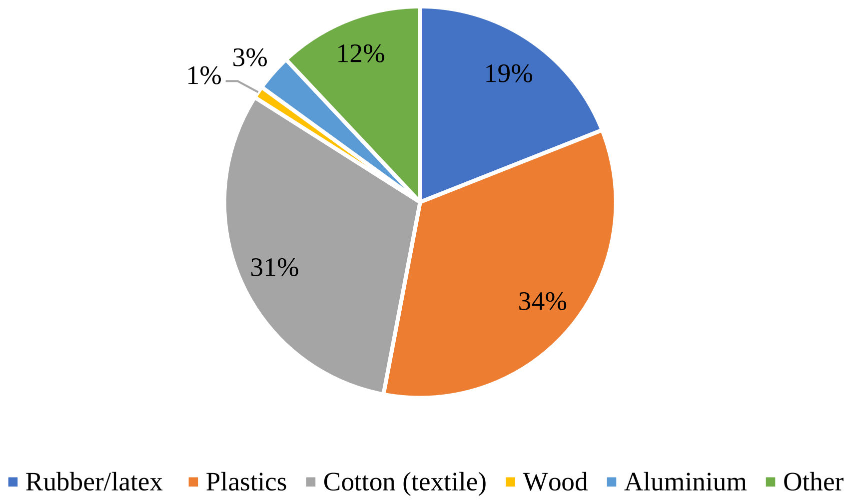

Figure 4.1. Levelized results of treated healthcare waste morphological analysis.

The morphological analysis of the treated healthcare waste also highlighted some hot-spots significant for adaptation/planning of circular economy approaches for the treated healthcare waste.

Healthcare waste pre-treatment (sterilisation) process makes it difficult to separate waste into fractions. There are several reasons for this.

- Healthcare waste is shredded during the waste treatment process (e.g. chemical recycling) and the healthcare waste after such pre-treatment process is delivered from the treatment unit in small particles (3-5 cm).
- Healthcare waste is mechanically mixed (in both rotating autoclave and chemical recycling processes) and forms mixed fraction waste "balls" which are hard to recycle afterwards.
- Mixing of waste as a result of thermal treatment – some of the plastic may melt and adhere to the rest of the waste mass).

5. Decision-making framework on healthcare waste valorisation

Waste valorisation is a process when waste is reused, reprocessed, recovered, recycled to a valuable product (31). The valorisation of medical waste is possible primarily by removing its hazardous properties. Once this has been achieved or taken into account in the generation of the waste, the valorisation of medical waste is similar as the valorisation of municipal waste.

The intricacy of technological, regulatory, economic, environmental and social aspects of healthcare waste valorisation within "Panacea" project leads to a corresponding rise in the complexity of decision-making challenges. These challenges are marked by their extensive scope, particular performance indicators, coupled with uncertainties and risk factors. To ensure a valid framework for decision-makers, a certain methodological approach needs to be formulated to rank healthcare waste valorisation scenarios (taking into account environmental, economic, social and climate considerations, resources safety and quality requirements, availability of market players, national policy initiatives, etc.).

In "Panacea" project the decision-making framework is built on the following methodological concepts:

- **Multi-criteria decision-making (MCDA)** – multi-aspect (technological, economic, environmental, economic & business, social) indicator-based screening of healthcare waste valorisation alternatives through stakeholders' incorporation.
- **Life cycle assessment (LCA)** – evaluation of diverse environmental impacts related to valorisation scenarios.
- **Environmental life cycle cost assessment (E-LCCA)** – evaluation of environmental costs (damage costs) related to valorisation scenarios.
- **Social life cycle assessment (S-LCA)** – identification of social hot-spots within the healthcare waste supply chain. appropriateness

5.1. Selection of valorisation alternatives

Multi-criteria decision analysis (MCDA) encompasses a range of methods designed to facilitate structured and transparent decision-making for comparing alternative options. The primary objective of MCDA methods is to assist decision-makers in selecting the most favourable option from numerous alternatives, considering a diverse range of criteria that define the acceptability of each decision alternative. These criteria can also assess the quality of the alternatives when all options are deemed feasible, and the objective is to identify the optimal one reducing as much as possible the subjectivity of selection process (32).

Considering the scope of "Panacea" project and evidence about the appropriateness of the selected method in other environmental engineering studies, the combination of AHP (analytic hierarchy process) and TOPSIS (Technique for Order of Preference by Similarity to Ideal Solution) is selected as a proper method. This applied methodology was initially developed, tested and has shown reliable results regarding ranking of circular economy practices for municipal textile waste (33) and based on that adapted to the needs of "Panacea" project.

The main steps in MCDA are the following:

1. Select various criteria upon which to base their decision;
2. Identify multiple alternative solutions for their decision;
3. Offer ranking or weighting of criteria;
4. Assign values, rankings, or weighting to alternatives for each criterion.

Eleven criteria (see Table 5.1) describing valorisation of waste are defined incorporating such topics as circular economy, valorisation potential, regulatory requirements defined for the healthcare waste, properties of healthcare waste, business development and expansion perspectives in Latvia, deployment speed, etc. Within the AHP method, the focus lies on determining the weights of the criteria, thereby establishing the relative importance of these criteria through pairwise comparisons. The process of criteria weighting was conducted via AHP, leveraging verbal evaluations provided by 26 healthcare waste management, environmental engineering experts as well as decision-makers from Latvia and abroad. The higher the eigenvectors of a specific criterion, the higher dominance of the criterion is reflected in the decision process.

Table 5.1. Criteria selected for decision-making on healthcare waste valorization scenarios

	Criteria	**Weight**	**Description**	**Type of indicator**
Environmental	Circular economy approach of the technology	0.07	Conformity of the valorisation alternative to the waste management hierarchy level.	qualitative
	Rank of valorisation sector's environmental risk factor	0.06	Ranking of valorisation industries in terms of likelihood of environmental risks acc. to [6].	qualitative
	Recyclability rate of produced product	0.07	Recyclability rate defines a potential of a product to be recycled at the end-of-life stage.	qualitative
Economic & business	Added-value potential of final product	0.15	Correspondence of the final recovered product to the market value pyramid.	qualitative
	Valorisation sectors non-payment risk	0.11	Ranking of valorisation industries in terms of sector's non-payment risk acc.to [7].	qualitative
	Industrial symbiosis potential in Latvian conditions	0.06	Assessing existing symbiotic industries in Latvia and identifying potential niche opportunities based on market analysis of local industries.	qualitative
Technological	Share of healthcare waste in total feedstock	0.10	The proportion of healthcare waste within the entirety of materials used as feedstock within a given context or system.	quantitative
	Diversity of healthcare waste mix suitable for specific technology	0.08	Variability in healthcare waste composition tailored for specific technological solutions.	qualitative
	Pre-treatment of waste feedstock	0.11	Describes efforts spent on additional pre-treatment (shredding, washing, etc.) of sterilised waste feedstock prior to valorisation process.	qualitative
	Maturity of a recovery technology	0.08	Assessing technology readiness across various environments for expedited deployment.	qualitative
Social	Rank of valorisation sector's social risk factor	0.11	Ranking of valorisation industries in terms of likelihood of social risks acc. to [6]	qualitative

During the next step, the TOPSIS method was used to rank the valorisation alternatives of healthcare waste – in total analysing 12 valorisation scenarios (see Table 5.2) which were formulated based on a thorough desk review of the latest scientific surveys. In this study, the performance of the criteria regarding the valorisation scenario is characterised in a qualitative way, ranking the alternatives towards the factor from 1 to 3, where 3 is full (best) correspondence of a valorisation strategy to a specific factor.

Table 5.2. Valorization alternatives of disinfected healthcare waste

Product	**Technology**	**Reference**
Reinforced asphalt	Asphalt production when 6% of bitumen replaced by the healthcare waste recovered plastic.	(34–39)
Reinforced concrete	Concrete production when 20% of sand is replaced with the healthcare waste recovered textile waste	(40–43)
Refuse derived fuel (RDF)	Disinfected healthcare waste is entirely utilized for RDF production and later electricity and heat.	(44,45)
Syngas	Use of healthcare waste for production of syngas.	(46,47)

Acoustic panel	Use of healthcare waste recovered textile for production of sound absorption panels.	(48–50)
Hydroponic systems	Production of hydroponics and aquaponics elements (pipes, containers, etc.) from healthcare waste recovered plastics.	(51–53)
Ash reinforced concrete	Ash from incinerated biomedical waste used to replace the fine aggregate in reinforced concrete production.	(54)
Nanoglass	Production of nanoglass from healthcare waste glass fraction.	(55)
Polypropylene microbeads	Use of healthcare waste recovered polypropylene textile for production of microbeads or membranes.	(56)
Multifunctional carbon fibers	Production of multifunctional carbon fibers from healthcare waste recovered polypropylene textile.	(57)
Carbon solvents	Production of carbon solvents from healthcare waste recovered polypropylene textile.	(57)
Blended yarns	Production of blended yarns from healthcare waste recovered polypropylene textile.	(58)

Based on TOPSIS results (see Figure 5.1), the best alternatives for the healthcare waste valorisation are linked with production of plastic products used for hydroponic systems (0,66), ash reinforced concrete[1] (0,62), RDF and syngas (0,58), reinforced asphalt and reinforced cement (0,56), acoustic panels (0,53). Overall it might be concluded that the experts' given scores are more oriented on economic considerations and business opportunities, neglecting the circular economy targets and environmental perspectives. Therefore, the scoring of the valorisation alternatives is oriented on well-known, ready to deploy technologies on treated healthcare waste valorisation.

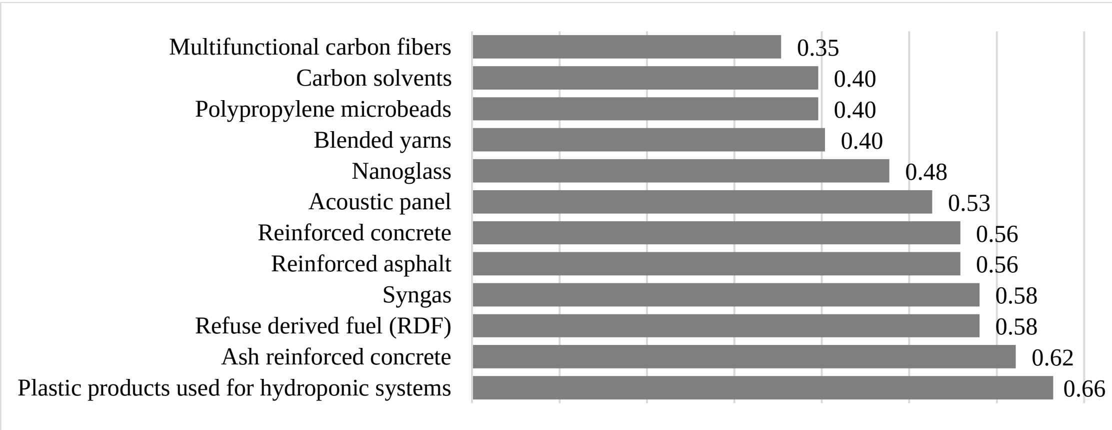

Figure 5.1. Decision-making results (expert based AHP weighting) for the healthcare waste valorisation alternatives via MCDA TOPSIS method (score equal to 1 is an ideal solution).

5.2. Life Cycle Assessment

Life cycle assessment (LCA) is a standardized technique for evaluating the environmental aspects and potential impacts associated with a product or service. LCA is an excellent decision-making tool, result is understandable as the impact is expressed in different categories. The environmental LCA methodology is performed in accordance with the ISO 14040 standard and applies the requirements of the ISO 14044 standard – goal and scope, life cycle inventory, life cycle impact assessment and life cycle interpretation. Seven scenarios were examined:

[1] Valorization alternatives linked to the use of healthcare waste ash as an agent for cement production were excluded from further research (LCA, E-LCCA) because of insufficient data available regarding the technological process.

- "Business as usual" scenario –current management approaches applied for the hazardous healthcare waste in Latvia.
- six scenarios (VS1-VS6 – see Figure 5.2) of using treated healthcare waste to produce an added value product partially or completely replacing one of the raw materials with treated healthcare waste.

System boundaries of the present environmental LCA are "gate-to-gate": from generation of the healthcare waste in healthcare facilities to end-of-life stage of the healthcare waste – landfilling or valorisation alternative.

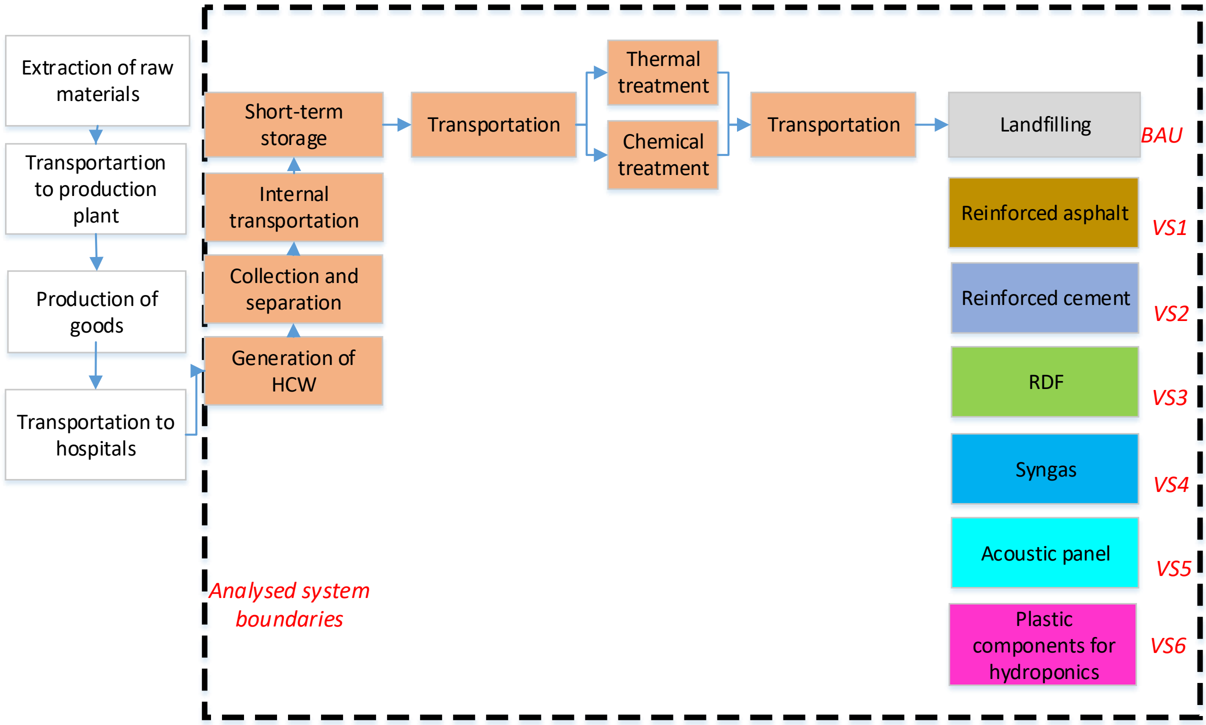

Figure 5.2. System boundaries of healthcare waste valorization scenarios.

The "IMPACT World+" Midpoint method is used as a core method for life cycle modelling. All midpoint indicators represent integrated impacts over an infinite time and temporal resolution is only considered at the damage level, except for climate change, as there is a short-term and long-term indicator. Some midpoint scores are considered reasonable proxies for other midpoints. By choosing to report results at the midpoint level, the resulting midpoint damage framework is useful for interpreting the environmental relevance of various midpoint indicators using midpoint damage models based on physical, biological, and chemical principles.

The aim of the LCA is to carry out an environmental impact assessment of the existing hazardous healthcare waste management systems in Latvia and to assess the impacts of using waste as a resource compared to landfilling. The functional unit (FU) of the present environmental LCA is the amount of treated infectious healthcare waste generated per year during provision of healthcare services in Latvia. Since the selected FU fluctuates over the years, an average data on generated healthcare waste in Latvia was calculated. Data reflecting the amount of processed infectious healthcare waste (18 01 03; 18 02 02; 18 02 07) in Latvia from 2015-2022 and the average amount of waste and in this LCA FU is 2246 tons per year used in current situation. While the current composition of waste corresponds to the data provided in **Error! Reference source not found.**.

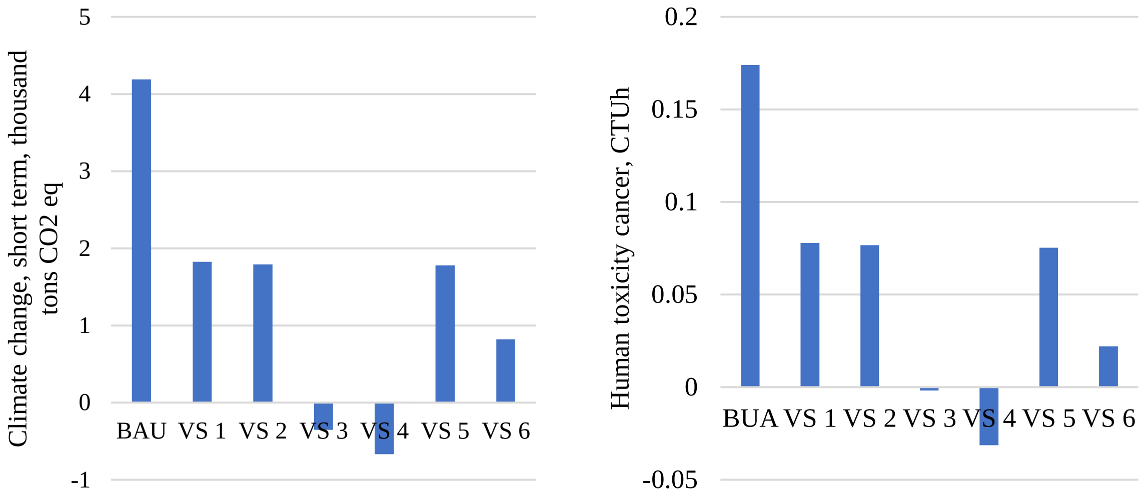

Figure 5.3. LCA results of the healthcare waste valorization scenarios.

The results of the LCA demonstrates, that all the proposed valorization scenario brings the environmental impact and impacts to human health reduction at least for 56 % from "business as usual" scenario. In addition, there is the potential to reach negative emissions potential in scenarios VS3 and VS4.

Because there is a strong need for the healthcare sector to follow the circular economy paradigm (focusing on redesign, reuse, and remanufacturing principles), a sensitivity analysis of the LCA was also performed based on potential changes in the amount of healthcare waste generated in Latvia (corresponding to the FU) and the morphological composition of healthcare waste (see the conditions applied in Table 5.3). The forecasted reduction potential of specific healthcare waste fractions is assumed based on (59–61).

Table 5.3. Modelled changes in morphological composition of healthcare waste driven by circular economy practices

Sensitivity scenario	Functional unit	Composition
Future 1	1980 tonnes	-20% rubber/latex -10% plastics -15% cotton (textile)
Future 2	1805 tonnes	-30% rubber/latex -20% plastics -23% cotton (textile)
Future 3	1638 tonnes	-40% rubber/latex -30% plastics -30% cotton (textile)

The effects of compositional changes to the LCA results are reflected in Figure 5.4.

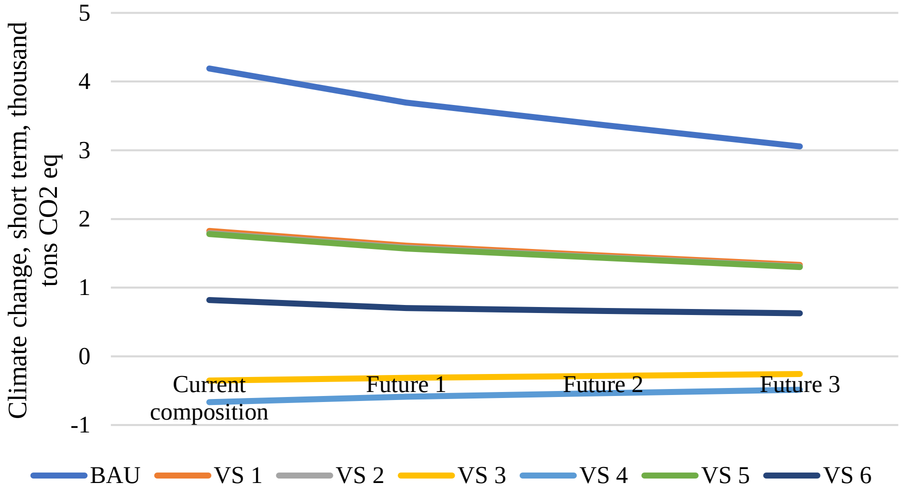

Figure 5.4. LCA sensitivity analysis considering changes in the amount of generated healthcare waste and its composition.

5.3. Environmental Life Cycle Costing

Life Cycle Cost (LCC) refers to and traces all relevant costs associated with a product/project for its entire life cycle. E-LCC summarizes all costs associated with the life cycle of a product that is directly covered by 1 or more of the actors in that life cycle (e.g., supplier, producer, the user or consumer, and those involved at the end of life).

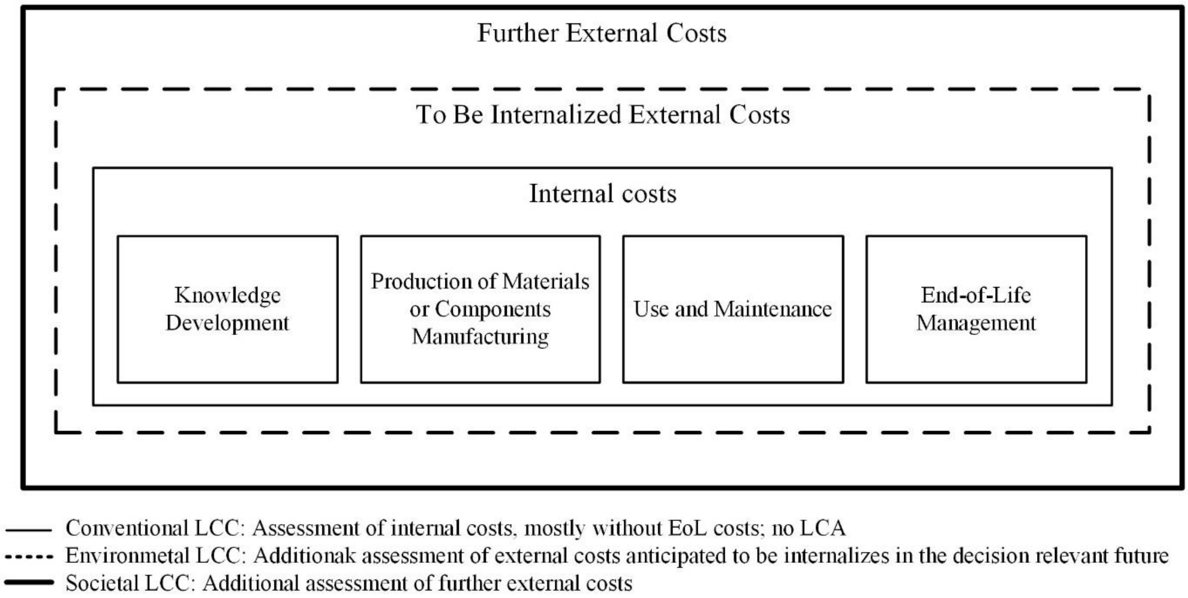

Figure 5.5. System boundaries for different types of LCC (62)***.***

Environmental Life Cycle Cost (E-LCC) uses equivalent system boundaries and functional units as those in LCA and is also based on the same product system model. As E-LCC uses the same system boundaries and product system and the E-LLC is not a stand-alone technique, it is complementary to the Life Cycle Assessment. E-LCC is an approach to estimate the economic dimension alone or as part of a sustainability assessment and it is used to provide an assessment that can be quantified and then be employed for measuring progress. With its comparative and systemic nature, aimed at decision-making in the sustainability context, it does not replace traditional detailed cost accounting or cost management practices.

Considering the needs of "Panacea" project, environmental prices are used to weight the environmental impacts calculated previously in the LCA, and they express the potential value of emissions relative to other assets in society. Results of using environmental prices as weighting factors are shown in Table 5.4 and is used as costs on 2022 EURO. Weighted E-LCC results is achieved from "ReCiPe" Midpoint (H) method, which was used for the LCA sensitivity analysis and "ReCiPe" method was used for environmental prices.

Table 5.4. Damage cost factors for LCA impact categories

Impact Category	Unit	Weighting factor (2022)
Climate change	€/kg CO_2-eq.	€ 0.07
Ozone depletion	€/kg CFC-eq.	€ 150.55
Human toxicity	€/kg 1,4 DB-eq.	€ 0.11
Photochemical oxidant formation	€/kg NMVOC-eq.	€ 1.41
Particulate matter formation	€/kg PM10-eq.	€ 47.98
Ionizing radiation	€/kg kBq U235-eq.	€ 0.06
Acidification	€/kg SO_2-eq.	€ 9.16
Freshwater eutrophication	€/kg P-eq.	€ 2.28
Marine eutrophication	€/kg N	€ 3.81
Terrestrial ecotoxicity	€/kg 1,4 DB-eq.	€ 10.64
Freshwater ecotoxicity	€/kg 1,4 DB-eq.	€ 0.04
Marine ecotoxicity	€/kg 1,4 DB-eq.	€ 0.01
Land use	€/m^2*year	€ 0.15
Noise >60dB*	€/dB/person	-

Damage cost factors are extracted from (63) and the World Bank Purchasing Power Parity methodology is applied to convert prices for Latvia (year 2022).

The results of E-LCCA is given in Figure 5.6, while the cost changes caused by the compositional restructure of healthcare waste and generation rates (see the text related to Table 5.3) is given in Figure 5.7.

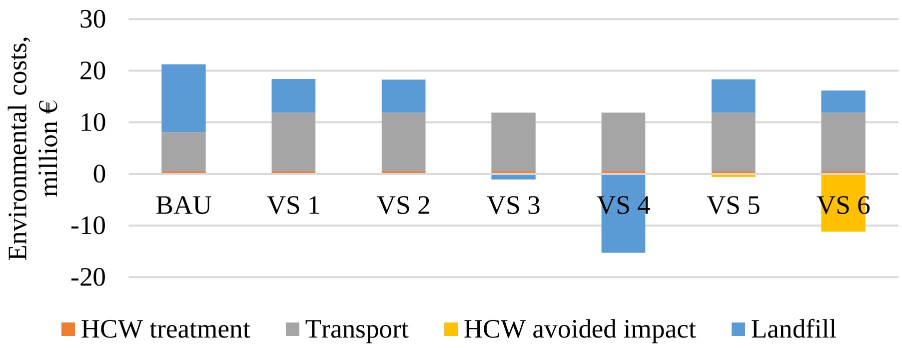

Figure 5.6. Weighted environmental costs of healthcare waste valorization scenarios.

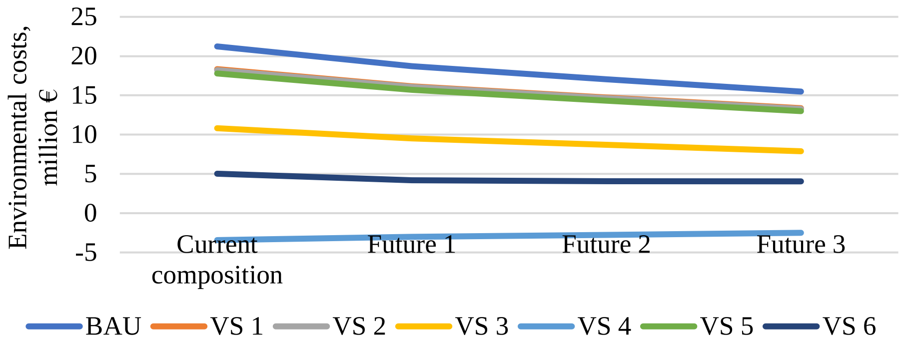

Figure 5.7. E-LCCA sensitivity analysis for environmental costs considering the changes in the amount of generated healthcare waste and its composition.

5.4. Social Life Cycle Assessment

The social dimension is fundamental to sustainability, indicating that a society achieves this status when the basic needs of all its members are fulfilled and when all benefit from sustainable development. Initially deemed difficult to quantify monetarily, businesses have increasingly recognized the value of responsible social impacts, realizing benefits such as fostering new business opportunities, driving innovation and retaining talent within local communities and society at large. From the end-user perspective, social impact evaluations are important as they allow consumers to buy and use products that do not negatively affect persons and society, contributing to collective wellbeing (64).

The methodology applied for S-LCA is based on UNEP (United Nations Environmental Programme) and SETAC (the Society of Environmental Toxicology and Chemistry) guidelines and Data sheets on S-LCA (65,66). Collection of related data was organised via 14 one-on-one interviews with persons related to the specific supply chain stage – waste generation at hospitals, waste transportation and treatment, end-of-life stage) supplemented with in person audit at facilities, as well as checking the documentation referred to during the interviews.

The goal of the implemented S-LCA was to define the social hotspots significant within the infectious healthcare waste supply chain and further transition of the healthcare sector towards circular economy targets.

Within the present research, two supply chains were analysed (see Figure 5.8): (1) ***linear supply chain*** (Supply chain 1) related to treatment of healthcare waste via chemical treatment technology and (2) ***circular supply chain*** (Supply chain 2) related to treatment of healthcare waste via thermal treatment technology.

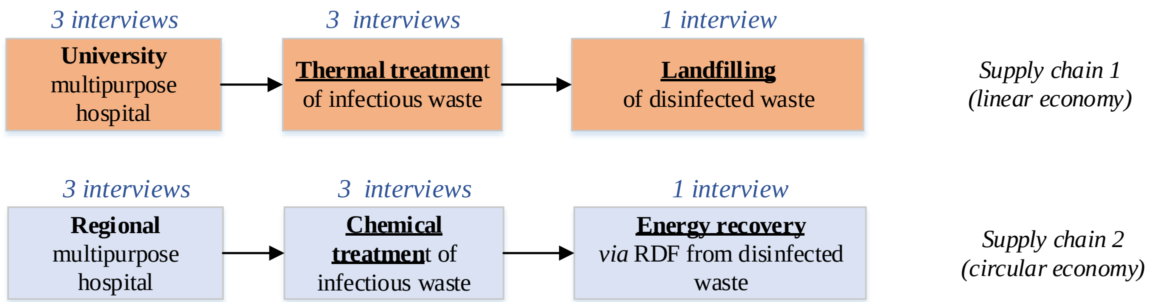

Figure 5.8. Supply chains analysed in the S-LCA.

When adapting "Panacea" proposed S-LCA methodology (interview based case study analysis), it is important to note that the findings of the survey have limitations:

- the findings are eligible within the boundaries of the specific system and considering the defined limitations;
- the findings cannot be directly generalised to other supply chains of the healthcare waste sector, but can serve for identification of potential hotspots only.
- the research is not a comparative S-LCA, thus the results of the "Supply chain 1" or any stage of the supply chain cannot be compared with "Supply chain 2".

To ensure correspondence of the S-LCA to five principles – usable, transparent, suitably/appropriately robust, inclusive, comprehensive – data collection for the social life cycle inventory was coming from questionnaires and supplemented with specific documentation of the entities responsible for the unit processes analysed. Structured interviews (questionnaire based) are carried out to gather the necessary information. Six main social impact categories are analysed: "Workers", "Local communities", "Value chain actors", "Consumers", "Society" and "Children" in order to assess the overall impact of the supply chain scenario. Further, the categories are split in sub-categories and indicators. An example of the evaluation sheet for the category "Value chain actors" is given in Figure 5.9.

Category	Subcategory	Indicators	Weight (1/5)	Regional Hospital (score)	University Hospital (score)
VALUE CHAIN ACTORS	Fair competition	Fair competition is ensured	0,017		
		Participation in voluntary organisations that are centered on free and fair competition	0,017		
		Documents or procedures detailing free and fair competition are openly accessible at all levels	0,017		
		SUM	**0,050**		
	Promoting social responsibility	Clearly defined code of conduct that protects the human rights of employees among suppliers	0,017		
		Membership in an initiative that promotes social responsibility along the supply chain	0,017		
		Integration of ethical, social, environmental, and regarding gender equality criterions in purchasing policy, distribution policy, and contract signatures	0,017		
		SUM	**0,050**		
	Supplier relationships	Communication with suppliers	0,025		
		Sufficient lead time	0,025		
		SUM	0,05		
	Respect of intellectual property rights	Clearly defined policy and practise of the organisation on intellectual property rights issues	0,025		
		Use of local intellectual property	0,025		
		SUM	**0,050**		
	TOTAL FOR CATEGORY "VALUE CHAIN ACTORS"		**0,200**		

Figure 5.9. Example of the "Panacea" S-LCA assessment matrix.

The S-LCA results within the healthcare waste generation, treatment and end-of-life stages demonstrate performance above the average (60 % and above). Supply chain stage specific comments are:

1) The social responsibility of the hospitals in the field of healthcare waste management is not the highest priority for hospitals. The level of inclusion of social responsibility principles depends on the hospital's class (university, regional): **larger hospitals have higher management** (incl. social and environmental standards, public information campaigns etc.).

2) **Waste management companies** dealing with healthcare waste are **socially responsible** mainly due to national requirements set to take part in tendering procedures; however, the dialogue with the community and awareness raising specifically on healthcare waste topics needs to be improved.

3) Considering the fact that the healthcare waste y generators, social responsibility **depends highly on the field of activities of the company**.

The social hotspots within the healthcare waste management supply chain, where the lowest performance is indicated, are linked with poverty alleviation actions, awareness and educational activities for children, as well as focus on local employment. This connection is largely influenced by the fact that these issues are not actively discussed across the entire country in various sectors. Therefore, a similar performance in these sub-categories is also anticipated in other fields unrelated to healthcare waste.

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