



Limited mitigation potential of downstream waste management: A facility-level life cycle assessment of hospital PPE systems

Adam Kaposi^a, Viktoria Mannheim^{b,*}, Artur Szilagyi^c, Denes Kocsis^d

^a Department of Hospital Hygiene, University of Debrecen Clinical Centre, Debrecen, Hungary

^b Department of Engineering Management, Faculty of Engineering, University of Debrecen, Debrecen, Hungary

^c Department of Applied Sustainability, Széchenyi István University, Győr, Hungary

^d Department of Environmental Engineering, Faculty of Engineering, University of Debrecen, Debrecen, Hungary

ARTICLE INFO

Keywords:

Hazardous healthcare waste
Personal protective equipment
Life cycle assessment
End-of-life management
Waste segregation and routing
Environmental risk mitigation

ABSTRACT

Healthcare systems generate substantial volumes of plastic-rich waste, with single-use personal protective equipment (PPE) accounting for an increasingly large share. While healthcare waste management has received significant attention, the real-world mitigation potential of downstream interventions remains insufficiently quantified. This study presents a facility-level life cycle assessment (LCA) of hospital PPE waste management based on multi-year operational data (2019–2023) from a Hungarian hospital. Using a cradle-to-grave system boundary with defined upstream exclusions and the ReCiPe 2016 Midpoint (H) method, environmental impacts were evaluated across alternative end-of-life (EoL) routing and waste segregation scenarios under real operating conditions. Results show that impacts are primarily driven by upstream material production and consumption, with PPE throughput directly determining system-level burdens. Across all scenarios, human and freshwater toxicity dominate the environmental profile, exceeding climate-related impacts. Scenario analysis indicates that even under optimized conditions, downstream interventions—such as improved segregation and alternative EoL routing—provide limited mitigation within the studied system, reducing the combined normalized score for human and freshwater toxicity by <7%. These findings highlight a structural constraint in healthcare waste systems, where mitigation potential is inherently limited downstream relative to upstream drivers. While segregation remains an important operational parameter, effective mitigation requires prioritizing upstream strategies, such as demand reduction, material substitution, and procurement-based interventions.

1. Introduction

1.1. Environmental footprint of healthcare systems

The healthcare sector represents a significant global consumer of energy and materials. International assessments estimate that healthcare activities are responsible for approximately 4–5% of global greenhouse gas emissions (Bosurgi, 2019; Lenzen et al., 2020; Or and Seppänen, 2024). Beyond its contribution to climate change, the sector imposes a range of environmental burdens, such as particulate

matter formation, acidification, and eutrophication (Eckelman and Sherman, 2016; Pichler et al., 2019; Steenmeijer et al., 2022).

This situation presents a fundamental challenge because activities intended to protect human health are inherently resource-intensive and may indirectly compromise environmental and public health outcomes. Empirical evidence demonstrates that the majority of environmental impacts originate from upstream supply chains, which contribute 60–80% of total emissions, while direct on-site operations have a comparatively minor effect (Doucet et al., 2025; Malik et al., 2024; Olawade et al., 2025).

Abbreviations: 1,4-DCB, 1,4-dichlorobenzene; CC, climate change; COVID-19, coronavirus disease 2019; EoL, end-of-life; EWC, European Waste Catalogue; FET, freshwater ecotoxicity; FFP2, filtering facepiece class 2; FRS, fossil resource scarcity; FU, functional unit; GHG, greenhouse gas; GWP, global warming potential; HDPE, high-density polyethylene; HT-c, human toxicity-cancer; HT-nc, human toxicity-non-cancer; ISO, International Organization for Standardization; LCA, life cycle assessment; LCC, life cycle costing; LCI, life cycle inventory; LCIA, life cycle impact assessment; LDPE, low-density polyethylene; MCDA, multi-criteria decision analysis; MLC, Managed LCA Content; NPV, net present value; PMF, particulate matter formation; POF-HH, photochemical ozone formation-human health; PP, polypropylene; PPE, personal protective equipment; SI, Supplementary Information; TAP, terrestrial acidification.

* Corresponding author.

E-mail address: mannheim.viktoria@eng.unideb.hu (V. Mannheim).

<https://doi.org/10.1016/j.hazadv.2026.101555>

Received 12 May 2026; Received in revised form 22 August 2026; Accepted 6 September 2026

Available online 7 September 2026

2772-4166/© 2026 The Authors. Published by Elsevier B.V. This is an open access article under the CC BY license (<http://creativecommons.org/licenses/by/4.0/>).

In this context, understanding and optimizing material flows, particularly those related to healthcare waste streams, is essential to developing sustainable healthcare systems. Despite increasing attention, the contribution of downstream waste management to mitigating these environmental impacts remains insufficiently quantified.

1.2. Role of single-use PPE in healthcare material flows

Single-use personal protective equipment (PPE) is a fundamental element of infection prevention, providing a physical barrier that safeguards both patients and healthcare workers. The PPE categories most pertinent to routine hospital practice—including masks and respirators, gowns and aprons, gloves, and footwear covers—are primarily produced from fossil-based polymers such as polypropylene, polyethylene, and synthetic rubbers, resulting in durable materials that generate significant plastic waste after use (Karim et al., 2020; Uddin et al., 2022; Zhang et al., 2021). Consequently, discarded PPE contributes to ongoing plastic accumulation within clinical waste streams (Silva de Souza Lima Cano et al., 2025).

In practice, stricter infection-control practices typically entail increased consumption of single-use materials, creating a structural tension with efforts to reduce environmental burdens (Uddin et al., 2022; Zhang et al., 2021).

1.3. Pandemic-driven escalation of PPE consumption

The COVID-19 pandemic illustrates the scale of PPE consumption in healthcare systems. A life-cycle assessment of PPE supplied to health and social care services in England estimated that approximately 3 billion items distributed over six months in 2020 generated about 106,000 tons of CO₂-equivalent emissions, with gloves, aprons, and surgical masks contributing the largest shares (Rizan et al., 2021).

Global analyses similarly indicate that pandemic-related mask demand reached several hundred billion units between 2020 and 2022, generating life-cycle emissions exceeding 18 million tons of CO₂ equivalent (Li et al., 2023). These global totals indicate that each disposable mask generates average CO₂-equivalent emissions of tens of grams due to polymer production, manufacturing energy use, and end-of-life (EoL) treatment (Atilgan Türkmen, 2022; Tabatabaei et al., 2021).

PPE consumption, therefore, represents a persistent environmental hotspot within clinical protection practices and hospital waste systems (Ivanović et al., 2023).

1.4. Healthcare waste management and end-of-life pathways

Healthcare facilities generate heterogeneous waste streams, classified into non-hazardous and hazardous fractions, that require specialized treatment (Coban et al., 2023). Globally, hazardous waste accounts for approximately 10–25% of total healthcare waste (World Health Organization, 2024), although higher shares (40–46%) have been reported in large tertiary hospitals due to case mix complexity and infection-control practices (Kaposi et al., 2024; Nematollahi et al., 2025).

During the COVID-19 pandemic, healthcare waste generation increased sharply. In Wuhan, waste volumes rose five- to six-fold in early 2020 (Chen et al., 2021; Hanedar et al., 2022), while European hospitals reported increases from 0.2 to 1.4 to 5–8 kg per bed per day (Fraeyman et al., 2022). Such surges frequently exceeded treatment capacity and required emergency waste-routing decisions (Peng et al., 2020).

Incineration and non-incineration disinfection represent the dominant EoL pathways, often combined with landfill disposal (Liu et al., 2022; Nematollahi et al., 2025).

Incineration ensures rapid pathogen destruction and substantial volume reduction (~90%) but involves trade-offs, including greenhouse gas emissions and potential release of toxic pollutants such as dioxins

and furans under suboptimal conditions (Ajaj et al., 2023; Lin et al., 2015). Although energy recovery may partially offset these burdens, outcomes remain context-dependent (Deepak et al., 2022).

Sterilization-based treatments, such as steam autoclaving, are widely used to inactivate pathogens in infectious waste streams (Maamari et al., 2016). However, they do not eliminate material flows, resulting in plastic-rich residues typically disposed of via landfill or energy recovery. Consequently, these approaches may shift rather than eliminate long-term environmental burdens (Windfeld and Brooks, 2015).

Life cycle assessment (LCA) studies demonstrate that the environmental performance varies significantly across EoL pathways (Çetin et al., 2025; Kumar et al., 2021; Zlaugotne et al., 2025). Landfill-based systems tend to increase toxicity-related impacts, whereas thermal treatments entail higher energy use and emissions, leading to trade-offs that depend on system boundaries and impact categories (Ji et al., 2024; Mazhandu et al., 2023; Zlaugotne et al., 2025).

Recent life cycle assessments indicate that EoL routing and treatment choices for hospital plastic waste can influence environmental outcomes, highlighting the role of organizational waste-management decisions alongside upstream consumption patterns (Cho et al., 2024; Keul et al., 2024).

Segregation quality is a key determinant of downstream treatment intensity (Asare et al., 2025; Evliya Felek et al., 2025).

Within this context, improving segregation and routing fidelity is often the most actionable intervention at the institutional level, as even small changes in hazardous waste fractions directly affect treatment pathways and impact profiles (Nsanzimana et al., 2025).

This is particularly relevant for PPE, which is frequently over-classified as hazardous, increasing downstream treatment intensity despite unchanged waste volumes.

These findings highlight the need to evaluate EoL strategies under realistic operational constraints rather than as purely technology-optimization problems (Mushtaq et al., 2022; Zhao et al., 2021).

Table 1 summarizes the methodological characteristics and key findings of selected process-based LCA studies on PPE and healthcare waste management. Product- and PPE-level studies generally apply cradle-to-grave boundaries and identify material production as a major contributor (Rizan et al., 2021; Atilgan Türkmen, 2022; Li et al., 2023), whereas healthcare waste-management studies primarily compare downstream treatment, segregation, and recovery scenarios whose outcomes depend strongly on system boundaries, waste composition, and local energy conditions (Deepak et al., 2022; Cho et al., 2024; Ji et al., 2024; Asare et al., 2025).

1.5. Research gap and study objective

Much of the existing literature on healthcare waste treatment relies on hypothetical end-of-life scenarios or aggregated waste streams that are not grounded in real hospital operating conditions (Mazzei and Specchia, 2023). These approaches often assume simplified waste compositions and routing structures, limiting their applicability to actual facility-level decision-making.

This limitation is particularly relevant for PPE waste, a relatively homogeneous polymer-based stream whose classification as hazardous or non-hazardous directly determines downstream treatment pathways and associated environmental burdens. As a result, the mitigation potential achievable through institutionally controllable downstream interventions remains insufficiently quantified.

Facility-level analyses that assess realistic interventions—such as improved segregation or feasible adjustments to EoL routing—and scale results to annual hospital quantities remain limited. Addressing this gap is essential for supporting decision-making under real operational and infection-control constraints.

This study addresses this gap by conducting a facility-level LCA of PPE waste management using multi-year operational data. The analysis quantifies the environmental impacts of hospital-wide single-use PPE waste and

Table 1

Key methodological characteristics and findings of selected process-based life cycle assessment studies on PPE and healthcare waste management.

Study	Assessed system and data basis	Functional unit, system boundary and comparison	Key findings
Product- and PPE-level life cycle assessments			
Atılğan Türkmen (2022)	Disposable three-layer medical mask; primary manufacturing data from Türkiye with the Ecoinvent background database.	FU: one mask; cradle-to-grave, including raw materials, manufacturing, packaging, distribution, use and disposal; packaging and transport sensitivity analyses.	Raw-material supply dominated GWP (40.5%), followed by packaging (30.0%) and manufacturing (15.5%); incineration dominated several toxicity-related categories.
Kumar et al. (2021)	Disposable PPE kit (goggles, gloves, shoe covers, mask and body suit); measured item masses and manufacturer/literature specifications.	FU: 1 t of PPE kits; cradle-to-grave; centralized incineration, decentralized incineration and landfill disposal.	Decentralized incineration performed best overall; landfill had higher impacts in all assessed categories except GWP, and transport was non-negligible.
Li et al. (2023)	Disposable surgical mask; field data from the Chinese industrial chain with Ecoinvent background data.	FU: one mask; cradle-to-grave, including component production, assembly, packaging, transport and final disposal; landfill and incineration compared.	Each mask generated 20.5 g CO ₂ eq.; the nylon-66 ear loops were the largest source of total life-cycle impact (25.8%), and the EoL ranking depended on the energy mix.
Rizan et al. (2021)	Eight PPE items supplied to health and social care in England; item measurements, manufacturer information and national distribution data.	Item-level cradle-to-grave assessment scaled to six-month national quantities; domestic manufacture, reduced glove use, reuse and recycling scenarios.	Material production and clinical-waste disposal contributed, on average, 46% and 39% of item carbon footprints; combined interventions reduced the baseline footprint by 75%.
Snigdha et al. (2023)	Disposable polypropylene and reusable cotton-polyester body coveralls; India-specific inventory from literature, reports, interviews and expert consultation.	FU: 1000 kg of each coverall type; cradle-to-grave; 15 uses for reusable coveralls; landfill, incineration and electricity-supply sensitivity assessed.	Reusable coveralls performed better in all assessed categories except water consumption; electricity was the principal contributor, and solar electricity further reduced impacts.
Healthcare waste management life cycle assessments			
Asare et al. (2025)	Mixed waste from five Ghanaian hospitals; facility-specific data compiled from published Ghanaian hospital studies and literature-derived treatment inventories.	FU: 1 kg of mixed hospital waste; generation to treatment/final disposal; current practice and five scenarios combining 20–95% segregation with six treatment options; LCA, systems analysis and MCDA.	Segregation efficiency and treatment choice were the dominant levers; non-burn options ranked best and incineration with landfill worst. Reported reductions were relative to facility-specific baselines.
Çetin et al. (2025)	Istanbul medical-waste system; official municipal operating data, GaBi datasets, and literature-derived inputs.	FU: 1 t of medical waste; collection, transport, incineration, steam sterilization, landfill and energy recovery; baseline and four routing/minimization scenarios.	The segregation/minimization scenario with mixed treatment had the lowest aggregate environmental score; the incineration-intensive scenario performed worst overall, although GWP trade-offs remained.
Cho et al. (2024)	Plastic packaging from three medical-device procedures in one Korean hospital unit; measured waste masses and polymer composition.	FU: 1 kg of medical-device plastic packaging waste; gate-to-grave operational boundary; hazardous incineration, segregated general-waste landfill and mechanical recycling.	Segregation enabled large reductions relative to hazardous incineration, and recycling had the lowest overall impacts; upstream packaging production was outside the boundary.
Deepak et al. (2022)	Common biomedical-waste treatment facility in northern India; field surveys and semi-structured interviews with ecoinvent background data.	FU: 2547 kg day ⁻¹ , representing all waste collected by the facility; gate-to-gate; baseline integrated treatment compared with incineration with energy recovery.	Energy recovery reduced GWP and toxicity/ecotoxicity impacts by approximately 9.7–13.3%; incineration remained the largest treatment burden, with energy and consumables as influential parameters.
Hong et al. (2018)	Three medical-waste treatment facilities in southeastern China; actual 2015–2016 monitoring and cost data.	FU: 1 t of medical waste; gate-to-gate; pyrolysis, chemical disinfection and steam sterilization with residual disposal; combined LCA and LCC.	Steam sterilization had the highest overall environmental burden; energy and chemical production were dominant contributors, and energy recovery could change technology rankings.
Ji et al. (2024)	Industry-average Chinese medical-waste technologies; 37 verified inventory sources from enterprises and literature, supplemented by ten-city data.	FU: 1 t of medical waste; treatment-stage boundary; eight incineration/sterilization-residue combinations; LCA, LCC and NPV; transport and upstream waste burdens excluded.	Microwave sterilization with residue incineration had the lowest environmental impact, whereas steam sterilization with landfill was most economical; industry averages differed materially from single-facility results.
Mushtaq et al. (2022)	Five public hospitals in Pakistan; daily waste quantification and categorization over five months.	FU: 1 t of hospital waste; segregation, transport, treatment and disposal; current incineration/landfill compared with source segregation, decontamination and recycling.	The integrated scenario reduced net GHG emissions from 1078.40 to 989.31 kg CO ₂ eq. t ⁻¹ (8.3%) and enabled recovery of recyclable materials.

EoL, end-of-life; FU, functional unit; GHG, greenhouse gas; GWP, global warming potential; LCA, life cycle assessment; LCC, life cycle costing; MCDA, multi-criteria decision analysis; NPV, net present value; PPE, personal protective equipment.

evaluates the mitigation potential of alternative end-of-life routing and segregation strategies under real-world conditions. By integrating real operational data, the study bridges the gap between theoretical LCA modeling and practical hospital waste management.

This study builds upon previous PPE life cycle assessments by employing a facility-level approach based on multi-year operational data, rather than relying on generalized or model-based assumptions. By explicitly incorporating real-world segregation practices and treatment routing, the analysis identifies operational constraints that affect environmental outcomes. This method provides a more decision-focused assessment of mitigation potential in downstream waste management.

Against this background, the present study conducts a facility-level LCA of hospital-wide single-use PPE waste using multi-year operational data. As shown in Table 1, previous studies have generally centered on individual PPE products, national consumption scenarios, or downstream treatment systems (Kumar et al., 2021; Rizan et al., 2021; Atılğan Türkmen, 2022; Deepak et al., 2022; Li et al., 2023; Cho et al.,

2024; Ji et al., 2024; Asare et al., 2025). The present analysis integrates facility-specific procurement and waste-management data with a broader product-system boundary that retains upstream material production, observed segregation ratios, actual treatment routing, and annual hospital-scale quantities. Its specific contribution is to quantify the mitigation potential of institutionally controllable downstream interventions under real operating and infection-control constraints and to distinguish these achievable system-level reductions from the influence of upstream material flows.

2. Materials and methods

2.1. Goal and scope definition

The goal of this study is to operationalize a hospital-level, decision-support LCA framework for the facility-specific management of single-use PPE. Unlike previous PPE LCAs based on generalized assumptions,

this study uses multi-year facility-level operational data to capture real-world waste management practices. The analysis focuses on operational processes directly influenced by waste management practices, whereas upstream manufacturing choices and product design are treated as fixed background conditions due to limited data availability and the study's decision-oriented scope.

Two functional references are used. A functional unit of 1 kg of PPE waste enables consistent comparison across end-of-life options and product categories, aligning with the mass-based approach of waste management systems. Results are scaled to annual hospital volumes to facilitate the assessment of temporal trends and impacts relevant to facility-level decision-making.

The functional unit in this study is defined as 1 kg of single-use personal protective equipment (PPE) material entering the hospital waste-management system after use. This reference flow does not imply that PPE was collected as a physically separate waste stream. Rather, it represents a modeled PPE-specific material flow, based on institutional PPE utilization records and allocated to the hospital's documented non-hazardous and hazardous waste-management pathways.

The LCA was carried out in accordance with the principles and framework of the ISO 14040 and ISO 14044 standards (ISO, 2006a, 2006b). Inventory modeling used a process-based LCA approach, combining foreground data from hospital operational records with background datasets representing upstream material production and energy systems.

Foreground processes include waste generation, segregation, collection, transport, and EoL treatment under Hungarian regulatory conditions. Background processes were sourced from established life cycle inventory databases to reflect raw material production and upstream supply chains. This structure enables the identification of environmental impacts associated with institutionally controllable waste-management decisions while maintaining consistency with standard LCA practice.

The study is based on operational data from the University of Debrecen Clinical Centre, Nagyerdei Campus (Hungary). The broader composition of healthcare waste and the hospital-wide waste management practices of the investigated university hospital have been examined in detail in a previous study and provide the contextual background for the present PPE-focused LCA (Kaposi et al., 2024). The reference year for scenario analysis is 2023, while annual quantities are evaluated for the 2019–2023 period.

These previously reported primary waste characterization data were not used to define PPE material composition. Their role in the present study was limited to validating institutional waste-routing practices and supporting the allocation of PPE flows within the existing hospital waste management structure.

This design makes sure the analysis shows realistic operational limits while allowing comparison of different waste-management options.

2.2. System boundary and end-of-life scenarios

The life cycle assessment uses a cradle-to-grave system boundary with defined exclusions, emphasizing the environmental impacts of waste-management options at the facility level. The model includes raw-material production and background energy systems, facility-level PPE use, waste segregation, transport, and EoL treatment. Foreground processes comprise activities the hospital manages directly, whereas background processes are sourced from life cycle inventory databases. Product-specific manufacturing and assembly processes and upstream logistics beyond raw-material production are excluded because primary data were unavailable and transparency within PPE supply chains was limited.

Fig. 1 illustrates the system boundary of the life cycle assessment for hospital PPE waste management, including foreground processes related to hospital waste handling and conventional end-of-life treatment pathways, and background processes representing upstream material production and energy systems. The selected scenarios represent treatment technologies currently applied or technically feasible within European Union healthcare waste-management systems.

The broader system boundary aligns with recent healthcare sustainability frameworks. It includes raw material production for PPE components, facility-level use, waste segregation, transportation, and downstream treatment. Product-specific manufacturing processes, assembly, and upstream logistics beyond raw material production are excluded due to a lack of primary data and limited transparency in PPE supply chains.

Fig. 2 illustrates the PPE waste management system, encompassing use, waste segregation, and end-of-life treatment pathways. In 2023, non-hazardous treatment (EoL A, 56.8%) represented the predominant institutional end-of-life route, followed by hazardous autoclave and landfill (EoL C, 36.2%) and hazardous incineration (EoL B, 7.0%). These proportions served as the baseline configuration for subsequent impact assessments.

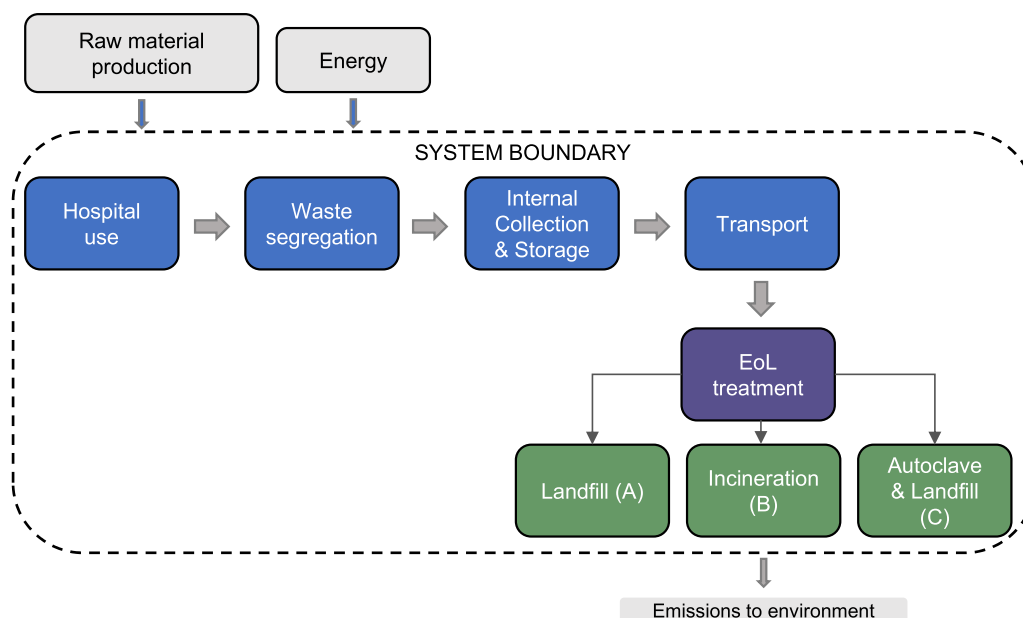


Fig. 1. System boundary and process flow of PPE waste management in a hospital setting.

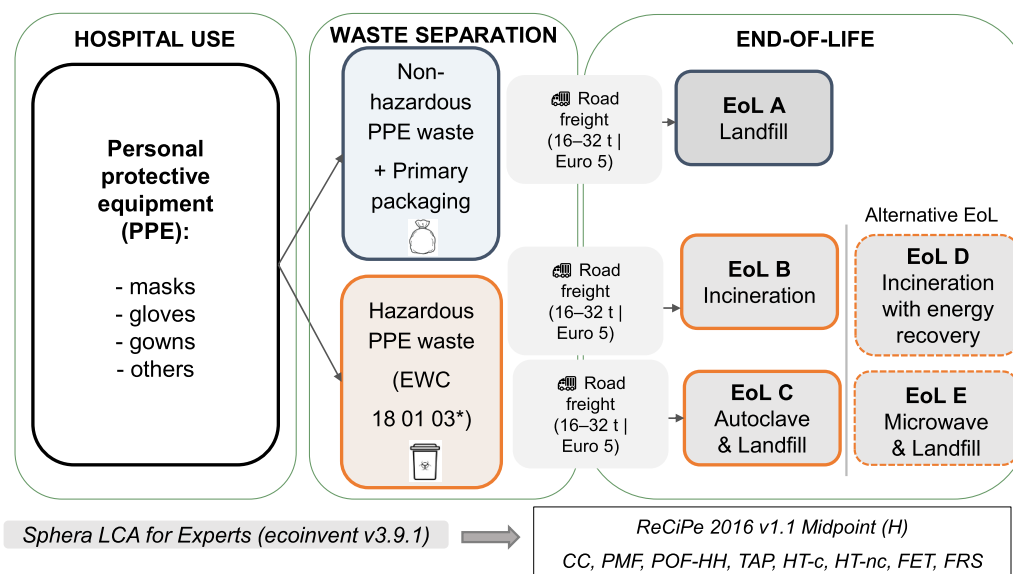


Fig. 2. System boundaries and pathways for PPE use, waste segregation, and end-of-life treatment. Institutional EoL distribution (2023): non-hazardous (EoL A) 56.8%, hazardous incineration (EoL B) 7.0%, hazardous autoclave and landfill (EoL C) 36.2%.

The EoL distribution describes the routing of the modeled PPE material flow within the existing hospital waste-management system. In standard practice, used PPE is directed either to the non-hazardous municipal-like healthcare waste stream or to the hazardous infectious healthcare waste stream, based on contamination status, location of use, and institutional segregation protocols. PPE was not managed as a separately collected waste fraction across the facility. Instead, PPE quantities were reconstructed from procurement and usage data, then allocated to the appropriate institutional treatment routes according to the established waste-segregation and treatment framework.

The evaluated system consists of single-use PPEs commonly used in clinical settings, including surgical masks, FFP2 masks, latex gloves, nitrile gloves, sterile surgical gloves, polyethylene aprons, surgical gowns, protective gowns, protective caps, and shoe covers. LCA includes primary packaging and waste-collection receptacles. It ensures that all auxiliary material flows related to PPE handling are systematically considered.

At the hospital-wide level, PPE waste is segregated into non-hazardous and hazardous streams in accordance with European Union and Hungarian healthcare waste regulations. Non-hazardous PPE waste, including primary packaging, is directed to landfill disposal (EoL A). This pathway excludes any sterilization or disinfection step, as waste assigned to EoL A is managed as non-hazardous, municipal-type healthcare waste under the institutional segregation system. Sterilization-based treatment is reserved exclusively for the hazardous infectious healthcare waste fraction, in accordance with relevant European Union and Hungarian waste management regulations (European Commission, 2000; Law CLXXXV, 2012; EMMI, 2017).

PPE designated as hazardous is classified as infectious healthcare waste under European Waste Catalogue (EWC) code 18 01 03*, which applies to waste requiring special collection and disposal measures to prevent infection. This category includes PPE contaminated with blood, body fluids, infectious agents, or waste generated during the care of infectious patients (EMMI, 2017; Law CLXXXV, 2012). Management of this waste involves either incineration without energy recovery (EoL B) or steam autoclave sterilization followed by landfill disposal of the treated residue (EoL C). In this context, sterilization refers to the process of inactivating pathogens.

In addition to the institutional reference configuration, two alternative end-of-life options were modeled for comparative decision-support: incineration with energy recovery (EoL D) and microwave

treatment followed by landfill disposal (EoL E). To maintain consistency, transport distances for alternative scenarios were assumed to be equivalent to those in the corresponding reference treatment routes.

Year-specific hospital-wide EoL distributions were obtained from available operational data, with the 2023 configuration serving as the reference for scenario-based analysis. The organizational-level EoL distribution for the reference year is reported in the Note accompanying Fig. 2. Overall, 56.8% of the waste stream is assigned to EoL A. The remaining 43.2% comprises hazardous PPE waste, split between EoL B and EoL C: 7.0% and 36.2%, respectively.

This system definition allows for a consistent comparison of waste management strategies controllable by institutions under realistic operational conditions.

2.3. Life cycle inventory and data sources

The life cycle inventory (LCI) utilized facility-specific primary data on hospital-wide personal protective equipment (PPE) volumes, waste segregation ratios, treatment routes, and transport distances. Material compositions and unit masses were determined from manufacturer specifications for each PPE category. The analyzed PPE stream should be considered plastic-rich rather than entirely plastic. Dominant materials comprised polypropylene (PP), low-density polyethylene (LDPE), high-density polyethylene (HDPE), polyester-based textile components, nitrile-butadiene rubber in nitrile gloves, and natural rubber latex in latex gloves. Minor components, including aluminum nose strips, low-alloy steel elements, paper-based packaging, and biobased textile materials, were incorporated as specified in the product documentation.

Data completeness was assessed against hospital-wide procurement records for 2019–2023, which were available for every included PPE category in each study year. Between one and five distinct products were identified within each category, with identical products sometimes supplied by multiple vendors. The product with the highest procurement volume was selected as representative, and it accounted for >80% of procured units in every category. Unit masses and material compositions, including primary packaging, were derived from the corresponding manufacturer documentation. No independent weighing or product disassembly was performed. Procurement quantities were used as a proxy for PPE consumption without adjustment for stock changes, write-offs, or returns.

Environmental burdens were quantified by linking product-specific

material compositions and unit masses to relevant background datasets for each material component. Total PPE-related impacts were calculated by multiplying unit-level material inventories by annual procurement quantities and allocating these flows to the respective end-of-life routes according to observed institutional segregation ratios.

Supplementary Table S1 summarizes the material composition and unit masses used to parameterize the PPE foreground and explicitly defines the waste-collection items included in the system. Primary packaging and waste-collection receptacles are modeled as foreground flows and parameterized using manufacturer specifications and facility-level data to ensure consistent representation of auxiliary processes.

Primary packaging and waste-collection receptacles were included as foreground flows and parameterized using manufacturer specifications and facility-level data, to ensure consistent representation of associated auxiliary flows. Background data were sourced from the Sphera Managed LCA Content (MLC) database (Professional Core), implemented in Sphera LCA for Experts (Sphera, 2023). Additional background data were obtained from the ecoinvent v3.9.1 database (Wernet et al., 2016) (see SI Table S1).

Water consumption was modeled at the user level as tap water, and the corresponding wastewater flow was directed to treatment. Transportation was modeled using heavy-duty truck processes (EURO5), with average distances based on standard organizational procedures.

Inventory data for autoclave and microwave treatment were derived from measured values or manufacturer-provided operational parameters. Autoclave and microwave treatment inventories represent industrial-scale, electrically operated systems consistent with current healthcare waste management practices.

Process-level inventory inputs for each modeled end-of-life route, such as transport, landfill, incineration, autoclave sterilization, and microwave treatment, are detailed in Supplementary Table S2. This table outlines the primary foreground inputs, associated background processes, quantities, units, and data sources for each treatment option.

A simplified material flow allocation approach was implemented to enhance inventory transparency. Annual quantities of personal protective equipment (PPE) were converted into total material flows using product-specific masses, allocated to non-hazardous and hazardous waste streams, and subsequently distributed across the modeled end-of-life routes based on observed institutional treatment shares.

This life cycle inventory structure maintains consistency between facility-level operational data and background system representations.

2.4. Impact assessment and analytical approach

During the life cycle impact assessment (LCIA), the ReCiPe 2016 Midpoint (H) method was employed, which is commonly used in healthcare-related LCA studies and enables consistent comparisons across environmental impact categories.

The selected midpoint indicators comprise Climate Change (including biogenic carbon) (CC), Particulate Matter Formation (PMF), Photochemical Ozone Formation - Human Health (POF-HH), Terrestrial Acidification (TAP), Human Toxicity - cancer (HT-c), Human Toxicity - non-cancer (HT-nc), Freshwater Ecotoxicity (FET), and Fossil Resource Scarcity (FRS). Biogenic carbon is attributed to biomass-derived materials, including paper packaging, latex gloves, and biobased textiles.

For outcome-focused interpretation, a subset of indicators was grouped into climate- and resource-related, air-quality-related, and human- and freshwater-toxicity-related impacts. Normalization was applied using ReCiPe 2016 Midpoint (H) World method, including biogenic carbon (person-equivalent) factors.

The contribution analysis identified dominant life-cycle stages and process groups for each functional unit, and annual scaling enabled evaluation of temporal trends and institutional relevance. Sensitivity analysis was conducted through deterministic scenario modeling of alternative EoL routing and waste segregation ratios, focusing on parameters under direct hospital decision-making control.

3. Results

3.1. Baseline functional-unit results

Supplementary Table S3 reports the environmental impacts per 1 kg functional unit for each PPE option across the selected midpoint indicators.

These baseline results provide a harmonized reference for comparing the environmental performance of individual PPE items independent of organizational consumption levels. FFP2 masks show the highest CC impact, while surgical gowns exhibit the lowest values. For human toxicity non-cancer (HT-nc), nitrile gloves appear as the most impact-intensive option among the analyzed PPE items (see SI Table S3).

3.2. Contribution analysis of the institutional system

Facility-level activity data used to scale functional-unit results to annual impacts are presented in Supplementary Table S4. Between 2019 and 2023, total PPE mass ranged from approximately 84 t to 164 t and peaked in 2021. In 2023, waste-collection receptacles contributed approximately 19.2 t, and primary packaging accounted for approximately 8.14 t at the hospital scale (see SI Table S4).

Fig. 3 presents the relative contribution of EoL-related impacts by process group at the 1 kg functional-unit level, illustrating the relative contributions of material production, transport, and end-of-life treatment processes.

The underlying process-level inventory assumptions for each end-of-life route, including transport requirements and treatment-specific inputs, are provided in Supplementary Table S2. Across all routes, PPE material production constitutes the dominant contribution, while EoL treatment processes, transport, primary packaging, and waste bins play secondary roles.

Overall, the contribution analysis highlights that the environmental profile of hospital-wide PPE waste streams is largely determined upstream, at the stage of material production rather than at end-of-life treatment.

3.3. Institutional impacts and temporal trends

The temporal distribution of PPE quantities also captures the impact of the COVID-19 pandemic, with a pronounced peak in 2021 corresponding to the highest system-wide pressure at the study site and elevated PPE use still evident in 2022. This result is consistent with trends reported for healthcare PPE consumption during the pandemic (Kumar et al., 2021).

Fig. 4 presents annual trends (2019–2023) in institutional EoL-related impacts, disaggregated by treatment route (EoL A, EoL B, EoL C) across the selected midpoint indicators. The results are based on the complete facility-level system and therefore include PPE materials, primary packaging, transport, and waste-collection receptacles.

Across all impact categories, a pronounced peak is observed in 2021, followed by a partial attenuation in 2022–2023. This temporal pattern is consistent across all assessed midpoint indicators, indicating a system-wide scaling effect rather than category-specific behavior.

For all categories, EoL A remains the dominant contributor at the organizational level, followed by EoL C, while EoL B accounts for a substantially smaller share. This reflects the predominance of non-hazardous waste flows within the EoL distribution (56.8%).

The relative ordering of treatment routes remains stable over time, suggesting that year-to-year variation is primarily driven by changes in activity levels rather than shifts in the EoL mix.

Toxicity-related indicators (HT-c, HT-nc, FET) largely follow the same temporal profiles as climate- and resource-related categories, indicating no disproportionate sensitivity to treatment routing under the observed hospital-scale configuration. A minor deviation is observed in 2021 for HT-nc in EoL B, where the throughput-related peak is less

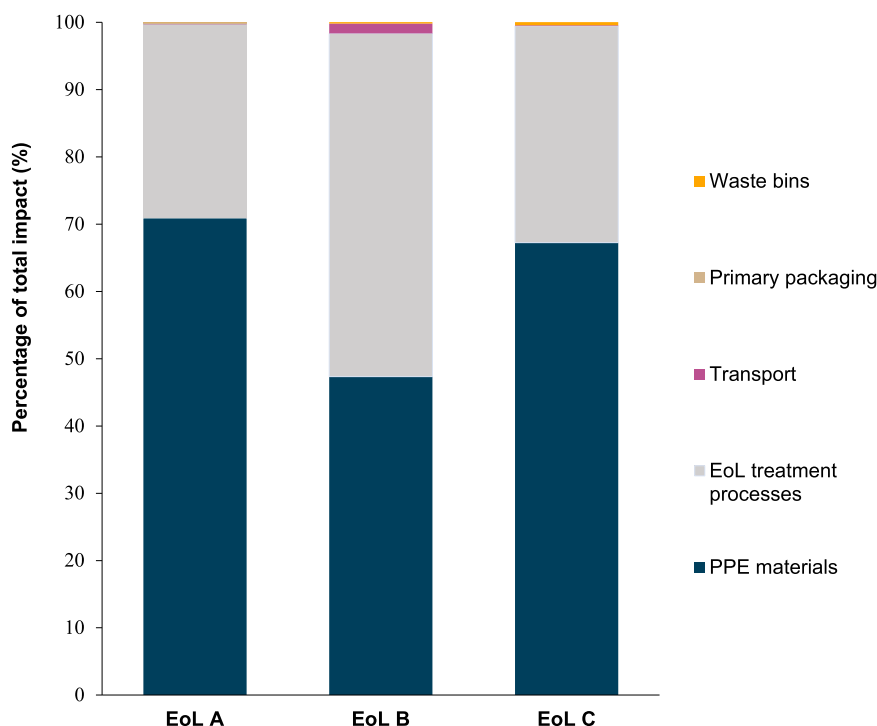


Fig. 3. Contribution of process groups to total environmental impacts for each end-of-life pathway at the 1 kg functional unit. PPE material production dominates across all scenarios.

pronounced.

This reflects the fact that non-carcinogenic toxicity from incineration is driven by a limited set of specific emission flows whose contributions do not scale linearly with waste throughput in midpoint LCIA frameworks, as also discussed in a healthcare waste LCA (see Fig. 4).

Table 2 summarizes the annual aggregated impacts of the complete system under the reference EoL mix (EoL A + EoL B + EoL C), explicitly including PPE materials, primary packaging, transport, and waste-collection receptacles.

Across all impact categories, 2021 represents a clear outlier, with total impacts increasing by approximately 80–106% relative to 2020. CC burdens nearly doubled (+96%), closely mirrored by PMF (+96%) and FRS (+100%). Toxicity-related indicators show slightly lower but still pronounced increases, with approximately +79% for HT-c, +88% for HT-nc, and +90% for FET.

3.4. Interpretation of normalized impact profiles

In the 2023 reference year, Fig. 5 consolidates midpoint indicators into three decision-relevant impact groups at the institutional level. The results are presented on a logarithmic scale to address differences in magnitude across categories.

Human and freshwater toxicity-related impacts dominate the overall profile across all EoL routes, exceeding air-quality-related outcomes by roughly one order of magnitude and climate- and resource-related burdens by a factor of ~3–5, depending on the treatment route.

Process-level contribution analysis identified category-specific drivers within this group (Table S5). Landfill treatment accounted for 81.2% of FET and 83.8% of HT-nc, whereas HT-c was distributed mainly among synthetic rubber production (30.5%), hazardous-waste incineration treatment (15.4%), and natural rubber latex production (12.6%).

Within this grouping, EoL A shows the highest absolute toxicity burden, while EoL B yields the lowest values, reflecting the combined effect of treatment efficiency and the hazardous fraction size under the observed waste distribution.

By contrast, differences between routes are comparatively smaller

for climate- and resource-related burdens, indicating that downstream EoL choices modulate toxicity outcomes more strongly than energy- and resource-driven categories.

3.5. Scenario analysis, sensitivity analysis, and mitigation potential

The scenario analysis evaluates the influence of alternative EoL routings on the annual environmental impacts of the PPE waste stream. The assessed scenarios include variations in the relative shares of incineration and sterilization-based treatment routes, reflecting operationally plausible adjustments within the existing waste management framework. Scenario results are summarized in Table 3.

Table 3 shows that, in the combined best-case scenario, reductions in the non-toxicity indicators range from 4.54% for POF-HH to 6.17% for CC. Among the toxicity indicators, HT-c demonstrates the highest relative sensitivity, with reductions ranging from 2.41% to 11.20%. In contrast, HT-nc and FET show only marginal changes, including minor increases of up to 0.31% for HT-nc and 0.54% for FET in selected scenarios.

Overall, even under optimized combined scenarios, reductions remain in the single digits, indicating limited mitigation potential under current operational constraints for EoL routing and segregation measures.

Fig. 6 presents human and freshwater toxicity-related impacts, utilizing normalized results to examine decision-relevant EoL and segregation adjustments while maintaining a constant total waste mass.

As illustrated in Fig. 6, increasing the hazardous waste fraction by 10–20% results in a proportional increase in impacts (+2.39% to +4.79%), while equivalent reductions in hazardous routing yield comparable decreases (−2.39% to −4.58%). This indicates that misclassification systematically worsens outcomes, whereas improved segregation provides measurable but limited benefits.

In contrast, isolated EoL technology shifts within the hazardous stream result in only minor reductions (~−1.6%), highlighting the limited effect of treatment substitution when applied to a relatively small waste fraction. Across combined scenarios, the maximum

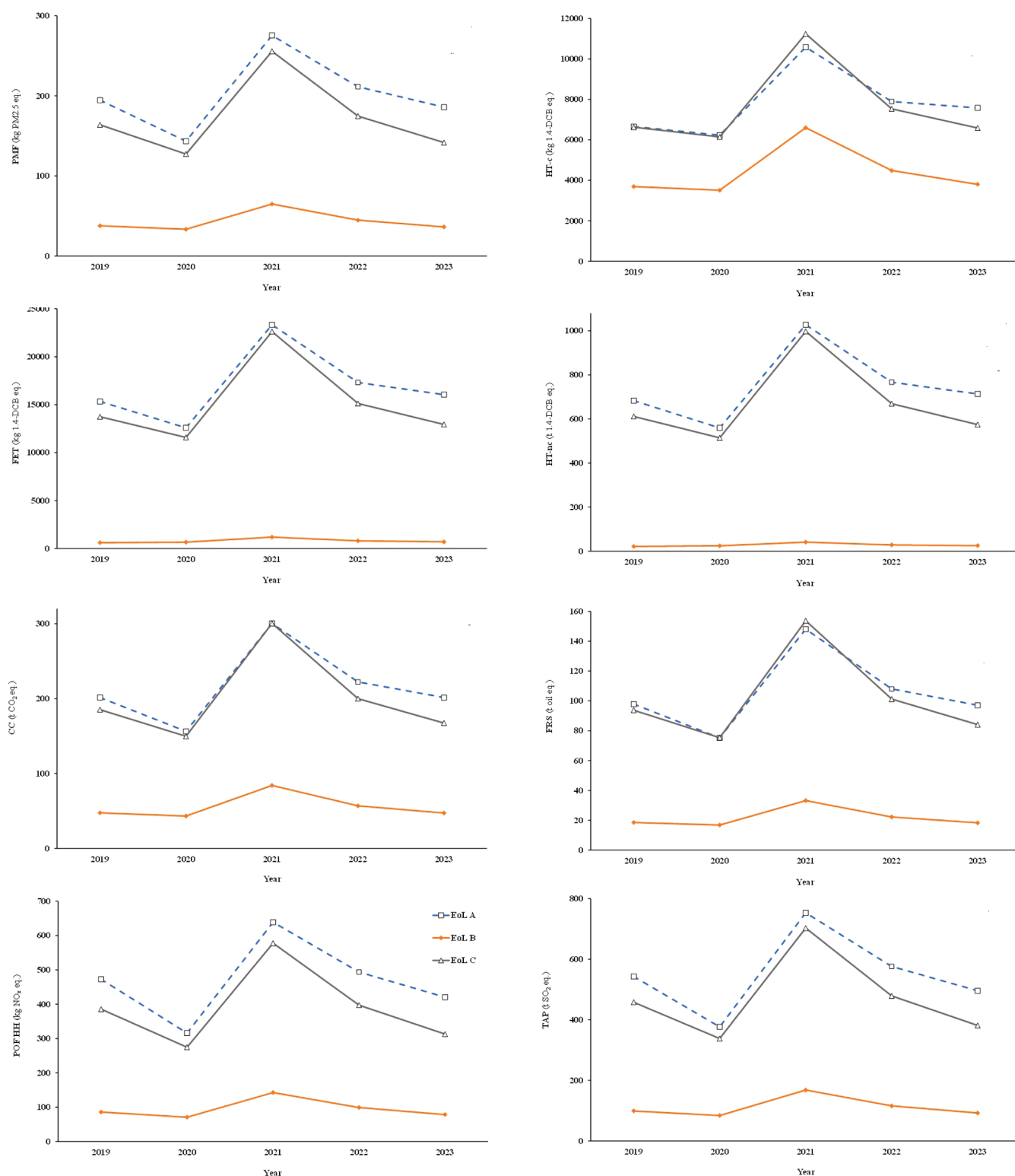


Fig. 4. Trends in environmental impacts of PPE end-of-life pathways (2019–2023) across multiple ReCiPe midpoint indicators. Panels (a–h) represent climate change (CC), fossil resource scarcity (FRS), particulate matter formation (PMF), human toxicity—cancer (HT-c), photochemical oxidant formation—human health (POF-HH), human toxicity—non-cancer (HT-nc), terrestrial acidification (TAP), and freshwater ecotoxicity (FET), respectively.

reduction reaches 6.58% relative to the baseline.

These findings are consistent with previous LCA studies, which report similarly modest improvements from EoL interventions (Van Caneghem et al., 2019; Rizan et al., 2021; Deepak et al., 2022). Although alternative treatments such as microwave sterilization may

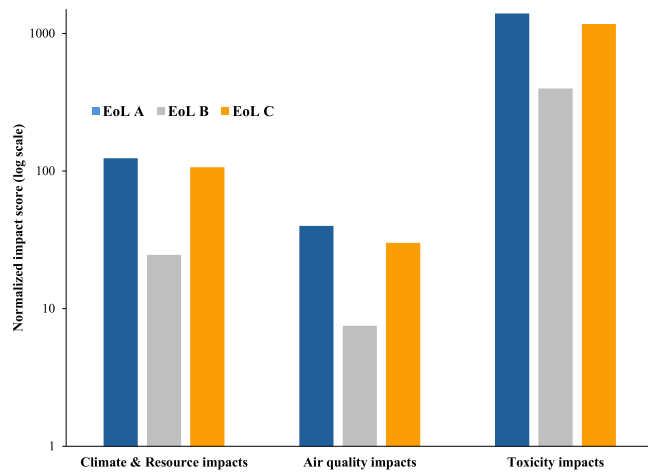
offer slight environmental advantages over steam autoclaving, these differences remain context-dependent and sensitive to system boundaries and energy inputs (Soares et al., 2013; Zhao et al., 2021).

Overall, the environmental profile remains largely governed by upstream material production, indicating that EoL strategies play a

Table 2

Annual environmental impacts of the institutional PPE system (reference year: 2023, EoL mix).

Year	CC [kg CO ₂ eq]	PMF [kg PM _{2.5} eq]	POF-HH [kg NO _x eq]	TAP [kg SO ₂ eq]	HT-c [kg 1,4-DCB eq]	HT-nc [kg 1,4-DCB eq]	FET [kg 1,4-DCB eq]	FRS [kg oil eq]
2019	434,418	396	944	1100	16,977	1316,056	29,691	210,195
2020	349,431	304	661	799	15,886	1097,968	24,847	167,454
2021	684,730	596	1359	1624	28,421	2065,724	47,137	335,054
2022	479,116	431	990	1171	19,908	1463,858	33,246	231,500
2023	416,194	364	812	970	17,966	1312,932	29,687	199,528

**Fig. 5.** Normalized environmental impacts (logarithmic scale) for climate and resource use, air quality, and toxicity-related categories across end-of-life pathways for the reference year 2023.

secondary role in reducing impacts, in line with recent scenario-based LCAs of healthcare waste systems (Keul et al., 2024; Lingegård et al., 2025).

4. Discussion

This study presents a facility-level assessment of PPE waste management under real-world conditions, focusing on the environmental impacts of end-of-life routing and waste segregation. The findings indicate that while downstream interventions produce consistent, predictable outcomes, their overall capacity to mitigate environmental impacts is limited. By integrating operational data and institutional constraints, the analysis provides decision-relevant insights into the structural role of waste management in healthcare systems and underscores the predominant influence of upstream material flows.

4.1. Structural drivers of environmental impacts in healthcare waste systems

The environmental profile of hospital PPE waste is primarily influenced by upstream material production and consumption volumes,

rather than by downstream EoL routings. Unit masses and material compositions are consistent with previous PPE life cycle assessments (Bouchet et al., 2021; Li et al., 2023), which supports the representativeness of the foreground inventory. Contribution analysis demonstrates that the modeled raw-material production processes consistently dominate environmental impacts across all EoL scenarios.

Therefore, mitigation strategies that focus on reducing materials, redesigning products, or substituting with lower-impact materials tend to be more effective than changes to downstream waste management. Institutional-scale temporal trends closely follow PPE consumption, which explains why adjustments to treatment pathways result in only incremental impact reductions. Similar throughput-driven patterns have been observed in cradle-to-grave LCAs of hospital products, where downstream management plays a secondary role compared to material production and use-phase scaling (Hernandez et al., 2023).

Excluding product-specific manufacturing, assembly, and upstream logistics limits the completeness of the absolute product footprints and may affect how impacts are distributed across upstream processes. However, the PPE mix, material composition, and total mass remain constant across the evaluated EoL scenarios. Including these omitted stages would therefore add a common upstream burden without altering the absolute differences or the ranking between the downstream configurations. A more comprehensive supply-chain representation may redistribute contributions among raw-material production, manufacturing, and logistics, but would not be expected to weaken the conclusion that the relative mitigation achievable through downstream interventions is limited, and may further reinforce it.

As summarized in Table 1, direct numerical comparison with previous studies is constrained by methodological heterogeneity. Product-level PPE studies commonly use item- or product-specific functional units within cradle-to-grave inventories (Rizan et al., 2021; Atılğan Türkmen, 2022; Li et al., 2023; Snigdha et al., 2023), whereas healthcare waste-treatment studies generally apply mass-based functional units and gate-to-gate or treatment-stage boundaries that exclude product manufacture (Hong et al., 2018; Deepak et al., 2022; Ji et al., 2024). The present analysis combines a 1 kg PPE reference flow with annual hospital-scale quantities and multi-year, facility-specific data, while retaining raw-material production alongside observed segregation ratios and actual treatment routing. This broader boundary explains why downstream processes account for a smaller share of total impacts than in studies restricted to waste treatment. Nevertheless, the predominance of upstream processes is consistent with product-level evidence: raw-material supply accounted for 40.5% of GWP in Atılğan

Table 3

Percentage change results for impact-reducing EoL and waste-fraction scenarios in comparison to the baseline.

Relative change (%)								
Scenario name	CC	PMF	POF-HH	TAP	HT-c	HT-nc	FET	FRS
Baseline (proxy EoL)	0	0	0	0	0	0	0	0
EoL B → EoL D	-2.57	-2.95	-2.43	-2.39	-2.41	-0.42	-0.48	-1.59
EoL C → EoL E	-1.37	-1.65	-1.21	-1.70	-2.47	-0.61	-0.37	-1.83
Reduced hazardous waste fraction (10%)	-1.95	-1.42	-1.20	-1.38	-4.18	0.22	0.17	-1.78
Reduced hazardous waste fraction (20%)	-3.72	-2.73	-2.28	-2.65	-8.18	0.31	0.54	-3.40
Combined best-case (EoL D + EoL E + 10% lower hazardous share)	-5.14	-5.15	-4.14	-4.69	-8.12	-0.62	-0.52	-4.54
Combined best-case (EoL D + EoL E + 20% lower hazardous share)	-6.17	-5.58	-4.54	-5.19	-11.20	0.00	0.02	-5.52

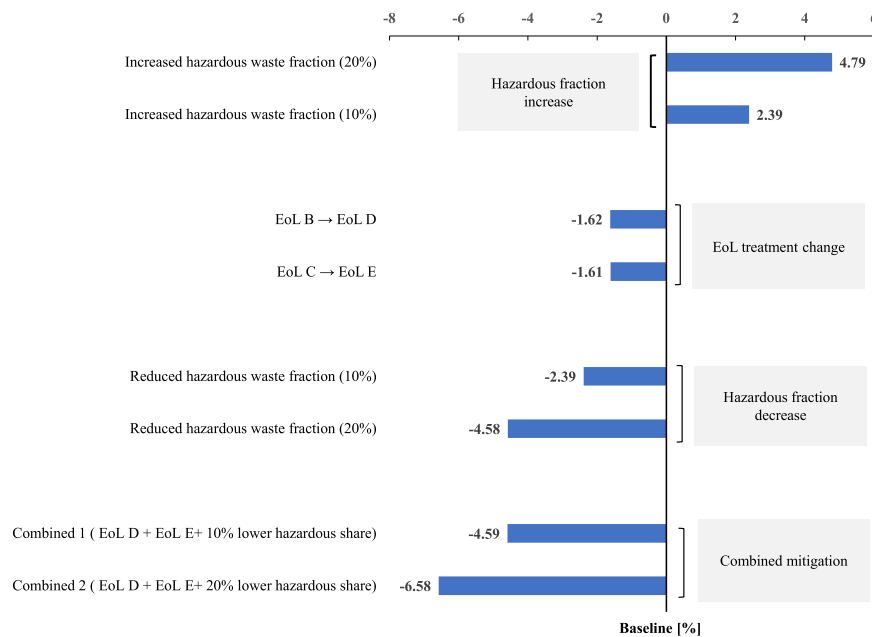


Fig. 6. Percentage relative change in human and freshwater toxicity impacts across end-of-life pathways and waste-fraction scenarios for the reference year 2023, relative to the baseline configuration.

Türkmen (2022), while Rizan et al. (2021) attributed, on average, 46% of PPE carbon footprints to material production and 39% to clinical-waste disposal.

From a waste management perspective, this finding challenges the common implicit assumption in healthcare waste policy and practice that optimization of treatment technologies alone can substantially reduce environmental burdens. Instead, the results show that waste-generation intensity, driven by infection-control protocols and procurement choices, is the primary system-level driver. This suggests that healthcare waste systems should be conceptualized not only as downstream treatment infrastructures but also as material-flow management systems integrated into clinical decision-making and procurement structures.

4.2. Limited impact of downstream interventions

Scenario analysis indicates that realistic improvements in waste separation and EoL routing yield only minimal environmental benefits. Even under best-case scenarios, downstream optimization yielded only limited reductions within the studied system configuration.

From a decision-support perspective, the limited differences between EoL A and EoL C underscore the restricted mitigation potential achievable solely through feasible end-of-life adjustments. While EoL C generally results in lower per-mass impacts compared to EoL A, the absolute annual reductions at the facility scale remain minimal. EoL B has a negligible effect on total impacts, given its low proportion of hazardous waste, despite its higher treatment intensity per kilogram.

Operationally, two implications arise: (1) switching between incineration, sterilization, or other treatment methods changes the impact profiles but does not significantly alter overall system outcomes; (2) improvements in segregation reduce burdens but have diminishing returns, making them necessary yet insufficient interventions.

These findings indicate that optimization within existing treatment systems offers incremental gains but cannot compensate for high material throughput.

The relative ordering of EoL-related outcomes observed at the functional-unit level is consistent with patterns reported in previous healthcare and PPE LCA studies (Kumar et al., 2021; Rizan et al., 2021).

The magnitude of the present changes is also comparable with the

incremental improvements reported in treatment-focused studies. Deepak et al. (2022) reported reductions of 9.7–13.3% in GWP and toxicity/ecotoxicity impacts after introducing energy recovery, while Mushtaq et al. (2022) reported that the integrated segregation, decontamination, and recycling strategy reduced net GHG emissions by 8.3%. In the present analysis, reductions generally remained below 6–7%, although HT-c showed a larger response (−11.20%) in the sensitivity analysis. Differences in functional units, LCIA methods, system boundaries, and scenario definitions preclude direct numerical ranking, but the results consistently indicate that feasible downstream interventions provide incremental, not transformative, reductions.

4.3. Role of waste segregation as a control parameter

Although its overall mitigation potential is limited, waste segregation remains a highly effective operational factor in institutional decision-making.

The limited mitigation potential observed is therefore not a shortcoming of the analyzed scenarios but rather a structural characteristic of institutional PPE waste systems operating under infection-control constraints.

The results indicate that misclassification of hazardous waste increases impacts (+2–5%), while better segregation decreases impacts (−2–5%), consistent with previous findings on improper waste segregation (Nsanzimana et al., 2025). It shows that segregation quality directly influences treatment intensity, routing choices, and related environmental burdens, as noted in the previous literature sources (Asare et al., 2025; Nsanzimana et al., 2025).

From a system-design perspective, segregation should be treated as a control variable that determines system efficiency, rather than a purely administrative task (Asare et al., 2025). These measures can improve environmental performance without requiring infrastructural changes.

4.4. Dominance of toxicity-related impacts and implications for treatment choices

Normalized results demonstrate that human and freshwater toxicity are the predominant contributors to the environmental profile, exceeding climate- and resource-related burdens by approximately a

factor of 3–5, depending on the treatment route. This pattern is consistent with findings reported by Snigdha et al. (2023) and Zheng et al. (2025).

Process-level contributions indicate that the underlying drivers differed among the toxicity indicators. Landfill treatment dominated FET and HT-nc, whereas HT-c was driven mainly by upstream polymer production, with an additional contribution from hazardous-waste incineration (Table S5).

Kumar et al. (2021) also reported that landfill scenarios significantly increase human toxicity and ecotoxicity, whereas climate impacts remain comparatively lower without energy-intensive treatment. Hong et al. (2018) also identified landfill as an important contributor in several impact categories, although its influence varied by treatment technology and impact category. Plastic-rich PPE fractions, including single-use polymer items, are major contributors to non-carcinogenic toxicity and ecotoxicity, primarily via disposal processes such as open burning and recycling (Zheng et al., 2025). Component-level evidence identifies elements like aluminum nose pieces as significant sources of human and aquatic toxicity (Ajaj et al., 2023).

The results underscore a fundamental trade-off in waste management systems: landfill-based methods increase toxicity, while thermal treatments result in higher energy consumption and emission intensity.

Consequently, optimal system design should account for multiple environmental impact categories rather than focusing exclusively on climate change.

From a policy perspective, healthcare waste management strategies should integrate toxicity-sensitive indicators, conduct long-term environmental risk assessments, and implement material-specific routing methods.

4.5. Implications for healthcare waste management policy and system design

The findings indicate that effective mitigation necessitates a transition from treatment-focused approaches to system-oriented strategies.

Given that waste management outcomes are closely associated with material selection, product design, and consumption intensity, it is essential to integrate procurement into waste management frameworks and to introduce LCA-based procurement criteria.

Because annual impacts closely tracked PPE throughput and polymer production contributed substantially to toxicity, procurement should first target high-volume, high-impact products, particularly gloves. After clinical and infection-control requirements have been met, tenders could compare product mass, material composition, packaging intensity, and available product-level environmental data. Demand-management measures should include protocol-based PPE use, monitoring consumption by product group, and preventing losses from expired stock. Reusable gowns and other alternatives should be evaluated only where equivalent protective performance can be ensured, and the impacts of laundering, sterilization, and transport are included.

This study demonstrates that LCA can be implemented as a decision-support tool under real-world constraints, rather than serving solely as a theoretical assessment. Facility-level LCA can inform routing decisions, segregation policies, and investment prioritization.

As a future extension, the framework could be formulated parametrically by linking PPE throughput and composition, segregation ratios, EoL routing shares, transport distances, treatment performance, and energy mixes to the impact calculations. This would enable exploration of operational configurations and prospective scenarios without rebuilding the LCA model, while clinical, infection-control, and regulatory requirements could define feasible parameter ranges. Such an approach could strengthen facility-level decision support by identifying environmentally preferable configurations across varying operational conditions (Spreafico and Ördök, 2025).

Overall, the results suggest that healthcare waste systems should be conceptualized as coupled material and clinical systems, in which

clinical safety requirements, material flows, and waste management infrastructure interact dynamically.

This perspective advances beyond technology-centered optimization toward system-level optimization within operational constraints.

The analytical framework is likely transferable to healthcare systems with comparable reliance on single-use PPE and infection-control requirements. The limited mitigation potential of downstream interventions is also likely transferable in order of magnitude, as supported by the incremental reductions reported in other treatment-focused healthcare waste LCAs (Deepak et al., 2022; Mushtaq et al., 2022). However, the precise reduction magnitudes, normalized impact profile, and treatment rankings depend on the local PPE mix, segregation performance, treatment infrastructure, transport distances, energy system, and regulatory framework. Application elsewhere therefore requires local parameterization.

4.6. Limitations

This study identifies downstream waste management as a structurally constrained process in healthcare systems dominated by infection-control-driven material throughput. It must be interpreted within several system boundaries.

First, the single-hospital case limits generalizability, although the observed dominance of material production is consistent with previous healthcare LCAs, suggesting broader relevance.

Second, uncertainties in foreground inventory data, manufacturer-based material compositions, background datasets, and transport assumptions were not propagated quantitatively through the model. These uncertainties may affect absolute impact estimates and the magnitude or ranking of the relatively small differences between downstream scenarios; accordingly, these results should be interpreted as deterministic estimates under the stated assumptions.

Third, the scenario results assume constant total waste mass. Therefore, they isolate the effect of EoL routing and segregation rather than reflecting full system dynamics.

Fourth, the scope did not include product-specific manufacturing, assembly processes, upstream logistics beyond raw-material production, or upstream interventions such as reuse and redesign. Therefore, the limited mitigation potential identified pertains only to downstream interventions within the studied system configuration, not the entire healthcare PPE system.

Finally, dedicated bioenergy and biofuel production routes were not modeled as independent EoL options. These emerging valorization pathways may provide additional recovery opportunities consistent with zero-waste and bioeconomy principles and should be assessed in future research (Zlaugotne et al., 2025).

These limitations reinforce the main conclusion that meaningful impact reduction requires system-level strategies beyond end-of-life optimization. Therefore, these results should be considered specific to the system studied and not assumed to be universally applicable.

5. Conclusions

This study assessed the environmental performance of hospital PPE waste management using a cradle-to-grave life cycle assessment based on several years of operational data.

The results indicate that environmental impacts are predominantly driven by PPE consumption, with annual burdens closely tracking material throughput. Pandemic-related surges increase impacts by approximately 100% across multiple categories.

In all scenarios, human and freshwater toxicity impacts dominate the environmental profile, surpassing climate and resource-related burdens. This trend is primarily linked to landfill-based treatment and the plastic-intensive composition of PPE waste streams.

The analysis further reveals that downstream interventions, such as improved waste segregation and alternative end-of-life routing, offer

only limited mitigation potential. Even under optimized conditions, impact reductions remain below 7%, suggesting that treatment-focused strategies alone are insufficient under current operational conditions for achieving substantial environmental improvements at the system level.

Nevertheless, waste segregation remains a critical operational parameter because its quality directly influences treatment intensity and environmental outcomes. Although its absolute mitigation potential is modest, it serves as an important control variable within institutional waste management systems.

This study advances the waste management literature by providing facility-level, real-world LCA evidence, quantifying the decision-relevance of downstream interventions, and demonstrating the structural limitations of treatment-based mitigation strategies.

Accordingly, the most effective institutional strategy is to reduce avoidable PPE consumption while maintaining clinical safety. Procurement should prioritize high-volume and high-impact products, particularly gloves, and evaluate clinically equivalent lower-mass, lower-impact, or reusable alternatives while accounting for reprocessing requirements.

CRedit authorship contribution statement

Adam Kaposi: Writing – review & editing, Writing – original draft, Visualization, Investigation, Data curation, Conceptualization. **Viktoria Mannheim:** Writing – review & editing, Writing – original draft, Visualization, Validation, Methodology, Formal analysis. **Artur Szilagy:** Formal analysis, Data curation. **Denes Kocsis:** Writing – review & editing, Supervision, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Supplementary materials

Supplementary material associated with this article can be found, in the online version, at [doi:10.1016/j.hazadv.2026.101555](https://doi.org/10.1016/j.hazadv.2026.101555).

Data availability

Data will be made available on request.

References

- Ajaj, R., Dweik, R.A., Syed Ali, S.A., Stietiya, M.H., 2023. Life cycle assessment studies to evaluate the sustainability of various facemasks used during COVID-19: a UAE case study. *J. Environ. Chem. Eng.* 11, 110491. <https://doi.org/10.1016/j.jece.2023.110491>.
- Asare, E.A., Abdul-Wahab, D., Kaufmann, E.E., Wahi, R., Ngaini, Z., Buah-Kwofie, A., 2025. Integrated life cycle assessment–systems thinking approach for medical waste management in Ghanaian hospitals. *Clean. Water* 4, 100130. <https://doi.org/10.1016/j.clwat.2025.100130>.
- Atılgen Türkmen, B., 2022. Life cycle environmental impacts of disposable medical masks. *Environ. Sci. Pollut. Res.* 29, 25496–25506. <https://doi.org/10.1007/s11356-021-17430-5>.
- Bosurgi, R., 2019. Climate crisis: healthcare is a major contributor, global report finds. *BMJ* 367, 15560. <https://doi.org/10.1136/bmj.15560>.
- Bouchet, A., Boucher, J., Schutzbach, K., Senn, N., Genton, B., Vernez, D., 2021. Which strategy for using medical and community masks? A prospective analysis of their environmental impact. *BMJ Open* 11, e049690. <https://doi.org/10.1136/bmjopen-2021-049690>.
- Çetin, E., Eşenlikçi Yıldız, İ.A., Öz Yaşar, Ç., Yulistyörini, A., 2025. Life cycle assessment of medical waste management: case study for Istanbul. *Appl. Sci.* 15, 4439. <https://doi.org/10.3390/app15084439>.
- Chen, C., Chen, J., Fang, R., Ye, F., Yang, Z., Wang, Z., Shi, F., Tan, W., 2021. What medical waste management system may cope with COVID-19 pandemic: lessons from Wuhan. *Resour. Conserv. Recycl.* 170, 105600. <https://doi.org/10.1016/j.resconrec.2021.105600>.
- Cho, Y., Withana, P.A., Rhee, J.H., Lim, S.T., Lim, J.Y., Park, S.W., Ok, Y.S., 2024. Achieving sustainable waste management of medical plastic packaging using a life cycle assessment approach. *Heliyon* 10, e38185. <https://doi.org/10.1016/j.heliyon.2024.e38185>.
- Coban, M., Karakas, F., Akbulut Coban, N., 2023. Quantitative analysis of healthcare waste generation and composition in Antalya, Turkey. *Waste Manag.* 160, 80–89. <https://doi.org/10.1016/j.wasman.2023.02.008>.
- Deepak, A., Sharma, V., Kumar, D., 2022. Life cycle assessment of biomedical waste management for reduced environmental impacts. *J. Clean. Prod.* 349, 131376. <https://doi.org/10.1016/j.jclepro.2022.131376>.
- Doucet, C., Lioussis, M., Yamano, N., Mueller, M., 2025. Measuring Greenhouse Gas Emissions in the Health Sector. OECD Publishing, Paris. <https://doi.org/10.1787/4d15c6ef-en>.
- Eckelman, M.J., Sherman, J., 2016. Environmental impacts of the U.S. health care system and effects on public health. *PLoS One* 11, e0157014. <https://doi.org/10.1371/journal.pone.0157014>.
- EMMI, 2017. Decree 12/2017 (VI.12.) of the Ministry of Human Capacities on Waste Management Activities Related to Waste Generated by Healthcare Providers. *Hungarian Gazette [In Hungarian]*.
- European Commission, 2000. Commission Decision 2000/532/EC establishing a list of waste pursuant to Directive 75/442/EEC on waste and Directive 91/689/EEC on hazardous waste. *Off. J. Eur. Communities L* 226, 1–73.
- Evliya Felek, B.N., Karadağ Erkoç, S., Özçelik, M., Yörükoglu, D., 2025. Impact of waste segregation training on medical and recyclable waste in an operating theater: a quasi-experimental study. *Sci. Rep.* 15, 18430. <https://doi.org/10.1038/s41598-025-02797-z>.
- Fraeyman, N., Van Braeckel, E., Verhasselt, B., De Waegemaeker, P., Mahnik, S., Hoffmann, M., Gemmel, P., Eeckloo, K., Mortier, E., 2022. Solid medical hospital waste in times of corona: increased volume but no increased biohazard risk. *Detritus* 19, 94–103. <https://doi.org/10.31025/2611-4135/2022.15197>.
- Hanedar, A., Çifçi, D.I., Zafer, N., Görgün, E., 2022. The impact of COVID-19 pandemic on medical waste amounts: a case study from a high-populated city of Turkey. *J. Mater. Cycles Waste Manag.* 24, 1760–1767. <https://doi.org/10.1007/s10163-022-01428-3>.
- Hernandez, C., Rodrigues, C., Marques, P., Freire, F., 2023. Life cycle assessment of a large volume parenteral for hospital use. *Resour. Conserv. Recycl.* 198, 107120. <https://doi.org/10.1016/j.resconrec.2023.107120>.
- Hong, J., Zhan, S., Yu, Z., Hong, J., Qi, C., 2018. Life-cycle environmental and economic assessment of medical waste treatment. *J. Clean. Prod.* 174, 65–73. <https://doi.org/10.1016/j.jclepro.2017.10.206>.
- International Organization for Standardization (ISO), 2006a. *Environmental Management – Life Cycle Assessment – Principles and Framework (ISO 14040:2006)*. International Organization for Standardization, Geneva, Switzerland.
- International Organization for Standardization (ISO), 2006b. *Environmental Management – Life Cycle Assessment – Requirements and Guidelines (ISO 14044:2006)*. International Organization for Standardization, Geneva, Switzerland.
- Ivanović, T., Gräbsch, C., Som, C., Nowack, B., 2023. The effect of the SARS-CoV-2 pandemic on the use of personal protective equipment in hospitals. *J. Mater. Cycles Waste Manag.* 25, 3093–3103. <https://doi.org/10.1007/s10163-023-01745-1>.
- Ji, A., Guan, J., Zhang, S., Ma, X., Jing, S., Yan, G., Liu, Y., Li, H., Zhao, H., 2024. Environmental and economic assessments of industry-level medical waste disposal technologies: a case study of ten Chinese megacities. *Waste Manag.* 174, 203–217. <https://doi.org/10.1016/j.wasman.2023.11.036>.
- Kaposi, A., Nagy, A., Gomori, G., Kocsis, D., 2024. Analysis of healthcare waste and factors affecting the amount of hazardous healthcare waste in a university hospital. *J. Mater. Cycles Waste Manag.* 26, 1169–1180. <https://doi.org/10.1007/s10163-024-01890-1>.
- Karim, N., Afroj, S., Lloyd, K., Oaten, L.C., Andreeva, D.V., Carr, C., Farmery, A.D., Kim, I.-D., Novoselov, K.S., 2020. Sustainable personal protective clothing for healthcare applications: a review. *ACS Nano* 14, 12313–12340. <https://doi.org/10.1021/acsnano.0c05537>.
- Keul, C., Spierling, S., Venkatachalam, V., Endres, H.-J., Barner, L., Wyssusek, K., 2024. Potential of polyethylene terephthalate (PET) in a circular economy from a life cycle assessment perspective. *Front. Environ. Sci.* 12, 1415604. <https://doi.org/10.3389/fenvs.2024.1415604>.
- Kumar, H., Azad, A., Gupta, A., Sharma, J., Bherwani, H., Labhsetwar, N.K., Kumar, R., 2021. COVID-19 creating another problem? Sustainable solution for PPE disposal through LCA approach. *Environ. Dev. Sustain.* 23, 9418–9432. <https://doi.org/10.1007/s10668-020-01033-0>.
- Law CLXXXV, 2012. Act CLXXXV of 2012 on Waste. *Hungarian Gazette [In Hungarian]*.
- Lenzen, M., Malik, A., Li, M., Fry, J., Weisz, H., Pichler, P.-P., Chaves, L.S.M., Capon, A., Pencheon, D., 2020. The environmental footprint of health care: a global assessment. *Lancet Planet. Health* 4, e271–e279. [https://doi.org/10.1016/S2542-5196\(20\)30121-2](https://doi.org/10.1016/S2542-5196(20)30121-2).
- Li, Y., Tang, Y., Liu, M., Yuan, X., Zuo, J., Feng, K., Wang, Q., Ma, Q., Mu, R., Wang, W., Hong, J., 2023. Life-cycle assessment reveals disposable surgical masks in 2020–2022 led to more than 18 million tons of carbon emissions. *One Earth* 6, 1258–1268. <https://doi.org/10.1016/j.oneear.2023.08.008>.
- Lin, X., Zhan, M., Yan, M., Dai, A., Wu, H., Li, X., Chen, T., Lu, S., Yan, J., 2015. Suppression of dioxins in waste incinerator emissions by recirculating SO₂. *Chemosphere* 133, 75–81. <https://doi.org/10.1016/j.chemosphere.2015.03.080>.
- Lingegård, S., Martin, M., Gheitsi, F., 2025. Assessment of the environmental and economic performance for developing more circular trocar systems in healthcare. *Resour. Conserv. Recycl.* 218, 108269. <https://doi.org/10.1016/j.resconrec.2025.108269>.
- Liu, J., Li, H., Liu, Z., Meng, X., He, Y., Zhang, Z., 2022. Study on the process of medical waste disinfection by microwave technology. *Waste Manag.* 150, 13–19. <https://doi.org/10.1016/j.wasman.2022.06.022>.

- Maamari, O., Mouaffak, L., Kamel, R., Brandam, C., Lteif, R., Salameh, D., 2016. Comparison of steam sterilization conditions efficiency in the treatment of infectious health care waste. *Waste Manag.* 49, 462–468. <https://doi.org/10.1016/j.wasman.2016.01.014>.
- Malik, A., Goodlet, J., Li, M., Mora, C.J., Fry, J., Munro, A., Mill, S., Noonan, A., Lenzen, M., 2024. Assessing waste and carbon impacts of health system at a regional level. *Resour. Conserv. Recycl.* 209, 107750. <https://doi.org/10.1016/j.resconrec.2024.107750>.
- Mazhandu, Z.S., Muzenda, E., Belaid, M., Nhuhu, T., 2023. Comparative assessment of life cycle impacts of various plastic waste management scenarios in Johannesburg, South Africa. *Int. J. Life Cycle Assess.* 28, 536–553. <https://doi.org/10.1007/s11367-023-02151-3>.
- Mazzei, H.G., Specchia, S., 2023. Latest insights on technologies for the treatment of solid medical waste: a review. *J. Environ. Chem. Eng.* 11, 109309. <https://doi.org/10.1016/j.jece.2023.109309>.
- Mushtaq, M.H., Noor, F., Mujtaba, M.A., Asghar, S., Yusuf, A.A., Soudagar, M.E.M., Hussain, A., Badran, M.F., Shahapurkar, K., 2022. Environmental performance of alternative hospital waste management strategies using life cycle assessment (LCA) approach. *Sustainability* 14, 14942. <https://doi.org/10.3390/su142214942>.
- Nematollahi, H., Tuyserkani, M., Nematollahi, A., 2025. Medical waste management in the modern healthcare era: a comprehensive review of technologies, environmental impact, and sustainable practices. *Results Eng.* 28, 107210. <https://doi.org/10.1016/j.rineng.2025.107210>.
- Nsanzimana, J., Busumbigabo, A., Mukamana, F., Umuhoza, H., Musafili, A., 2025. Determinants of improper healthcare waste segregation in a tertiary referral hospital in Southern Rwanda: a cross-sectional study. *Crit. Public Health* 35, 1–10. <https://doi.org/10.1080/09581596.2025.2518181>.
- Olawade, D.B., Popoola, T.T., Egbon, E., David-Olawade, A.C., 2025. Sustainable healthcare practices: pathways to a carbon-neutral future for the medical industry. *Sustain. Futures* 9, 100783. <https://doi.org/10.1016/j.sft.2025.100783>.
- Or, Z., Seppänen, A.-V., 2024. The role of the health sector in tackling climate change: a narrative review. *Health Policy (New York)* 143, 105053. <https://doi.org/10.1016/j.healthpol.2024.105053>.
- Peng, J., Wu, X., Wang, R., Li, C., Zhang, Q., Wei, D., 2020. Medical waste management practice during the 2019–2020 novel coronavirus pandemic: experience in a general hospital. *Am. J. Infect. Control* 48, 918–921. <https://doi.org/10.1016/j.ajic.2020.05.035>.
- Pichler, P.-P., Jaccard, I.S., Weisz, U., Weisz, H., 2019. International comparison of health care carbon footprints. *Environ. Res. Lett.* 14, 064004. <https://doi.org/10.1088/1748-9326/ab19e1>.
- Rizan, C., Reed, M., Bhutta, M.F., 2021. Environmental impact of personal protective equipment distributed for use by health and social care services in England in the first six months of the COVID-19 pandemic. *J. R. Soc. Med.* 114, 250–263. <https://doi.org/10.1177/01410768211001583>.
- Silva de Souza Lima Cano, N., Marino, M., Brooks, A.L., Eckelman, M.J., Bilec, M.M., 2025. Advancing the circular economy of healthcare plastics: a systematic literature review. *Resour. Conserv. Recycl.* 219, 108317. <https://doi.org/10.1016/j.resconrec.2025.108317>.
- Snigdha, Hiloidhari, M., Bandyopadhyay, S., 2023. Environmental footprints of disposable and reusable personal protective equipment – A product life cycle approach for body coveralls. *J. Clean. Prod.* 394, 136166. <https://doi.org/10.1016/j.jclepro.2023.136166>.
- Soares, S.R., Finotti, A.R., Prudêncio da Silva, V., Alvarenga, R.A.F., 2013. Applications of life cycle assessment and cost analysis in health care waste management. *Waste Manag.* 33, 175–183. <https://doi.org/10.1016/j.wasman.2012.09.021>.
- Spreafico, C., Ördek, B., 2025. Parametric LCA model for Ti6Al4V powder production. *Clean. Eng. Technol.* 27, 101032. <https://doi.org/10.1016/j.clet.2025.101032>.
- Sphera, 2023. *Managed LCA Content Database Documentation*. Sphera Solutions GmbH, Stuttgart, Germany.
- Steenmeijer, M.A., Rodrigues, J.F.D., Zijp, M.C., Waaijers-van der Loop, S.L., 2022. The environmental impact of the Dutch health-care sector beyond climate change: an input-output analysis. *Lancet Planet. Health* 6, e949–e957. [https://doi.org/10.1016/S2542-5196\(22\)00244-3](https://doi.org/10.1016/S2542-5196(22)00244-3).
- Tabatabaei, M., Hosseinzadeh-Bandbafha, H., Yang, Y., Aghbashlo, M., Lam, S.S., Montgomery, H., Peng, W., 2021. Exergy intensity and environmental consequences of the medical face masks curtailing the COVID-19 pandemic: malign bodyguard? *J. Clean. Prod.* 313, 127880. <https://doi.org/10.1016/j.jclepro.2021.127880>.
- Uddin, M.A., Afroj, S., Hasan, T., Carr, C., Novoselov, K.S., Karim, N., 2022. Environmental impacts of personal protective clothing used to combat COVID-19. *Adv. Sustain. Syst.* 6, 2100176. <https://doi.org/10.1002/adsu.202100176>.
- Van Caneghem, J., Van Acker, K., De Greef, J., Wauters, G., Vandecasteele, C., 2019. Waste-to-energy is compatible and complementary with recycling in the circular economy. *Clean Technol. Environ. Policy* 21, 925–939. <https://doi.org/10.1007/s10098-019-01686-0>.
- Wernet, G., Bauer, C., Steubing, B., Reinhard, J., Moreno-Ruiz, E., Weidema, B., 2016. The ecoinvent database version 3 (part I): overview and methodology. *Int. J. Life Cycle Assess.* 21, 1218–1230. <https://doi.org/10.1007/s11367-016-1087-8>.
- Windfeld, E.S., Brooks, M.S.-L., 2015. Medical waste management – a review. *J. Environ. Manage.* 163, 98–108. <https://doi.org/10.1016/j.jenvman.2015.08.013>.
- World Health Organization, 2024. *Health-Care Waste*. WHO, Geneva.
- Zhang, E.J., Aitchison, L.P., Phillips, N., Shaban, R.Z., Kam, A.W., 2021. Protecting the environment from plastic PPE. *BMJ* 372, n109. <https://doi.org/10.1136/bmj.n109>.
- Zhao, H.-L., Wang, L., Liu, F., Liu, H.-Q., Zhang, N., Zhu, Y.-W., 2021. Energy, environment and economy assessment of medical waste disposal technologies in China. *Sci. Total Environ.* 796, 148964. <https://doi.org/10.1016/j.scitotenv.2021.148964>.
- Zheng, X., Zhong, S., Alam, O., Hossen, S.J., Du, D., 2025. Microplastics and heavy metals emissions from healthcare waste management: a comparative life cycle assessment. *Waste Manag.* 204, 114932. <https://doi.org/10.1016/j.wasman.2025.114932>.
- Zlaugotne, B., Zandberga, A., Guska, J., Kalnins, S.N., 2025. Environmental life cycle assessment of healthcare waste valorisation alternatives. *Environ. Clim. Technol.* 29, 51–67. <https://doi.org/10.2478/rtuct-2025-0004>.