Life Cycle Assessment (LCA) For Prosthetic and Orthotic Materials in the Health Care Sector

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Abstract

Life Cycle Assessment (LCA) has become a circular analytical framework for quantifying the environmental performance of medical devices throughout their full life cycles. This review integrates methodological fundamental, database selection guidelines, and impact-assessment Pertinent approaches to healthcare applications, with Concentrate on prosthetic and orthotic technologies. By integrating ISO-compliant model-Eling practices, robust inventory datasets like ELCD 3.2 and Eco invent, and modern impact-assessment methods such as ReCiPe 2016 Midpoint (H), the study shows how methodological strictness ensures reliability and reproducibility in environmental evaluations. Case studies on upper-limb prostheses, reprocessed pneumatic sleeves, remanufactured electrophysiology catheters, and repaired surgical equipment collectively highlight consistent environmental hotspots driven by material extraction, energy-intensive manufacturing, and sterilization processes. Proof shows that circular-economy approaches, remanufacturing, and repair offer substantial reductions in greenhouse-gas emissions and resource consumption while maintaining clinical performance. The findings underscore LCA's essential role as a decision support tool for promoting sustainable innovation, guiding eco-design pathways, and accelerating the transition toward environmentally responsible healthcare systems.

Keywords

life cycle assessment; life cycle inventory databases; life cycle impact assessment; medical sector; eco-design; composite materials.

Introduction

viability now plays a main role in guiding modern industrial and technological development, prompting the widespread adoption and preventing environmental hazards of Life Cycle Assessment (LCA) across sectors such as healthcare, manufacturing, construction, energy systems, and consumer products [1,2].As global environmental pressures continue to intensify, industries increasingly rely on LCA as a scientifically grounded approach for quantifying the full environmental impact of products from the extraction of raw materials to end-of-life management [1,3]. This system-based perspective enables decision-makers to identify the life-cycle stages responsible for the highest contributions to emissions, resource depletion, and ecological stress, thereby supporting strategies that enhance environmental performance across multiple fields [1,2]. Traditional manufacturing processes, regardless of industry, involve energy-intensive operations such as polymer molding, metal machining, large-scale material processing and transportation, all of which significantly contribute to greenhouse gas emissions and waste generation [1,4]. Consequently, systematic and transparent assessment tools such as LCA have become basic for supporting sustainable Material selection, improving industrial processes, enhancing product design, and informing long-term policy development [2,5]. LCA gives a strong, ISO standardized framework composed of several structured Stages, including objective definition, life cycle inventory, impact assessment, and interpretation of results [3]. Within this framework, impact categories such as climate change, human toxicity, ecosystem damage, and resource depletion are commonly evaluated using harmonized ways such as ReCiPe 2016 [6]. Comparative studies have also tested methodological differences between

ReCiPe and alternative approaches such as ILCD, CML-IA, and IMPACT 2002+, particularly in sectors Such as energy production and building materials [7]. Reliable databases play a key role in ensuring methodological transparency and accuracy. Widely consumption LCI sources, including Ecoinvent [8], ELCD 3.2 [8,9], and GaBi [10], provide extensive datasets for materials, energy systems, industrial processes, and waste management, enabling consistent comparisons across sectors [11,12]. The quality of life-cycle inventory (LCI) data and the choice of databases strongly followed LCA outcomes, as variations in energy sources, fiber treatment processes, and end-of-life scenarios can result in substantial differences in environmental impact results [13,14]. The general life cycle framework associated with prosthetic limb production is illustrated in Figure 1.

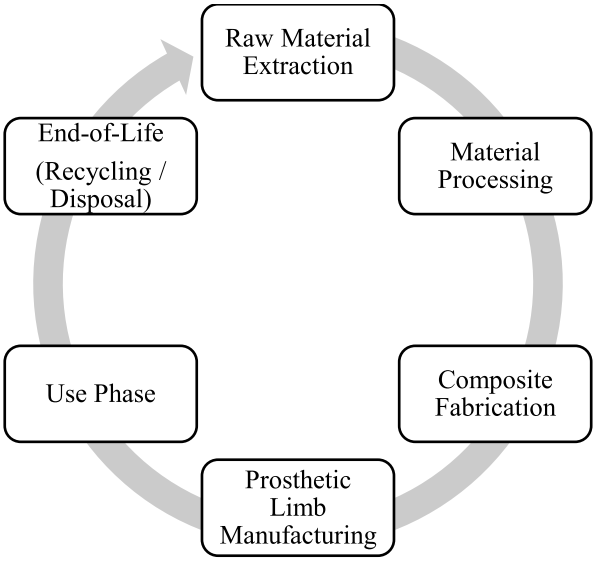


Figure 1: General life cycle framework for prosthetic limb production.

Transparent reporting of system boundaries, functional units, and assumptions is particularly important when assessing emerging bio-composites for industrial, energy, and biomedical applications [13,15,16] Recent advancements in sustainable materials research demonstrate a growing shift toward natural-fiber-reinforced polymer composites as environmentally preferable alternatives to conventional polymers. Studies by Al-Oqla and Sapuan highlight the feasibility and environmental advantages of natural fibers such as date-palm fibers in industrial applications, offering competitive performance with substantially lower ecological burdens [17,18]. Complementary work by Al-Oqla et.al focuses on the relevance of biopolymers and biomimetic materials in environmentally conscious medical and electronic applications [18]. Natural-fiber-based composites, when appropriately treated and integrated into polymer matrices, can significantly reduce the environmental impact of structural materials com-pared to synthetic or glass-fiber-reinforced composites [19,20]. Fully bio-based composites, including those reinforced with natural fibers like flax or coir, can reduce global warming potential and other environmental indicators by up to 30% while maintaining acceptable mechanical performance [19,21]. Hybrid composites Mixing natural fibers with recycled textile fibers offers both improved mechanical properties and lower life cycle impacts, making them optimum for demanding applications, including biomedical devices [21]. Natural fiber composites present intrinsic sustainability advantages and benefits, such as renewability, potential biodegradability, lower density, and reduced reliance on fossil-based raw materials, contributing to lighter, ecofriendly products with lower material and processing costs [20,22]. However, challenges include fiber-matrix compatibility, variability in fiber properties, moisture absorption, and flammability, which can affect long-term durability and mechanical performance [23,24]. Surface modification techniques such as alkalization, silane treatment, plasma treatment, acetylation, and polydopamine coating have been employed to improve fiber matrix adhesion, dimensional stability, and overall performance [21,24]. Applications in energy, construction, and biomedical sectors demonstrate that careful management of manufacturing, transportation, and end-of-life processes allows natural-fiber composites to reduce re-source depletion, greenhouse gas emissions, and hu-man toxicity impacts while maintaining sufficient performance [25,26,27]. Biodegradable polymer blends reinforced with natural fibers combine environmental sustainability with mechanical durability, offering alternatives for both load-bearing and non-load-bearing components [23,24,28]. In the healthcare sector, LCA has gained momentum in assessing the environmental impacts of prosthetic and orthotic devices, medical equipment, pharmaceutical packaging, and digital health solutions [4,11,29]. The adoption of LCA for prosthetic and orthotic devices benefits from findings on natural-fiber composites, as life cycle thinking enables identification of staged and phases that contribute most to environmental impacts and informs techniques for material selection, design optimization, and sustainable end-of-life management [25,26,27]. By integrating high-quality LCI information and leveraging the benefits of bio-based composites, LCA provides a robust framework for assessing the sustainability of prosthetic systems.

This research talks about how LCA can be effectively applied to prosthetic devices, focus the methodological choices, impact criteria, and databases relevant to this field. By linking LCA principles with real-world examples from upper and lower limb prostheses, this study aims to demonstrate how life cycle thinking can enhance the sustainability and inclusivity of future prosthetic systems.

Overview of Life Cycle Assessment in the medical Sector

Life Cycle Assessment (LCA) has become a critical methodological tool for assessing environmental sustainability within the healthcare industry, providing a thorough, ISO-aligned framework that evaluates environmental impacts across every stage of a product's life span from the extraction of raw materials to final end-of-life treatment [1,2,3].Grounded in the principles Founded by ISO 14040 and ISO 14044, LCA gives a scientifically rigorous basis for quantifying resource use, emissions, and waste flows, thereby enabling transparent and reproducible evaluation of healthcare related systems [3]. The increasing integration of LCA within the healthcare system reflects a broader shift toward lifecycle thinking, where environmental insight is coordinated into material selection, design strategies, and processing routes for medical technologies [1].

This is particularly relevant for prosthetic and orthotic devices, whose production often involves energy critical processes, polymeric materials, advanced composites, and complex additive-manufacturing pathways [11,29,30]. Through the identification of environmental hotspots and the assessment of trade-offs among mechanical performance, durability, cost, and Environmental impact, LCA supports more sustainability decision-making and guides eco-design implementations across healthcare supply chains [1,29,30]. A conventional LCA study is structured into four methodologically interconnected stages, Figure 2 provides a clear representation of the sequential steps involved in conducting an LCA, focusing on the methodological flow from goal definition to final interpretation.

Figure 2: The steps for conducting an LCA adapted from [1] (under license: CC BY 4.0).

1.The Goal and Scope Definition phase establishes the functional unit, defines the system boundaries, and identifies the intended impact categories., ensuring methodological clarity and comparability across studies [1,2].
2. Life Cycle Inventory (LCI) involves systematic data collection on energy consumption, material flows, emissions, and auxiliary processes that occur throughout the life cycle of the healthcare product [1,3].

3. Life Cycle Impact Assessment (LCIA) translates these inventory flows into environmental impact indicators using characterization models such as ReCiPe 2016, which quantifies midpoint impacts including climate change, resource depletion, particulate matter formation, and human toxicity [6,7,31].

4. Interpretation synthesizes the results to identify improvement opportunities, evaluate uncertainties, and support strategic design choices for reducing environmental burdens [2,3].

Recent applications of LCA in healthcare demonstrate its value across diverse contexts. Studies on upper limb prostheses reveal that material extraction and manufacturing stages dominate environmental impacts, highlighting opportunities for material substitution and process optimization [29,30]. Broader reviews indicate same patterns across medical devices, where polymers, composites, and additive manufacturing present Recurrent environmental challenges [4,11]. At the system level, LCA has also been used to assess hospital supply chains, showing that product reprocessing, waste minimization, and energy-efficient production can substantially reduce environmental footprints [12]. The methodological robustness of LCA is strengthened by checking background databases and harmonized impact-assessment frameworks. Databases like ecoinvent and the European Reference Life Cycle Database (ELCD) offer high-quality datasets that improved the reliability of healthcare-related LCAs [8,9], while integrated LCIA methods such as ReCiPe 2016 ensure consistent characterization of environmental impacts across studies [6,7]. Together, these tools enable more comprehensive and policy-relevant assessments that support sustainability transitions within the healthcare sector. With environmental accountability becoming increasingly central to global healthcare innovation, LCA now Acts as a critical instrument for aligning technological progress with ecological stewardship [1,2]. Its holistic perspective enables manufacturers, clinicians, and policymakers to advance toward sustainable healthcare systems without compromising safety, functionality, or patient results

Software, Databases, and Impact Assessment Criteria Used in LCA Studies

Life Cycle Assessment (LCA) research within the healthcare sector highly depends on advanced software tools and reliable databases to accurately simulate environmental impacts. Widely adopted LCA platforms Like GaBi®, openLCA®, and SimaPro® provide systematic process modeling, access to comprehensive Life Cycle Inventory (LCI) data, and compatibility with vary impact assessment methodologies [1,3,32]. GaBi® is commonly applied in large-scale industrial LCA studies due to their powerful and well-structured modeling capabilities [3]. In contrast, openLCA® is an open-source platform that enables flexible system modeling and seamless interoperability with different databases, making it suitable for a wide use and applications [32]. SimaPro®, as one of the earliest developed LCA software tools, is widely recognized for its advanced scenario analysis characters and its transparent modeling framework, which has led to its extensive use in both academic research and industrial practice [32]. The selection of an appropriate database plays a circular role in determining the credibility of LCA outcomes. Databases such as ecoinvent, which is well known for its transparent documentation and globally representative system models [8], and the European Reference Life Cycle Database (ELCD), which gives harmonized and quality-assured European environmental data [9], are among the most frequently used data sources in healthcare-related LCA studies [32]. To quantify environmental impacts, researchers commonly employ standardized impact assessment methods like ReCiPe 2016 Midpoint (H) which harmonizes midpoint indicators across environmental classes including climate change, toxicity, and resource use [8] as well as CML 2001, which provides scientifically validated midpoint indicators for comparative assessments [17,18]. The combined use of advanced LCA software, reliable and transparent databases, and internationally recognized impact assessment ways ensures methodological rigor and scientific credibility when evaluating the environmental burdens associated with medical devices and prosthetic systems [10,16,18]. Table 1 compares commonly used LCA software tools, highlighting differences in database integration, usability, flexibility, and computational performance.

Table 1: Comparative Evaluation of LCA Software Tools Used in Environmental Assessment Studies

Criterion	GaBi®	openLCA®	SimaPro®	Reference
Integration with Databases	Supports major databases like ecoinvent, ELCD	Supports ecoinvent, ELCD, highly flexible for custom datasets	Supports ecoinvent, ELCD, and proprietary SimaPro databases	[8,9,32]

Ease of Use / Interface	User-friendly GUI, draganddrop modeling, ready-made reporting templates	Requires advanced LCA knowledge, more complex GUI, manual process editing	Intuitive GUI, structured workflow, good visualization tools	[3,32]
Flexibility / Customization	Limited editing of predefined flows; good for standard LCA applications	Full control over process modeling, flows, and custom datasets	Moderate flexibility; allows user-defined flows but with less open customization than OpenLCA	[3,32]
Computational Performance	Fast calculations and report generation	May require longer computation time for large or complex systems	Efficient for medium complexity models. can slow for very large datasets	[3,32]
Suitability for Beginners	Excellent for newcomers due to intuitive interface and automated reporting	Best for experienced users or researchers needing customized LCA models	Good for intermediate users; easier than OpenLCA but more structured than GaBi	[3,32]
Main Advantages	Rapid results, professional reports, easy implementation	High flexibility, customizable processes, opensource accessibility	Strong visualization and scenario analysis tools, reliable commercial support	[3,32]

Main Limitations	Less flexibility for non-standard processes, proprietary license costs	Steeper learning curve, requires more time to set up and validate models	Proprietary license costs; customization less open than OpenLCA	[3,32]

Comprehensive Overview of Life Cycle Inventory (LCI) Databases and Their Relevance to Prosthetic LCA

Life Cycle Inventory (LCI) Structured data repositories represent a diverse and complex data landscape, ranging from regional and national inventories to world, multi-sector databases and industry-focused datasets. This diversity reflects differences in geographical coverage, system boundaries, underlying methodological options, and levels of data details [8,9,10]. Within the European context, databases such as the European Reference Life Cycle Database (ELCD) and other EU-aligned inventories give high-quality, standardized datasets covering key sectors including energy production, transportation, industrial materials, and waste management. These databases play an important role in ensuring methodological coherence and consistency for LCA studies conducted at the European level [10]. North American inventories, including USLCI (U.S. Life Cycle Inventory), emphasize region-specific electricity mixes, manufacturing technologies, and transportation structures, offering geographically relevant data for studies situated in the U.S. or Canada [10]. Global, process-based databases such as ecoinvent extend coverage to plastics, metals, chemicals, fuels, and composite materials, and are widely used because of their transparency, documentation rigor, and multiple system-modeling options (cut-off, attributional, consequential) [8,10].

The review by Martínez-Rocamora, Solís-Guzmán, and Marrero (2016) further identifies more than 40 LCI databases spanning global, regional, and sector-specific repositories [10]. Among the most prominent are Eco invent, ELCD, USLCI, GaBi Database, BEDEC, Plastics Europe, Eurofer, and other national or specialized databases covering wood, metals, polymers, and construction materials [10]. Additional specialized inventories focus on natural resources (e.g., wood-based datasets), European construction products, and material-specific datasets for PVC, aluminum, ceramics, and other industrial materials [10]. These databases vary in completeness of material categories, methodological transparency, traceability, system modeling approaches (e.g., allocation, cut-off), and licensing models (open vs commercial) [10]. For example, ecoinvent provides a highly comprehensive and transparent multi-sector database covering polymers, metals, energy, and transport [10], while ELCD offers harmonized European data aligned with industrial and policy-relevant flows, such as steel recycling via Eurofer [10]. USLCI is particularly useful for U.S.-based processes in wood, plastics, and metals [10], and specialized databases like Plastics Europe or BEDEC supply refined information on polymers, enabling detailed LCA of plastic components [10].

Within prosthetic device LCA, database selection must prioritize those that accurately represent thermoplastics (PP, PE, ABS), fiber-reinforced composites, metallic alloys (aluminum, stainless steel), and manufacturing operations such as machining, molding, lamination, and finishing [3,6,30]. Accordingly, the combination of ecoinvent, ELCD, USLCI, and material-specific databases such as BEDEC or Plastics Europe provides both the breadth and depth necessary to model the diverse materials and complex production, maintenance, and end-of-life processes of prosthetic limbs [10,29,33]. The use of these databases ensures methodological robustness, high material specificity, and reliable geographic representation, which are essential for generating credible and reproducible environmental assessments in prosthetic LCAs [3,10,29]. As presented in Table 2, major LCI databases vary significantly in scope, geographic coverage, material resolution, and methodological transparency.

Table 2: Comparative Overview of Life Cycle Inventory (LCI) Databases.

Database	Type / Scope	Geographic Coverage	Materials & Processes Included	Advantages	Limitations	Reference
ecoinvent	Global, multi-sector processbased	Worldwide	Polymers, metals, chemicals, fuels, composites; energy & transport flows	Highly comprehensive; transparent; multiple system modeling options (cut-off, attributional, consequential); widely cited	Subscription required; complex for beginners	[8,10]
ELCD (European Reference Life Cycle Database)	Regional, policy-aligned	Europe	Energy systems, transport, industrial materials, waste flows, steel (Eurofer)	Harmonized EU data; high quality and policy relevant; detailed energy profiles	Limited global coverage; fewer sector-specific datasets	[9,10]
USLCI (U.S. Life Cycle Inventory)	Regional, national	United States & Canada	Electricity mixes, plastics, metals, wood, transport	Geographically relevant for North America; reliable process data	Limited international applicability: smaller material coverage compared to ecoinvent	[10]

GaBi Database®	Commercial, multi-sector	Global with regional datasets	Industrial processes, materials, energy, transport, composites	Extensive industry-focused datasets; strong modeling and software integration	Commercial license required; some datasets not publicly accessible	[10]
BEDEC	Sectorspecific	Europe	Detailed polymer datasets, plastic manufacturing	High-resolution polymer data; supports detailed LCA of plastic components	Limited to polymer-related datasets. European focus	[10]
PlasticsEurope	Sectorspecific, polymerfocused	Europe	Polymers, plastics, recycling processes	Refined polymer inventories. specialized for plastics LCA	Limited coverage outside plastics. European focus	[10]
Eurofer	Industry specific, metals	Europe	Steel production, recycling, alloys	High-quality data for steel; supports harmonized European industrial assessments	Focused only on steel; limited applicability for non-metal components	[10]

Comparison of Impact Assessment Methods and Selection Rationale

In Life Cycle Assessment (LCA), impact assessment methods can be modeled at two levels: midpoint and endpoint. Midpoint indicators represent environmental impacts at an intermediate phase of the cause effect chain, including examples like climate change, eutrophication, and human toxicity, concentrating on problem-oriented categories that reduce uncertainty and improve methodological transparency [6,31]. Conversely, endpoint indicators aggregate these midpoint impacts into damage categories same human health, ecosystem quality, and resource depletion thus providing outcomes that are easier to interpret but inherently more uncertain because of additional modeling steps [6,31]. Selecting the appropriate Life Cycle Impact Assessment (LCIA) method is basic for reliable evaluation of prosthetic systems. Among the most applied methodologies are ReCiPe 2016 (Midpoint/Endpoint), ILCD 2011, CML-IA, and IMPACT 2002+, each variating in characterization models, spatial/temporal resolution, and interpretability [1,6]. ReCiPe 2016 offers harmonized midpoint and endpoint pathways with global normalization factors, making it widely adopted in healthcare and prosthetic-device LCAs due to its comprehensive coverage of 18 impact categories [6,11]. ILCD, developed by the European Commission, arranged according to priority methodological transparency and quality assurance, making it suitable for studies requiring strict comparability across datasets [7,9]. CML-IA provides problem-oriented midpoint indicators without weighting, favored in prosthetic and medical-device assessments for its scientific robustness and reduced modeling uncertainty [6,33]. IMPACT 2002+ integrates midpoint and endpoint modeling within a single framework, facilitating interpretation while maintaining compatibility with various industrial and healthcare applications [7,11]. Overall, the choice between midpoint and endpoint approaches and between ReCiPe, ILCD, CML-IA, and IMPACT 2002+ depends on the required balance between scientific precision, interpretability, and relevance to prosthetic-device decision-making. In the study Comparison of ReCiPe 2016, ILCD 2011, CML-IA baseline and IMPACT 2002+ LCIA methods: a case study based on the electricity consumption mix in Europe, the authors presented Figure 3 to show the number of scientific articles published between 2020 and 2023 that employed each of these four LCIA methods. This distribution highlights how frequently each method is used in recent research and serves to justify the choice of these LCIA approaches in the study.

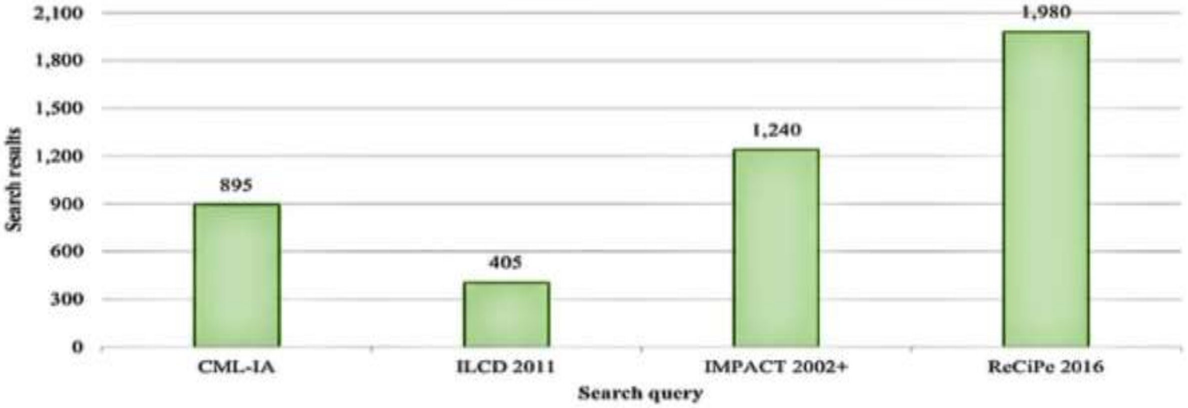


Figure 3: Number of scientific articles published between 2020 and 2023 that employed each of these four LCIA methods; adapted from [7] (under license: CC BY 4.0).

The ReCiPe 2016 framework, developed by Huijbregts et al. (2017), provides a harmonized approach that translates life cycle inventory results into 18 midpoint and 3 endpoint indicators [6]. Midpoint indicators (e.g., climate change, ozone depletion, and particulate matter formation) represent environmental mechanisms at an intermediate stage, allowing higher analytical resolution and lower uncertainty. Conversely, endpoint indicators aggregate results into damage categories Human Health, Ecosystem Quality, and Resource Scarcity providing more intuitive outcomes but with increased modeling assumptions [2, 6]. By contrast, CML-IA focuses purely on midpoint categories without normalization or weighting, making it suitable for comparative assessments of prosthetic materials where data transparency and simplicity are prioritized [1,3]. However, it lacks integration of regionalized or global normalization factors, which limits its representativeness in global medical device studies [3]. Table 3 summarizes the main characteristics of these three methods as used in recent LCA studies on medical and prosthetic devices.

Table 3: Comparison of common LCIA methods applied in prosthetic LCA.

Method	Type	Number of Indicators	Key Strengths	Limitations	Reference
ReCiPe 2016 Midpoint (H)	Mid-point	18	Detailed, globally normalized, lower uncertainty, suitable for process-level analysis	Requires extensive data; less intuitive for policy use	[1, 6]
ReCiPe 2016 Endpoint (H)	End-point	3 (Human Health, Ecosystems, Resources)	Aggregated, easier interpretation, supports sustainability communication	Higher uncertainty due to aggregation; potential information loss	[2, 6]
CML-IA (2001)	Mid-point	11	Transparent, simple, widely used in material-level LCAs	Lacks normalization and weighting; limited spatial sensitivity	[1, 3]

Selection of LCI Database, LCA Method, and Impact Indicators

Considering data accessibility, reproducibility, and methodological transparency, this research employs the ELCD 3.2 database as the life cycle inventory (LCI) source and adopts the ReCiPe 2016 Midpoint (H) method for impact assessment. ELCD 3.2, maintained by the European Commission's Joint Research Centre, provides open-access European datasets consistent with ISO 14040/44 standards, making it suitable for academic studies and prosthetic-related LCAs [8].

Among the available midpoint indicators, five were selected for this study due to their relevance to prosthetic production and human exposure pathways:

1. Human Toxicity (impacts from hazardous substances in manufacturing): Characterization factors for human toxicity and ecotoxicity incorporate three principal aspects: the environmental persistence of a chemical (fate), its bioaccumulation through the human food chain (exposure), and its intrinsic toxicity (effect) [36]. The cause effect pathway initiates with the chemical's emission into the environment, progresses through fate and exposure mechanisms, and affects species and disease incidence, ultimately resulting in quantifiable damage to ecosystems and human health [36].
2. Ozone Depletion (influences from polymer and composite processes): Emissions of ozone-depleting substances (ODSs) lead to higher exposure to UVB radiation, which can negatively affect human health by increasing the risk of skin cancer and cataracts [36]. ODSs are relatively persistent chemicals containing

chlorine or bromine functional groups, which interact primarily with ozone in the stratosphere [36]. Following their release, ODS concentrations rise first in the troposphere and subsequently in the stratosphere, leading to a reduction in atmospheric ozone levels [36]. The diminished ozone layer allows a greater fraction of UVB radiation to reach the Earth's surface, thereby increasing the potential for human health impacts [36].

3. Global Warming Potential (GHG emissions during material and energy use): For the climate change impact category, damage modeling follows several sequential steps [36]. The emission of a greenhouse gas (kg) increases its atmospheric concentration (ppb), which subsequently raises radiative forcing (W/m²) and leads to a rise in global mean temperature (°C) [36]. This temperature increase ultimately causes damage to human health, terrestrial ecosystems, and freshwater ecosystems. In this study, such damages were quantitatively estimated [36].
4. Fine Particulate Matter Formation (emissions from processing and transport):
   The cause-and-effect chain for fine dust (particulate matter) emissions describes the pathway from emission sources to the resulting damage to human health [36]. Fine dust released into the atmosphere can be transported and deposited in various environmental compartments, leading to inhalation exposure by humans, which may cause respiratory and cardiovascular diseases, ultimately contributing to quantifiable human health impacts [36].
5. Global Warming – Human Health (temperature-related health effects from emissions):
   The environmental cause and effect pathway of radionuclide emissions can be described in four sequential steps, beginning with anthropogenic releases [36]. These emissions primarily arise from the nuclear fuel cycle including mining, processing, and waste disposal as well as other human activities such as coal combustion and phosphate rock extraction [36]. The first step involves the dispersion of radio nuclides in the environment, followed by an exposure assessment to determine the effective collective dose received by the population Exposure to ionizing radiation from these radio nuclides can cause DNA damage [36]. During the effect assessment, incidences of nonfatal cancers, fatal cancers, and severe hereditary effects are evaluated individually [36]. Finally, these effects are aggregated to estimate overall human health damage in terms of disability-adjusted life years (DALY) [36]. It is essential to note that no standardized impact assessment methods currently exist to quantify the effects of ionizing radiation on ecosystems [36]. This combination enables a balanced assessment of both environmental and human health dimensions, aligning with current sustainability assessment practices for medical and prosthetic devices. Figure 4 summarizes the workflow adopted for selecting the LCA software, database, impact assessment method, and the main midpoint impact categories considered in LCA studies.

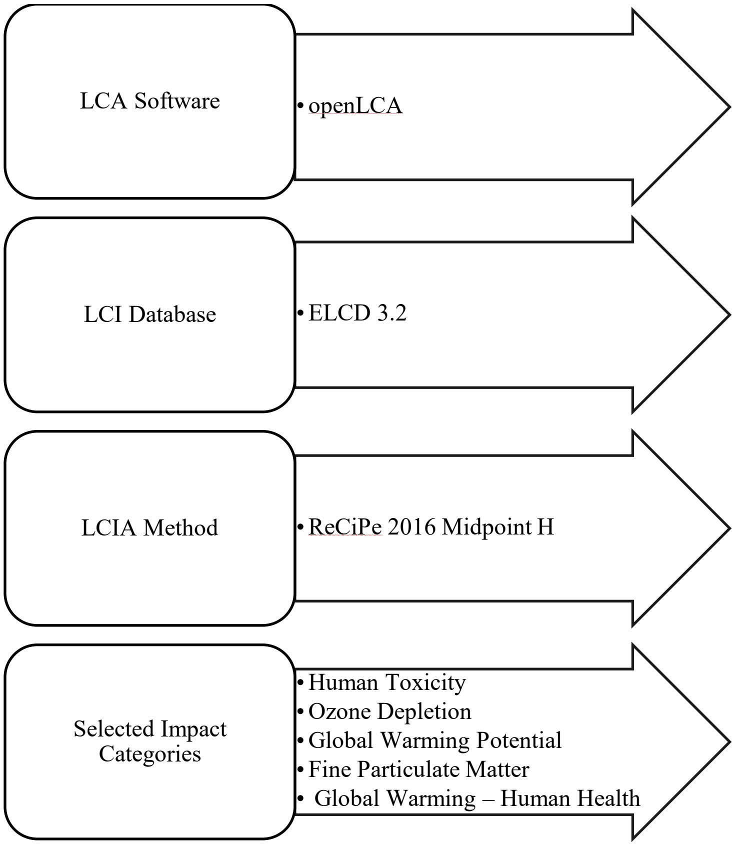


Figure 4: General framework for the selection of LCA software, database, LCIA method, and midpoint impact categories applied in LCA studies, (developed by the authors).

Justification for Selected Database and Impact Method

The selection of the ELCD 3.2 database and the Recipe 2016 Midpoint (H) method is clarified by their methodological robustness, accessibility, and compatibility with product level environmental analysis. According to Wolf et al. [9], the European Reference Life Cycle Database (ELCD 3.2) provides transparent, peer reviewed datasets consistent with ISO 14040 and 14044 standards, making it particularly appropriate for academic research and public applications. In contrast to commercial databases like GaBi Professional [10] or Ecoinvent [8], ELCD gives free access while maintaining European data quality standards, an important advantage for reproducibility in prosthetic LCA studies. The ReCiPe 2016 Midpoint (H) method, as described by Huijbregts et al. [6], offers a balanced framework between scientific detail and interpretability. It quantifies 18 midpoint indicators, such as human toxicity, climate change, ozone depletion, fine particulate matter formation, and human health impacts from global warming. Compared with the Endpoint version, which aggregates impacts into broader damage categories (human health, ecosystem quality, and resources), the Midpoint approach provides more stable and traceable results with lower uncertainty an essential feature when comparing different prosthetic materials [1,3,6]. Furthermore, the review conducted by Kaynak et al. [1] and the bibliometric analysis presented by Moutik et al. [2] demonstrated that the ReCiPe 2016 Midpoint framework has been established as one of the most consistently applied LCIA approaches in assessments of medical and healthcare-related products. Their analyses showed that the midpoint-level structure offers enhanced compatibility with widely used European datasets such as the ELCD while providing sufficient resolution to examine category-specific impacts across the full life cycle. This alignment between methodological structure and database architecture has historically supported greater consistency, reproducibility, and methodological transparency in LCA studies of prosthetic devices and comparable healthcare systems. Figure 5 provides an integrated overview of the ReCiPe 2016 impact categories, clarifying how midpoint indicators align with broader areas of protection.

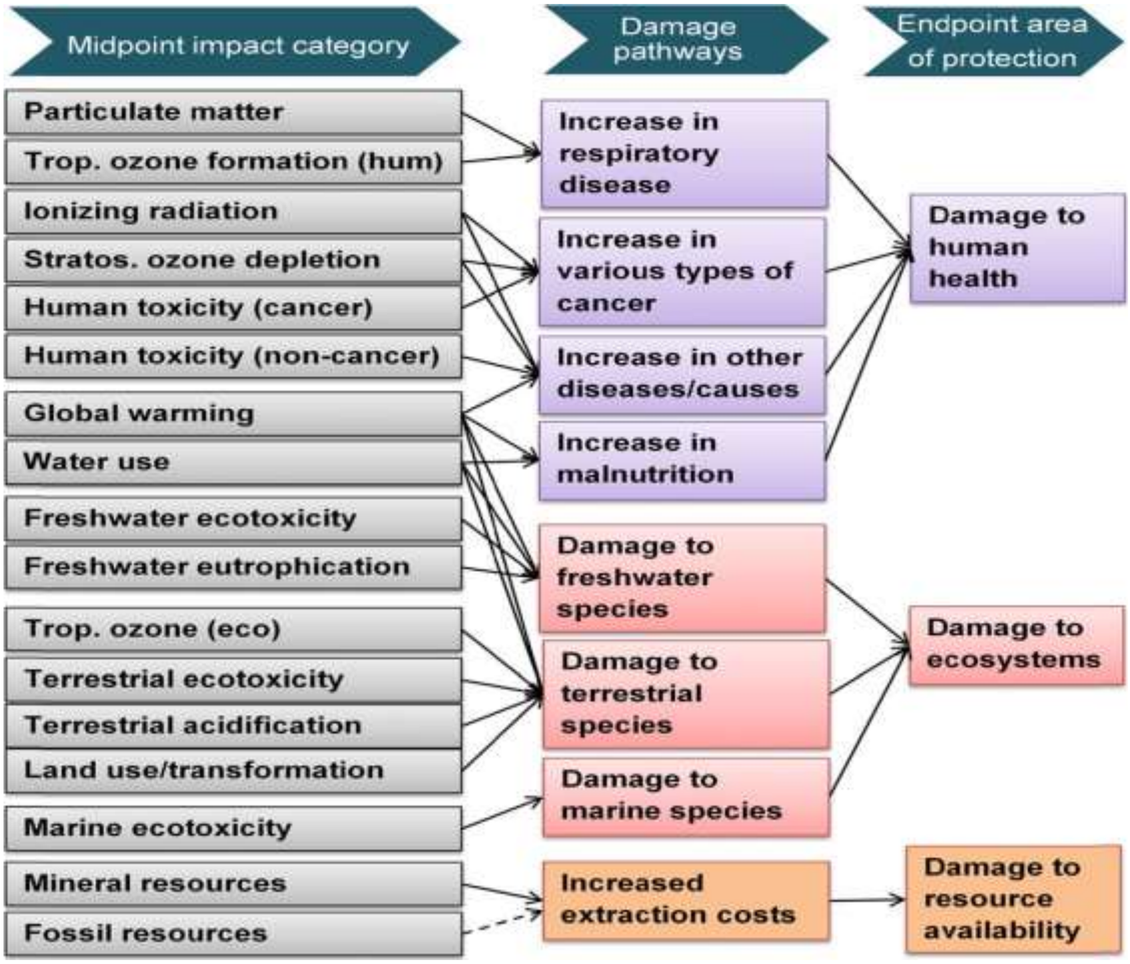


Figure 5: An overview of the impact categories included in the ReCiPe 2016 methodology and their corresponding relevance to the areas of protection; adapted from [6] (under license: CC BY 4.0)

LCA Applications in Medical Sector

Environmental Impacts of Upper-Limb Prostheses

A study for environmental impacts of upper-limb prostheses [29], the design for all assessed the life-cycle environmental burdens of prosthetic arms across different age groups, focusing on socket and structural materials used in fabrication were reported. The analysis followed cradle-to-grave boundaries covering raw material extraction, manufacturing, use, and disposal [29]. The functional unit was defined as a complete prosthetic arm over its service lifetime. Inventory data included primary measurements like component masses and energy consumed during manufacturing, supplemented with secondary datasets for background processes like polymer and metal production. Midpoint LCIA was also used to quantify impacts across relevant environmental categories. The outcomes showed that high-energy intensive materials such as advanced composites and processes such as curing and machining were the dominant contributors to the overall environmental footprint. Although lighter materials enhance user comfort and performance, they carry a higher environmental burden during production, creating a clear trade-off design. The study recommended changing to lower-impact materials, designing prostheses to be modular and repairable, and enhancing recycling strategies and techniques to reduce total life-cycle burdens without compromising device functionality. Table 4 highlights the main impact categories related to climate change, human health, resource use, and water consumption when studying the environmental impacts related to the production of prosthetic limbs for children.

Table 4: Selected midpoint environmental impacts associated with the production of a child prosthesis [29].

Impact category	Unit	Environmental impact values for child prosthesis
Global warming Potential (GWP)	Kg CO_2-eq	3.54
Human carcinogenic toxicity (HCT)	kg 1,4-DCB	0.176
Land use	$m^2 \cdot yr$ crop eq	10.23
Water consumption	m^3	4.12×10^{-2}

Life Cycle Assessment and Medical Device Methodology

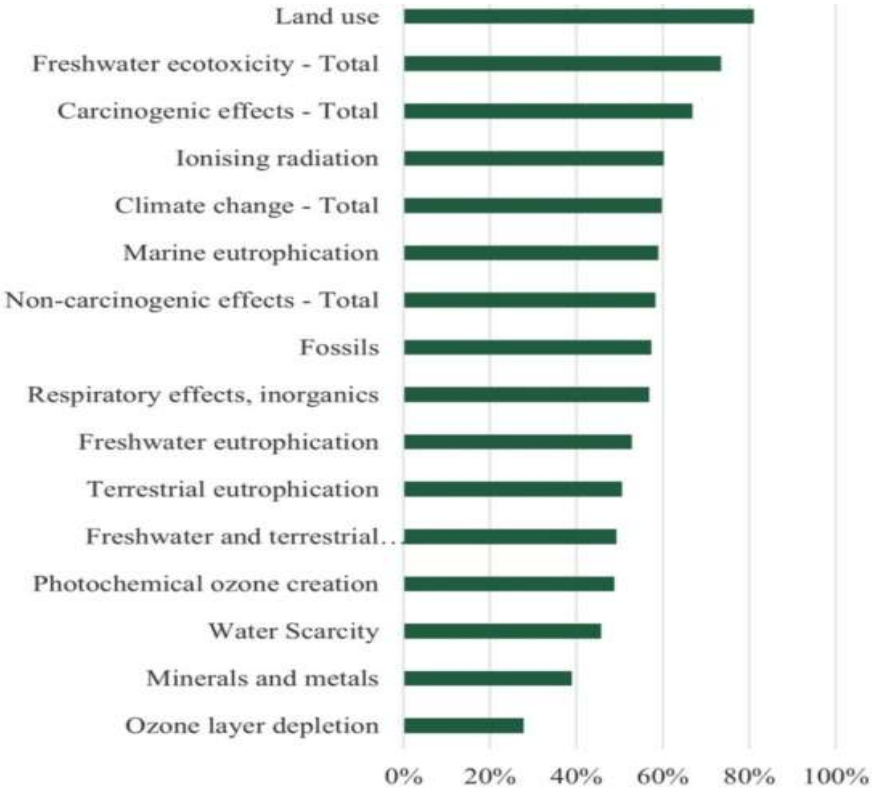
A study of life cycle assessment and environmental applications in medical devices provided a methodological framework for applying LCA to healthcare products, including prosthetic components [4]. It highlighted the essential of defining the goal and scope clearly, especially for customized, low-volume medical devices whose service life varies among users. It emphasized challenges in inventory quality, such as insufficient process-level data, geographic inconsistencies in background databases, and limited information about real-world use phases for specialized medical devices [4]. The authors stressed the need for sensitivity and uncertainty analyses to address variations in transport distances, recycling rates, and service lifetimes. Recommended impact categories for comparison included global warming potential, cumulative energy demand, resource depletion, and toxicity related categories, primarily using midpoint-level LCIA indicators. The study concluded that transparent documentation of assumptions and primary operational data is essential for generating reliable and comparable LCA results in medical-device research. As illustrated in Table 5, the meta-analysis highlights the most frequently used LCI databases and LCIA methods in medical-device LCA studies.

Table 5: Most frequently used LCI databases and LCIA methods reported in previous LCA studies [4].

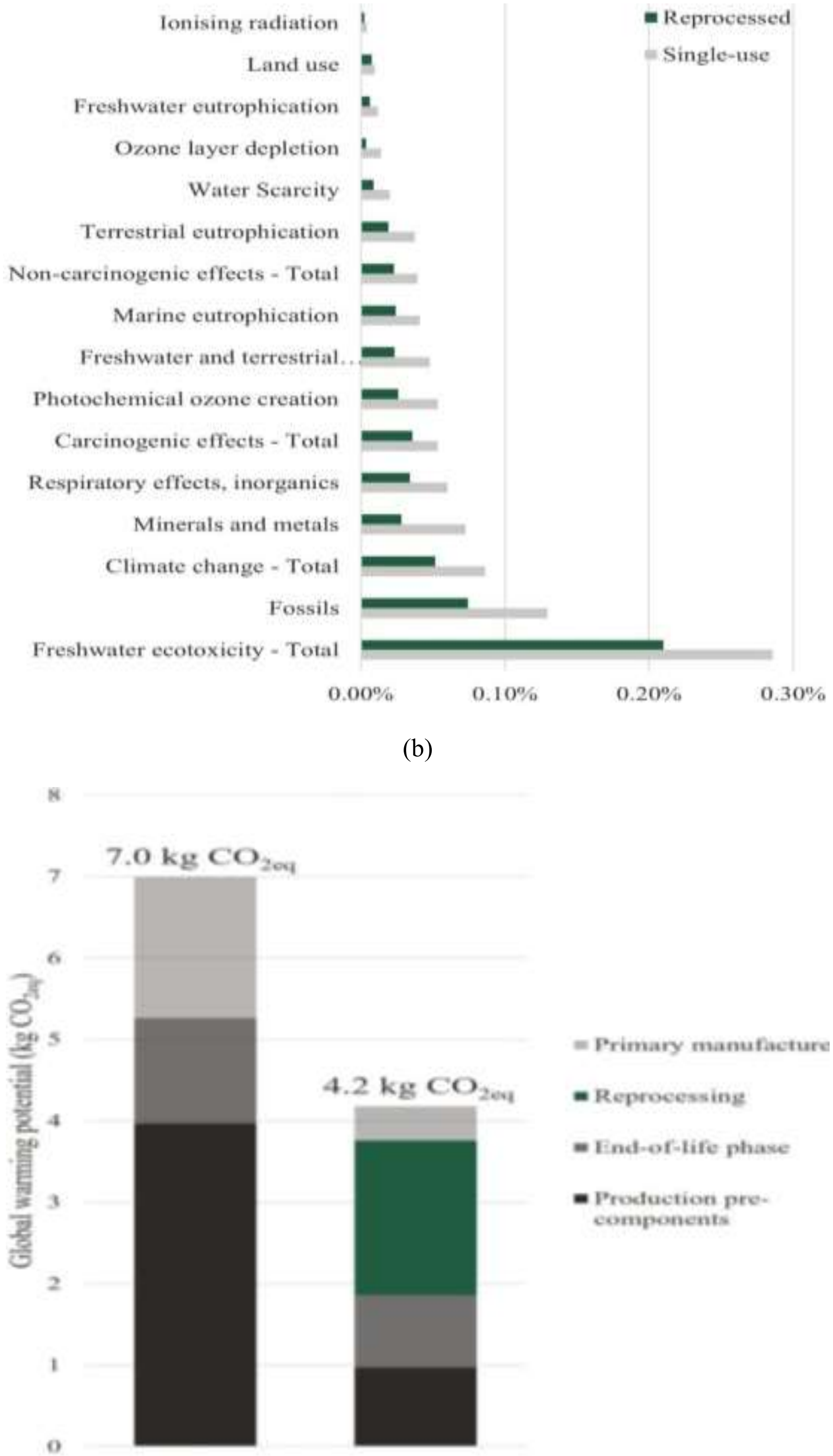
Category	Method/ database	Number of papers
LCI Database	Ecoinvent	9
LCI Database	GaBi	3
LCIA Method	ReCiPe	6
LCIA Method	Ecoindicator 99	3

Life Cycle Assessment of Reprocessed IPC Sleeves

Another study focused on the environmental and economic impacts of reprocessing intermittent pneumatic compression sleeves evaluated the sustainability benefits of reprocessed versus single-use compression sleeves in hospitals [34]. The functional unit represented five clinical treatments with IPC sleeves, modeled under a cradle-to-end-of-life system boundary that included manufacturing, clinical use, reprocessing cycles, transportation, and disposal. Primary data collected with the device manufacturer were combined with secondary datasets from the ecoinvent database to complete the inventory. The Environmental Footprint 3.0 (EF 3.0) method was used to assess impacts across multiple categories. Reprocessed sleeves achieved a 43% reduction in overall normalized environmental impacts and a 40% reduction in carbon footprint compared to single-use alternatives (7 kg CO2-eq reduced to 4.2 kg CO2-eq per five treatments) [34]. Electricity for reprocessing, transportation distances, and packaging materials were identified as major contributors to remaining impacts. Economically, hospitals reduced waste-disposal costs by 90% through reprocessing. The study demonstrated the effectiveness of circular-economy practices and recommended broader adoption of reprocessing systems for other medical devices. Figure 6 clearly demonstrates the substantial reduction in environmental burdens achieved through reprocessing compared to single-use IPC sleeves.



(a)



(b)

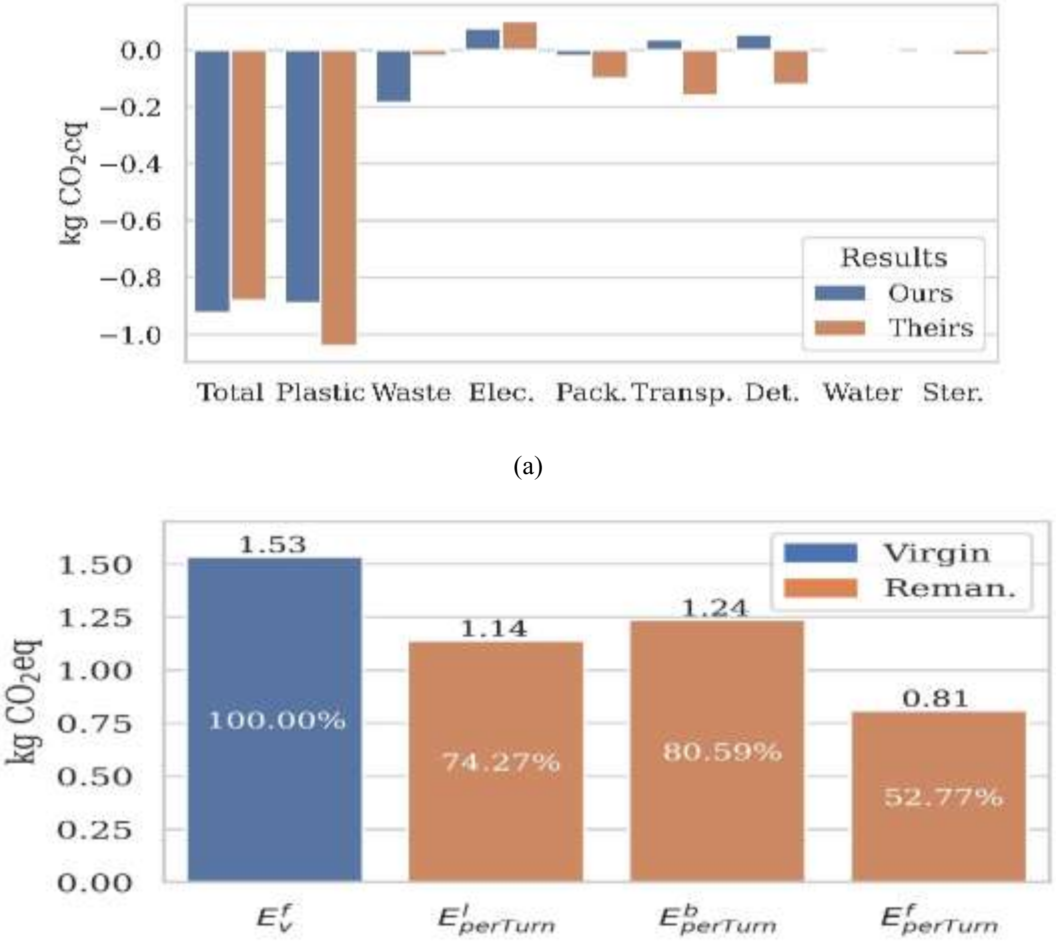
(c)

Figure 6: Contribution to environmental effects, (a) expressed as a percentage of the maximum impact in each category, for reprocessed compared to single-use IPC sleeves. (b) Product contribution to an individual's ecological footprint as determined by the Environmental Footprint 3.0 method across all impact categories. (c) Breakdown of accumulated impacts for the climate change category, comparing single-use and reprocessed IPC sleeves**.** Adapted from

[34] (under license: CC BY-NC 3.0)

Life Cycle Assessment of Remanufactured Electrophysiology Catheters

Life cycle greenhouse-gas emissions of remanufactured electrophysiology catheters were considered in [35]. It analyzed the environmental benefits of remanufacturing single-use EP catheters over multiple use remanufacture cycles. Using cradle to cradle boundaries, the study modeled virgin manufacturing, clinical use, collection, remanufacturing, transportation, and end of life disposal. The functional unit was defined as one catheter undergoing several remanufacturing turns. Inventory data incorporated detailed primary information from remanufacturing partners and complemented missing processes with ISO-aligned secondary datasets. Carbon-based LCIA showed that remanufacturing reduced CO2-equivalent emissions by up to 60% per turn in burden-free scenarios and approximately 57% when upstream burdens were included [35]. Sensitivity analyses and modeling of buy-back programs projected long-term reductions of up to 48% over the full-service life of the catheter [35]. The study concluded that remanufacturing is a highly promising circular-economy strategy and recommended designing catheters from the start to support dismantling, refurbishment, and repeated reuse. As shown in Figure 7, summarizes the study results, showing reduced emissions for remanufactured catheters compared to virgin ones, and the variation in total remanufacturing emissions depending on the emission metric used.



(a)

(b)

Figure 7: The study results are summarized, highlighting reduced emissions for remanufactured catheters compared to virgin ones, and illustrating the variation in total remanufacturing emissions depending on the emission metric applied (a) compares our virgin vs. remanufactured catheter emission results against the case study. (b) illustrates how much the total remanufacturing emissions may vary depending on the selected emission metric. adapted from [35]

(under license: CC BY 4.0).

Environmental and Economic Benefits of Repairing Surgical Scissors

A study reported in [33] considered environmental and economic benefits of repairing surgical scissors where the system boundary was cradle-to-grave, including raw material extraction, manufacturing, decontamination, repair (onsite or offsite), and disposal. Inventory data were based on primary information from manufacturers and repair centers, with background processes modeled using ecoinvent 3.6 and ELCD, especially for steam sterilization cycles. ReCiPe 2016 midpoint and endpoint indicators were used to quantify environmental burdens across 18 impact categories. The per-use carbon footprint dropped from approximately 70 g CO2-eq for un-repaired scissors to 57 g CO2-eq with offsite repair and 56 g CO2-eq with onsite repair. Sterilization dominated environmental burdens, accounting for 95–97% of total emissions when repair was included. From a financial perspective, repairs minimize life-cycle cost per use by roughly 32% [33]. The study emphasized and focused on the sustainability advantages of repair strategies and concentrated on the need for optimizing decontamination procedures, as well as designing surgical instruments to support repairability and extended use. As shown in Figure 8, repairing surgical scissors significantly reduces both environmental impacts and life-cycle costs relative to complete devices replacement.

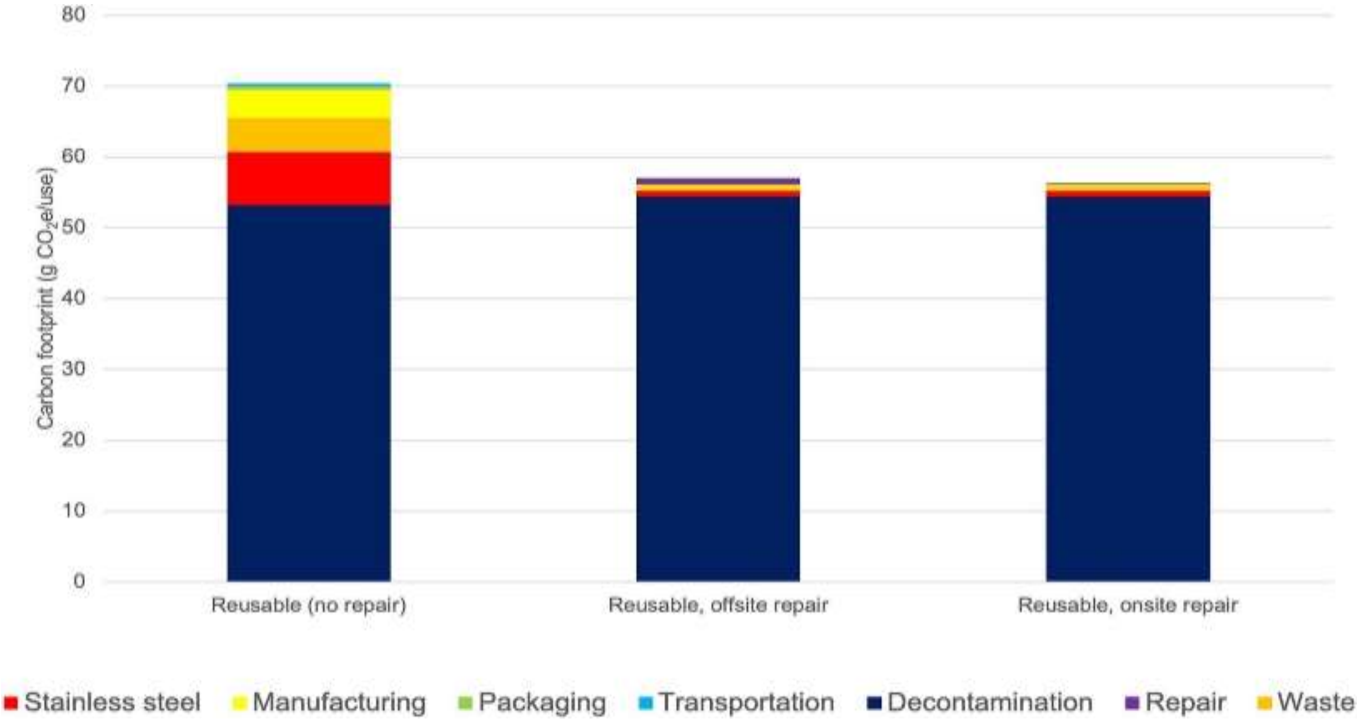


Figure 8: Results: Environmental and Cost Impacts of Repairing Reusable Surgical Scissors adapted from [33] (under license: CC BY 4.0).

Conclusions

This research reviews and emphasizes the importance of life cycle assessment as a critical scientific methodology for advancing environmental sustainability across medical-device systems. The collective evidence from published case studies shows that environmental burdens are primarily driven by upstream material production, energy intensive fabrication, and repeated sterilization, underscoring the emergent need for efficient resource management and improved process design. The integration of robust LCI databases such as ELCD and ecoinvent with ReCiPe 2016 Midpoint (H) enables transparent, high-resolution quantification of environmental impacts, ensuring comparability across medical technologies and techniques. Essential economic practices particularly reprocessing, remanufacturing, and repair demonstrate substantial reductions in carbon footprint, waste generation, and life cycle cost, confirming their strategic relevance for sustainable healthcare. Advancing eco-design principles, improving device modularity, and enhancing end-of-life pathways will be essential for enabling low-impact clinical technologies. As global healthcare systems face escalating environmental pressures, LCA-guided decision-making will continue to serve as a central pillar for designing resilient, sustainable, and high-efficiency medical devices.

List of Abbreviations

LCA	Life Cycle Assessment
LCI	Life Cycle Inventory
LCIA	Life Cycle Impact Assessment
ISO	International Organization for Standardization
ELCD	European Reference Life Cycle Database
ReCiPe 2016 (H)	ReCiPe Life Cycle Impact Assessment Method
ILCD	International Reference Life Cycle Data System
CML -IA	Centre of Environmental Science Impact Assessment Method
CO_2-eq	Carbon Dioxide Equivalent
IMPACT 2002+	Integrated LCIA Method combining midpoint and endpoint
GaBi	Ganzheitliche Bilanzierung (LCA Software)
openLCA	Open Life Cycle Assessment software
SimaPro	Simulation Program for Life Cycle Assessment
GUI	Graphical User Interface
EU	European Union
USLCI	United States Life Cycle Inventory Database
ABS	Acrylonitrile Butadiene Styrene
ODS	Ozone Depleting Substances
UVB	Ultraviolet B Radiation
GHG	Greenhouse Gas
IPC	Intermittent Pneumatic Compression
EP	Electrophysiology
DALY	Disability Adjusted Life Years
USD	United States Dollar

Author Contributions

Conceptualization: F.A.; Methodology: S.S.; Investigation: S.S.; Data curation: S.S.; Formal analysis: S.S.; Writing original draft preparation: S.S.; Writing review and editing: F.A.; Supervision: F.A.; Project administration: F.A. All authors have read and agreed to the published version of the manuscript.

Conflicts of Interest

Authors have no conflicts of interest.

Funding

No external funding was received for this research.

Acknowledgments

The authors express their gratitude to the Hashemite University for supporting this research work.

AI-declaration

During the preparation of this manuscript, the authors used ChatGPT (OpenAI) to assist in improving the clarity and language of certain sentences. The AI tool was used solely for language editing purposes, and the authors take full responsibility for the content of the manuscript.

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