Environmental and Climate Technologies
2024, vol. 28, no. 1, pp. 842–854
https://doi.org/10.2478/rtuect-2024-0064
https://content.sciendo.com

Sustainable Operating Rooms: A Comprehensive Framework for Environmental Impact Analysis

Anna SAVIO[1*], Beatrice MARCHI[2], Andrea ROLETTO[3], Giuseppe MILANO[4], Simone ZANONI[5]

[1–3]*Department of Mechanical and Industrial Engineering, Università degli Studi di Brescia, Via Branze 38, 25123 Brescia, Italy*

[4]*Department of Medical and Surgical Specialties, Radiological Sciences, and Public Health, Università degli Studi di Brescia, Viale Europa 11, 25123, Brescia, Italy*

[5]*Department of Civil, Environmental, Architectural Engineering and Mathematics, Università degli Studi di Brescia, Via Branze 43, 25123 Brescia, Italy*

Received 15.05.2024; accepted 25.11.2024

***Abstract* – The healthcare sector is responsible for around 4.4 % of worldwide greenhouse gas emissions, according to estimates. Operating rooms are responsible for the greatest rate of resource consumption and overall hospital waste, varying from 20 % to 33 %. Hence, it is essential to fully discover the environmental impact of surgical procedures to obtain insight into the total emissions associated with the healthcare sector. Moreover, the lack of uniformity in data collection and the discrepancy of the data used by researchers makes it challenging, if not ineffective, to conduct a rigorous scientific comparison among the currently available studies on the environmental impacts of surgical procedures. This study aims to provide a practical and standardised framework that can be utilised to evaluate, simply and consistently, the environmental impacts of surgical procedures. To achieve this goal, a comprehensive literature review was conducted to assess the state of the art in environmental impact analyses related to surgical practices. This review highlighted significant variability and heterogeneity in existing methodologies, serving as the foundation for developing a more consistent approach. By simulating three different scenarios based on data availability, a methodology is proposed to conduct an environmental impact analysis tailored to the specific needs of researchers. Adopting a uniform methodology guarantees the inclusion of important variables and factors, preventing any oversights in the evaluation of the entire process.**

***Keywords* – Framework; greenhouse gas (GHG) emissions; healthcare; Life Cycle Assessment (LCA); surgery; waste management.**

1. Introduction

The growing concern for environmental sustainability, accentuated by the ongoing climate crisis, prompted a thorough examination of the primary industries accountable for substantial greenhouse gas emissions and excessive depletion of natural resources. Out of all the sectors, the healthcare industry accounted for approximately 4.4 % of the total global greenhouse gas emissions [1]. Practitioners are now compelled to consider which phases of the care process have the most significant influence on resource consumption as a result of this heightened awareness. Research conducted in both the United States and the United Kingdom reveals

* Corresponding author.
E-mail address: anna.savio@unibs.it

that operating rooms contribute to 20–33 % of the overall waste generated by hospitals [2], [3]. Multiple studies concentrate on the generation of waste in surgical theatres, examining waste sorting protocols and measuring the various categories of waste, to identify potential avenues for reducing and recycling waste [4]–[10]. The significant waste generation in operating rooms is associated with the extensive use of disposable instruments. While these instruments ensure complete traceability and patient safety, their usage has a more substantial environmental impact compared to reusable devices [11]–[17].

Additionally, the energy consumption of operating rooms is 2–3 times greater than other sections within healthcare facilities. The structure and arrangement of an operating block are focused on reaching functionality and minimising bacterial and viral contamination. Each facility and technological system must ensure efficiency and safety, adhering to criteria that promote the maintenance of hygienic conditions. This results in significant energy and resource utilisation: the energy consumption linked to HVAC (Heating, Ventilation and Air Conditioning) systems during a surgical procedure is one of the most influential factors [18].

This article aims to present a structured methodological framework that serves as a roadmap for conducting studies on the environmental impacts of surgical procedures. By outlining efficient approaches tailored to data availability and study scope, the framework provides a foundation for advancing research in this field. A comprehensive literature review was carried out to identify and compare previously employed methodologies, highlighting their strengths and limitations. This analysis supports the adoption of a consistent and standardized approach, which can enhance uniformity in research and foster the integration of sustainability principles into surgical practices.

The study underscores the importance of interdisciplinary collaboration, recognizing that combining expertise from fields such as engineering and medicine is essential to ensure the accuracy and reliability of data collection and analysis. Addressing this need, the framework proposes three distinct scenarios, each corresponding to a different level of analytical depth and data availability. These scenarios offer a structured methodology for tackling the issue of environmental sustainability in surgery, bridging disciplines that are crucial for both human and environmental wellbeing.

The results of this study are qualitative, focusing on methodological contributions rather than quantitative data. They include the systematic identification of key factors, such as resource consumption, waste management, and environmental impacts, and the development of scenario-based methodologies to address these factors comprehensively. By offering actionable tools and guidelines, this work equips researchers and practitioners with practical frameworks to integrate sustainability into operating room practices, paving the way for a more environmentally conscious approach to surgical care.

2. METHODS AND METHODOLOGY

The study aims to establish a clear and simple methodological approach for recording operational procedures, identifying necessary data, and choosing the most suitable methodology for environmental impact assessment. A standardised methodological framework is designed to assist and guide researchers in evaluating surgical procedures, considering the various factors that affect their duration, complexity, and outcomes.

A comprehensive review of the literature reveals that the objective of environmental impact analysis and the accessibility of relevant data vary significantly in the surgical setting. Based on these differences, three separate scenarios have been identified. Each scenario sets precise boundaries for analysing the different factors that affect the consumption of resources in the process being studied, ensuring that each evaluation is adapted to its specific needs.

2.1. Literature Review

A literature review was conducted in February 2024 using the Scopus and PubMed databases to identify original articles focused on the environmental impact of surgical procedures performed in operating rooms. The review process started with a preliminary selection, restricting the articles to those written in English and excluding reviews, editorials, and letters. Subsequently, after an initial screening of titles and a detailed review of abstracts, only open-access articles were included, and their full texts were obtained for further analysis. To expand the search, a manual review of references cited in the selected articles and reviews was performed to identify additional studies meeting the eligibility criteria.

Studies that: 1) focused exclusively on single medical devices or equipment used during surgical procedures; 2) evaluated potential eco-friendly initiatives by medical staff or; 3) consisted of abstracts or conference proceedings, were excluded.

The final analysis included only studies that quantified the overall environmental impact associated with the entire process of surgical procedures. For each selected article, data extraction was systematically carried out, collecting information on the year of publication, country of publication, medical field, focus of study and environmental impact assessment approach used.

2.2. Scenarios Identification

The results of the literature review made it possible to identify three potential scenarios, which are useful for effectively representing the different situations that require an environmental impact analysis to be undertaken in the operating room. Each scenario differs in terms of the availability of data to be processed and the type of environmental assessment that can be carried out. The aim of these three scenarios is to provide a clear and structured framework for researchers engaged in this type of analysis.

3. LITERATURE REVIEW

3.1. Study Selection

A comprehensive search conducted using the Scopus and PubMed databases identified a total of 277 research articles addressing the environmental consequences of surgical procedures. However, only a small subset of these studies: 17 articles, accounting for just 6 % of the total, specifically focused on conducting an environmental impact assessment related to the surgical process.

3.2. Characteristics of the Included Articles

Baseline characteristics of articles are summarised in Table 1.

The reviewed literature includes 17 papers examining the environmental effects of surgical procedures. 5/17 (29 %) studies are from the United States, 4/17 (24 %) from France, 3/17 (18 %) from the United Kingdom, and 2/17 (12 %) from India. New Zealand and Ireland provide 1/17 (6 %) respectively. This distribution indicates an increasing concern with the environmental consequences of surgery, particularly in industrialised nations, where resources for sophisticated environmental assessments are more accessible.

An examination of publication years reveals a significant rise in focus on the environmental effects of surgery, with 11/17 (65 %) released in the past three years (2021–2024). This trend signifies an increasing worldwide consciousness regarding climate change and the necessity to alleviate the environmental repercussions of healthcare systems.

TABLE 1. BASELINE CHARACTERISTICS OF ARTICLES

Study (yr)		Country	Medical Specialty	Focus of the Study	Environmental impact assessment approach
[19]	Campion *et al.* (2012)	US	Obstetrics and Gynaecology	Vaginal delivery and caesarean birth	Process-based LCA
[20]	Ditac *et al.* (2023)	France	Cardiology	Atrial fibrillation catheter ablation	Eco-audit
[21]	Ferrero *et al.* (2022)	France	Ophthalmology	Cataract surgery	EIO-LCA
[22]	Grinberg *et al.* (2021)	France	Cardiology	Conventional isolated cardiac surgeries	Eco-audit
[23]	Latta *et al.* (2021)	New Zealand	Ophthalmology	Cataract surgery	Carbon footprint
[24]	Namburar *et al.* (2018)	India	Ophthalmology	Glaucoma surgery	Waste audit
[25]	Power B. *et al.* (2021)	Ireland	Ophthalmology	Intravitreal injection	Hybrid LCA
[26]	Power N. *et al.* (2012)	US	General Surgery	Minimally invasive surgery	Carbon footprint and EEIO
[27]	Prakash *et al.* (2023)	UK	Orthopaedics	Primary hip and knee arthroplasty	Waste audit
[28]	Rizan *et al.* (2023)	UK	General Surgery, Orthopaedics, Otolaryngology	Carpal tunnel decompression, inguinal hernia repair, knee arthroplasty, laparoscopic cholecystectomy, tonsillectomy	Waste audit
[29]	Rougereau *et al.* (2024)	France	Orthopaedics	Arthroscopic rotator cuff repair	Waste audit
[30]	Ryan *et al.* (2023)	US	Otolaryngology	Tonsillectomy, adenoidectomy, sept rhinoplasty, endocrine surgery, tympanoplasty, and hearing implantation surgery	Waste audit
[31]	Stall *et al.* (2013)	UK	Orthopaedics	Total knee arthroplasty	Waste audit
[32]	Thiel *et al.* (2015)	US	Obstetrics and Gynaecology	Abdominal, vaginal, laparoscopic, and robotic hysterectomy	Carbon footprint
[33]	Thiel *et al.* (2017)	India	Ophthalmology	Cataract surgery	Process-based LCA
[34]	Woods *et al.* (2015)	US	Obstetrics and Gynaecology	Robotically-assisted laparoscopy, laparoscopy and laparotomy	Carbon footprint and EEIO
[35]	Zhang *et al.* (2023)	US	Orthopaedics General surgery	Carpal tunnel release	Carbon footprint

From a medical speciality viewpoint, ophthalmology represented 35 % (6/17) of the studies, with research exploring procedures such as cataract surgery, intravitreal injections, and glaucoma surgery. Orthopaedic surgery follows with 29 % (5/17), centred on hip and knee arthroplasties, and rotator cuff repairs. Additional disciplines encompass gynaecology and obstetrics (18 %, 3/17), cardiology (12 %, 2/17) otolaryngology and general surgery (24 %, 4/17) which includes tonsillectomies and carpal tunnel decompressions (10, 17).

The utilised methodological approaches exhibit considerable variation. Life Cycle Assessment (LCA) and its derivatives, including Economic Input-Output LCA (EIO-LCA), constitute 24 % (4/17) of the studies employed to evaluate the complete life cycle of surgical resources from "cradle-to-grave". Carbon Footprint has been utilised in 24 % (4/17) of the investigations to assess CO_2 emissions. Eco-audits, focused on resource impacts, constitute 12 % (2/17) of the research, whereas Waste audits appear as the most prevalent method, representing 29 % (5/17) of the studies.

The investigated papers reveal a considerable variation in approaches to environmental analysis, which vary significantly based on data availability and the processes examined. 65 % (10/17) of the studies examine the implications related to the acquisition of the examined resources, including electricity and natural gas [19]–[23], [25], [26], [28], [29], [32]. Waste management is a crucial subject, addressed in 65 % (11/17) of the enquiries highlighting the increasing necessity for effective and sustainable waste management regulations [19]–[21], [25]–[29], [32], [34], [35].

The chronological and thematic analysis clearly illustrates how the focus on the environmental impact of surgical operations is fast expanding. The growing interest is directly linked to the imperative of tackling climate change and the substantial influence of the healthcare industry. Despite significant advancements, deficiencies persist in methodological standardisation and the lack of uniformity in the factors considered, such as the specific resources consumed, creates challenges for those looking to enter this field. This inconsistency makes it difficult to establish a clear understanding of how to approach environmental assessments, limiting the ability of researchers and practitioners to adopt standard methodologies or draw reliable comparisons across studies.

4. SCENARIOS CONSIDERED

To clearly and effectively delineate the diverse contexts that necessitate an environmental impact analysis in the field of surgery, three potential scenarios have been identified. These scenarios aim to serve as a structured framework for researchers undertaking such analyses, providing a foundation for selecting the most suitable methodology tailored to the desired outcomes and the available data.

To establish the three scenarios clearly and logically, the temporal representation of the material and resource flows needed for a surgical operation was achieved by dividing the process into three distinct phases.

The pre-operative phase focuses on the processes that facilitate the presence of a resource in the operating rooms. Beginning with the extraction of raw materials and natural resources, we progress to the production and transportation of the necessary instrument/substance/machinery to carry out the procedure. During this stage, the energy provision for the facility is also encompassed.

The intra-operative phase refers to the use and depletion of resources specifically within the confines of the operating room. The energy and material flows vary depending on the specific procedure being carried out. Equipment, air conditioning, and lighting are major contributors to energy consumption, as they are necessary to maintain a climate and environment that meet the required hygiene standards. Materials and instruments can be categorised into two main types: disposables and reusables. Disposables are typically placed in designated containers for disposal, while reusable items are processed for recovery. Substances deemed beneficial encompass pharmaceuticals, anaesthetic gases, and disinfectants.

The post-operative phase involves two primary processes for what is removed from the operating room: waste management and reconditioning process. Consequently, the attention is redirected towards the management and disposal of waste and the processes of sterilising and laundering in hospitals. This stage requires a significant allocation of resources, both from the hospital itself and from external facilities.

The three phases impact the utilisation of natural resources and the release of damaging substances into the atmosphere in different ways. The boundaries of the three proposed scenarios are illustrated in Fig. 1, delineating the phases and processes that are considered in each case.

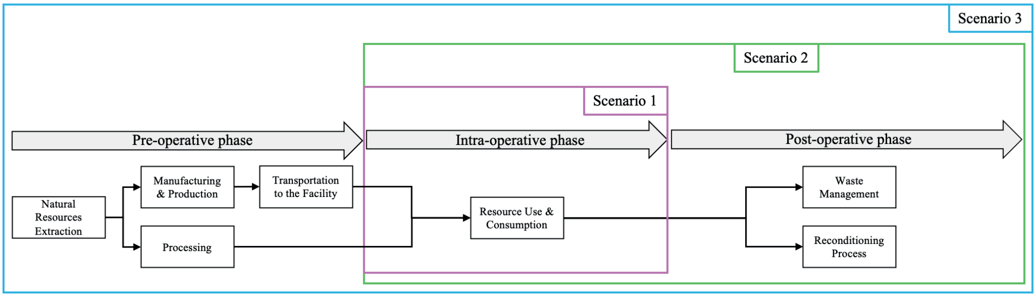

Fig. 1. Phases and processes of surgical operations and boundaries of different scenarios.

4.1. Scenario 1

Scenario 1 outlines a preliminary methodology for assessing the environmental consequences of surgical procedures conducted in the operating rooms. The objective is to offer an initial strategy that can guide the hospital toward a more structured analysis. In this situation, the duration of the surgery establishes the time limit for analysis. The proposed methodology aims to measure the amount of energy and materials used during surgery. Such analysis is highly valuable for comparing various surgical techniques used in performing surgery as it quickly provides a benchmark for comparison with simple data collection.

When there is limited information available on the utilisation of the devices or insufficient data on energy consumption in the operating room, it is possible to quantify the waste generated by conducting a waste audit. While this method of analysis is commonly used, a waste audit provides an even more approximate assessment of the true impact of various techniques because it does not consider a significant portion of consumption factors. In this case, it is crucial to clarify the waste classification policy implemented in the facility where the analysis will take place. The waste classification policy directly affects the quantity of specific waste generated in the operating room. Providing clear and detailed information about where materials are disposed of would enable the comparison of studies conducted in various facilities and countries.

The data collection on the primary factors affecting intra-operative consumption is summarised in Table 2. It is important to acknowledge that this data collection provides a measurement of the resources utilized but does not specify the actual environmental consequences. Nevertheless, it is highly advantageous to easily identify the primary discrepancies between procedures and highlight potential avenues for enhancement.

TABLE 2. PROCESS AND DATA COLLECTION FOR SCENARIO 1 (INTRA-OPERATIVE PHASE)

Phase	**Process/Item**		**Data collection**
Intra-operative	Energy and Water	HVAC	Duration of use (h) and energy (kWh)
		Lighting	Duration of use (h) and energy (kWh)
		Medical Equipment	Duration of use (h) and energy (kWh)
		Hot Water	Quantity (m^3)
	Chemicals	Pharmaceuticals	Quantity (mL/mg)
	Materials and Instruments	Disposable devices	Type and quantity (#)
		Reusable devices	Type and quantity (#)
		Linens	Type and quantity (#)
	Waste Audit	Non-recyclables	Quantity (kg)
		Recyclables	Quantity (kg)
		Biohazardous	Quantity (kg)

4.2. Scenario 2

Scenario 2 extends beyond the simple classification and measurement of resources utilised during a surgical procedure. The objective is to comprehend the effects caused by the utilisation of materials in the operating room by expanding the scope of analysis to the post-operative stage. This requires a more structured and complex data collection process compared to Scenario 1. It is important to note that collecting data on post-operative phases allows for the assignment of an emission factor to all the consumed resources in a simple and practical manner, without the need to gather detailed and specific information on every device, material, or substance used during the procedure. In particular, disposable materials and devices, once utilized, inevitably become waste that must be either disposed of or recovered. Therefore, it is sufficient to collect data on the type of waste produced and the applied disposal or recovery method (e.g., incineration, landfill, recycling) to assign the corresponding emission factor.

Emission factors for materials or resources are standardized values that quantify the greenhouse gas emissions (typically expressed in $kgCO_2eq$) associated with a specific quantity of material or resource. These factors are used to estimate the environmental impact of materials and resources in terms of carbon footprint, enabling accurate evaluations and comparisons between products, processes, or sectors. Emission factors for materials or resources are typically provided by international databases (e.g., *Ecoinvent* [36], government reports (e.g., UK GHG Conversion Factors [37], or published LCA studies.

Emission factors for energy consumption are closely linked to the country’s energy mix, which reflects the proportions of energy sources like fossil fuels, nuclear, and renewables. Regions with higher reliance on coal or natural gas will have greater emission factors than those using predominantly renewable energy, making it essential to use location-specific data.

In contrast, emission factors for waste depend on the type of waste and its disposal method. Non-recyclable, recyclable, and biohazardous waste have different impacts based on management practices. For example, incineration generates higher emissions than recycling, while landfilling produces methane from organic waste decomposition.

Table 3 provides a concise overview of the factors that need to be considered and examples of emission factors from UK GHG Conversion Factor report are also given. This simplified approach enables the effective quantification of the environmental impact of post-use resources, maintaining analysis precision without requiring an excessive level of detail.

TABLE 3. PROCESS AND DATA COLLECTION FOR SCENARIO 2 (INTRA E POST-OPERATIVE PHASES)

Phase	Process/Item		Data collection	Emission factor
Intra-operative	Energy and Water	HVAC	Duration of use (h) and energy (kWh)	Electricity 0.207 $kgCO_2eq/kWh$ Natural gas 0.183 $kgCO_2eq/kWh$ Water supply 0.177 $kgCO_2eq/m^3$
		Lighting	Duration of use (h) and energy (kWh)	
		Medical Equipment	Duration of use (h) and energy (kWh)	
		Hot Water	Quantity (m^3)	
	Chemicals	Pharmaceuticals	Chemical composition and quantity (mL/mg)	e.g., Sevoflurane 0.130 $kgCO_2eq/mL$
	Materials and Instruments	Disposable devices	Type and quantity (#)	Linked to Waste Management
		Reusable devices	Type and quantity (#)	Linked to Reconditioning Process
		Linens	Type and quantity (#)	Linked to Reconditioning Process
	Waste Audit	Non-recyclables	Quantity (kg) and disposal process	Linked to Waste Management
		Recyclables	Quantity (kg) and disposal process	
		Biohazardous	Quantity (kg) and disposal process	
Post-operative	Waste Management	Landfill	Type of waste and quantity (kg)	Non-recyclables landfill 520.33 $kgCO_2eq/kg$
		Incineration	Type of waste and quantity (kg)	Non-recyclables incineration 21.281 $kgCO_2eq/kg$
		Recycling	Type of waste and quantity (kg)	Plastic recycling 21.281 $kgCO_2eq/kg$
	Reconditioning Process	Laundry	1 cycle duration (h), power (kWh) and quantity of water (m^3)	Electricity 0.207 $kgCO_2eq/kWh$ Natural gas 0.183 $kgCO_2eq/kWh$ Water supply 0.177 $kgCO_2eq/m^3$
		Sterilization	1 cycle duration (h), power (kWh) and quantity of water (m^3)	

4.3. Scenario 3

The goal is to conduct a comprehensive LCA of the entire surgical process. The ISO 14040 series of standards is the internationally recognised reference for conducting LCA studies. The LCA framework consists of four primary steps:

– The objectives and scope of the study include the definition of the products and processes under investigation, the functional unit, system boundaries, assumptions, and limitations, intended application, rationale, and target audience of the study.

– Inventory analysis (LCI) involves the collection and calculation of data to measure the incoming and outgoing flows of a product system, based on the defined objective and scope.
– Life Cycle Impact Assessment (LCIA) is a process that seeks to measure the magnitude of possible environmental effects by utilising the findings of life cycle inventory analysis.
– Interpretation refers to a methodical procedure that involves identifying, assessing, confirming, and evaluating the outcomes of the inventory and impact assessment stages. The goal is to present these findings in a manner that fulfils the requirements of the stated objective and scope and to derive conclusions and recommendations based on them.

To achieve a comprehensive LCA of surgery, it is essential to supplement the information acquired during the intra- and post-operative phases with accurate data on the extraction, manufacturing, and processing cycles of all resources utilised in the operating theatre.

Fig. 2 presents a schematic representation of the resource flows and processes throughout the three stages that need to be considered. The emphasis has been placed on variables that can be measured, compared, and predicted together with a certain level of accuracy. The objective is to assess consumption factors that follow clearly defined cycles while excluding variables that are beyond the control or not directly linked to the surgical procedure (such as patient and medical staff transportation within the hospital).

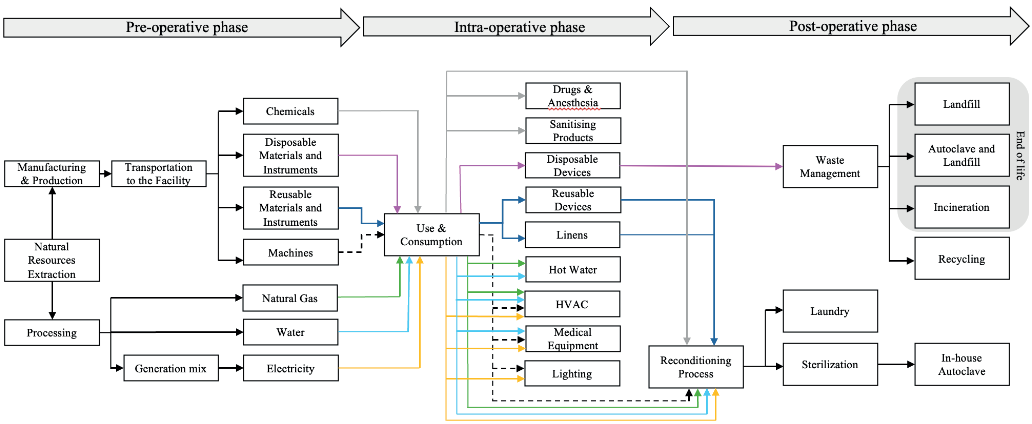

Fig. 2. Life Cycle Assessment main flowchart of resource consumption.

The challenge of conducting a LCA on a process derives from the requirement for precise data, the extensive amount of data that needs to be gathered, and the analysis of the environmental and human health effects of all factors considered [38]. To facilitate this intricate process, the use of specialized LCA software can be invaluable. Tools such as *SimaPro* [39] and *OpenLCA* allow for the systematic analysis of data, from resource extraction to waste management, and incorporate extensive libraries of emission factors and environmental impact categories. However, their effective use requires specialized skills, such as proficiency in data interpretation, environmental modelling, and an understanding of life cycle inventory data. For instance, setting system boundaries, integrating custom datasets, and interpreting the outputs in the context of healthcare require a multidisciplinary approach.

The adoption of such software can significantly enhance the accuracy and depth of LCA studies, enabling researchers to uncover insights that would be difficult to achieve through manual calculations alone. However, institutions embarking on such assessments should invest in training personnel or collaborating with specialists to maximize the potential of these tools.

The integration of life cycle assessment with the health industry is a significant challenge. Nevertheless, we believe that the development of the diagram depicted in Fig. 1 will be useful as a valuable reference and support for researchers seeking to conduct a life cycle analysis of a surgical procedure.

5. DISCUSSION AND CONCLUSION

Analysing the environmental impact of surgical procedures serves several critical purposes. It quantifies key environmental effects, such as carbon emissions, energy consumption, and resource use, while identifying opportunities for optimization. For instance, adopting reusable instruments and refining workflows can significantly reduce the ecological footprint of surgeries. This type of analysis not only raises awareness among healthcare professionals and patients but also supports compliance with sustainability regulations and fosters the development of eco-friendly surgical technologies. Additionally, it establishes measurable benchmarks for continuous improvement, aligning healthcare practices with stakeholder expectations and corporate social responsibility goals.

However, the inherent complexity of surgical procedures and associated challenges in data collection present significant barriers to effective analysis. Issues such as the aggregation of diverse resources, resistance from staff, and privacy concerns complicate the process. Addressing these challenges requires a multidisciplinary approach that combines expertise from healthcare, environmental science, and data management. Advanced technologies and tools are also essential to ensure accurate and actionable insights, allowing for more effective assessments and improvements.

Recognizing these challenges, this study developed a structured framework for assessing the environmental impact of surgical procedures. The framework is divided into three scenarios of increasing complexity, aimed at analysing resource use and material flows. The results highlight significant variability in resource consumption, waste management practices, and methodological approaches, emphasizing the urgent need for standardization. Without uniform assessment methods, it remains difficult to establish common benchmarks or draw reliable comparisons across studies.

The proposed three-scenario framework marks an important step toward promoting sustainability in operating rooms. Scenario 1 focuses on intraoperative resource consumption, providing a simple yet practical method for comparing different surgical techniques. While this approach offers immediate insights, its narrow scope, limited to intraoperative time, restricts its applicability for more comprehensive environmental evaluations. Scenario 2 extends the analysis to include post-operative phases, such as waste management and reconditioning processes, introducing emission factors to quantify the ecological impact of consumed resources. This broader perspective facilitates meaningful cross-sector comparisons but may still oversimplify the full environmental impact of surgical procedures. Finally, Scenario 3 adopts a comprehensive LCA approach, considering all stages from raw material extraction to end-of-life management. While this method delivers detailed and holistic insights, its implementation requires extensive data collection and interdisciplinary collaboration, making it resource-intensive and complex.

Future advancements in these methodologies should focus on establishing centralized databases of emission factors tailored to surgical procedures, which would enhance calculation accuracy and enable consistent assessments across studies. The use of specialized software tools such as *SimaPro* and *OpenLCA* can further streamline data analysis and promote more sophisticated approaches. However, leveraging these tools effectively requires expertise in environmental modelling and data interpretation, underscoring the need for collaboration between healthcare practitioners and environmental experts.

In conclusion, the proposed framework provides a robust foundation for understanding and mitigating the environmental impact of surgical procedures. Its implementation requires sustained efforts to improve data collection and analysis while fostering interdisciplinary collaboration and adopting advanced technologies. This framework not only has the potential to improve current practices but also sets the stage for establishing new standards for environmental sustainability in healthcare. Advancing this field represents a necessary and impactful response to the growing global awareness of climate change and highlights the healthcare sector's pivotal role in addressing this pressing challenge.

Study Limitations

The patient's journey through the healthcare system is not fully covered by this study. A comprehensive investigation of critical phases, such as pre-operative assessments, diagnostics, hospital stay, and post-operative rehabilitation therapies, has not been included in this analysis, even if we are fully aware that these elements may represent an important portion of the overall environmental impact of healthcare [40]. The environmental impact of surgical operations extends far beyond the walls of the operating theatre, reflecting a treatment pathway that includes numerous services and procedures. To obtain a more thorough evaluation of the environmental consequences, future studies should integrate these factors into the entire life cycle of surgical care. This would result in a more extensive and detailed analysis of the environmental impact caused by these procedures.

REFERENCES

[1] Karliner J., Slotterback S., R Boyd., Ashby B., Steele K. Healthcare's climate footprint: How the health sector contributes to the global climate crisis and opportunities for action. *European Journal of Public Health* 2020:30. https://doi.org/10.1093/eurpub/ckaa165.843

[2] Sustainable Development Unit, Public Health England, NHS England. Reducing the use of natural resources in health and social care. Cambridge: Sustainable Development Unit [Online]. [Accessed 30.04.2020]. Available: https://www.sduhealth.org.uk/policy-strategy/reporting/sustainable-development-in-health-and-care-report2018.aspx

[3] Lee B.-K., Ellenbecker M. J., Moure-Eraso R. Analyses of the recycling potential of medical plastic wastes. *Waste Management* 2002:22(5):461–470. https://doi.org/10.1016/S0956-053X(02)00006-5

[4] Deepak A., Sharma V., Kumar D. Life cycle assessment of biomedical waste management for reduced environmental impacts. *J Cleaner Production* 2022:349:131376. https://doi.org/10.1016/j.jclepro.2022.131376

[5] Rammelkamp Z., Dirnberger J., Johnson G., Waisbren S. An Audit of All Waste Leaving the Operating Room: Can the Surgical Suite Be More Environmentally Sustainable? *World Medical and Health Policy* 2021:13(1):126–136. https://doi.org/10.1002/wmh3.397

[6] Kooner S. *et al.* Waste and recycling among orthopedic subspecialties. *Canadian Journal of Surgery* 2020:63(3):E278–E283. https://doi.org/10.1503/cjs.018018

[7] Sullivan G. A., Reiter A. J., Hu A., Shah A. N., Dsida R., Raval M. V. Operating Room Recycling: Opportunities to Reduce Carbon Emissions Without Increases in Cost. *Journal Pediatric Surgery* 2023:58(11):2187–2191. https://doi.org/10.1016/j.jpedsurg.2023.04.011

[8] Lee R. J., Mears S. C. Reducing and Recycling in Joint Arthroplasty. *Journal of Arthroplasty* 2012:27(10):1757–1760. https://doi.org/10.1016/j.arth.2012.04.020

[9] Romano L., Giuliani A., Muselli M., Lupi E., Vistoli F. Toward Environmentally sustainable surgery: Waste recycling in general surgery operating room. Preliminary cognitive audit. *World Journal of Surgery* 2024:48(11):2637–2643. https://doi.org/10.1002/wjs.12237

[10] Zlaugotne B., Pubule J., Gusca J., Kalnins S. N. Quantitative and Qualitative Assessment of Healthcare Waste and Resource Potential Assessment. *Environmental and Climate Technologies* 2022:26(1):64–74. https://doi.org/10.2478/rtuect-2022-0006

[11] Mikusinska M. Comparative Life Cycle Assessment of Surgical Scrub Suits: The Case of Reusable and Disposable Scrubs used in Swedish Healthcare. KTH Royal Institute of Technology, Stocholm, 2012.

[12] Campion N., Thiel C. L., Woods N. C., Swanzy L., Landis A. E., Bilec M. M. Sustainable healthcare and environmental life-cycle impacts of disposable supplies: A focus on disposable custom packs. *Journal of Cleaner Production* 2015:94:46–55. https://doi.org/10.1016/j.jclepro.2015.01.076

[13] Boberg L., Singh J., Montgomery A., Bentzer P. Environmental impact of single-use, reusable, and mixed trocar systems used for laparoscopic cholecystectomies. *PLoS One* 2022:17. https://doi.org/10.1371/journal.pone.0271601

[14] Cohen E. S. *et al*. Environmental Impact Assessment of Reusable and Disposable Surgical Head Covers. *JAMA Surgery* 2023:158(11):1216–1217. https://doi.org/10.1001/jamasurg.2023.3863

[15] Le N. N. T., Hernandez L. V., Vakil N., Guda N., Patnode C., Jolliet O. Environmental and health outcomes of single-use versus reusable duodenoscopes. *Gastrointestinal Endoscopy* 2022:96(6):1002–1008. https://doi.org/10.1016/j.gie.2022.06.014

[16] Eckelman M., Mosher M., Gonzalez A., Sherman J. Comparative life cycle assessment of disposable and reusable laryngeal mask airways. *Anesthesia and Analgesia* 2012:114(5):1067–1072. https://doi.org/10.1213/ANE.0b013e31824f6959

[17] Vozzola E., Overcash M., Griffing E. An Environmental Analysis of Reusable and Disposable Surgical Gowns. *AORN Journal* 2020:111(3):315–325. https://doi.org/10.1002/aorn.12885

[18] MacNeill A. J., Lillywhite R., Brown C. J. The impact of surgery on global climate: a carbon footprinting study of operating theatres in three health systems. *The Lancet Planet Health* 2017:1(9):e360–367. https://doi.org/10.1016/S2542-5196(17)30162-6

[19] Campion N., Thiel C. L., DeBlois J., Woods N. C., Landis A. E., Bilec M. M. Life cycle assessment perspectives on delivering an infant in the US. *Science of the Total Environment* 2012:425:191–198. https://doi.org/10.1016/j.scitotenv.2012.03.006

[20] Ditac G. *et al*. Carbon footprint of atrial fibrillation catheter ablation. *EP Europace* 2023:25(2):331–340. https://doi.org/10.1093/europace/euac160

[21] Ferrero A., Thouvenin R., Hoogewoud F., Marcireau I., Offret O., Louison P., et al. The carbon footprint of cataract surgery in a French University Hospital. *Journal Français d'Ophtalmologie* 2021:45(1):57–64. https://doi.org/10.1016/j.jfo.2021.08.004

[22] Grinberg D. *et al*. Eco-audit of conventional heart surgery procedures. *European Journal of Cardio-Thoracic Surgery* 2021:60(6):1325–1331. https://doi.org/10.1093/ejcts/ezab320

[23] Latta M., Shaw C., Gale J. The carbon footprint of cataract surgery in Wellington. *The New Zealand medical Journal* 2021:134:1541.

[24] Namburar S., Pillai M., Varghese G., Thiel C., Robin A. L. Waste generated during glaucoma surgery: A comparison of two global facilities. *American Journal of Ophthalmology Case Reports* 2018:12:87–90. https://doi.org/10.1016/j.ajoc.2018.10.002

[25] Power B., Brady R., Connell P. Analyzing the carbon footprint of an intravitreal injection. *Journal of Ophthalmic and Vision Research* 2021:16(3):367–376. https://doi.org/10.18502/jovr.v16i3.9433

[26] Power N. E., Silberstein J. L., Ghoneim T. P., Guillonneau B., Touijer K. A. Environmental impact of minimally invasive surgery in the United States: An estimate of the carbon dioxide footprint. *Journal of Endourology* 2012:26(12):1639–1644. https://doi.org/10.1089/end.2012.0298

[27] Prakash R., Abid H., Wasim A., Sharma A., Agrawal Y. The Environmental Impact and Sustainability of Total Hip and Knee Arthroplasty. *Arthroplasty Today* 2023:24. https://doi.org/10.1016/j.artd.2023.101254

[28] Rizan C., Lillywhite R., Reed M., Bhutta M. F. The carbon footprint of products used in five common surgical operations: identifying contributing products and processes. *Journal of the Royal Society of Medicine* 2023:116(6):199–213. https://doi.org/10.1177/01410768231166135

[29] Rougereau G., Chatelain L., Zadegan F., Conso C. Estimation of the carbon footprint of arthroscopic rotator cuff repairs in France. *Orthopaedics and Traumatology: Surgery and Research* 2024:110(1):103755. https://doi.org/10.1016/j.otsr.2023.103755

[30] Ryan M. T., Malmrose J., Riley C. A., Tolisano A. M. Operating Room Waste Generated Across Otolaryngology Cases. *Military Medicine* 2023:188(7–8):E1697–E1700. https://doi.org/10.1093/milmed/usab548

[31] Stall N. M., Kagoma Y. K., Bondy J. N., Naudie D. Surgical waste audit of 5 total knee arthroplasties. *Canadian Journal of Surgery* 2013:56(2):97–102. https://doi.org/10.1503/cjs.015711

[32] Thiel C. L., Eckelman M., Guido R., Huddleston M., Landis A. E., Sherman J., et al. Environmental impacts of surgical procedures: Life cycle assessment of hysterectomy in the United States. *Environmental Science and Technology* 2015:49(3):1779–1786. https://doi.org/10.1021/es504719g

[33] Thiel C. L. *et al.* Cataract surgery and environmental sustainability: Waste and lifecycle assessment of phacoemulsification at a private healthcare facility. *Journal of Cataract and Refractive Surgery* 2017:43(11):1391–1398. https://doi.org/10.1016/j.jcrs.2017.08.017
[34] Woods D. L., McAndrew T., Nevadunsky N., Hou J. Y., Goldberg G., Kuo D. Y.-S., Isani S. Carbon footprint of robotically-assisted laparoscopy, laparoscopy and laparotomy: A comparison. *International Journal of Medical Robotics and Computer Assisted Surgery*. 2015:11(4):406–412. https://doi.org/10.1002/rcs.1640
[35] Zhang D., Dyer G. S. M., Blazar P., Earp B. E. The Environmental Impact of Open Versus Endoscopic Carpal Tunnel Release. *Journal of Hand Surgery* 2023:48(1):46–52. https://doi.org/10.1016/j.jhsa.2021.12.003
[36] Wernet G., Bauer C., Steubing B., Reinhard J., Moreno-Ruiz E., Weidema B. The ecoinvent database version 3 (part I): overview and methodology. *International Journal of Life Cycle Assessment* 2016:21(9):1218–1230. https://doi.org/10.1007/s11367-016-1087-8
[37] UK Government GHG Conversion Factors for Company Reporting. *Department for Environment, Food and Rural Affairs/ Department for Business, Energy & Industrial Strategy, London*, 2023 [Online]. [Accessed 16.08.2024]. Available: https://www.gov.uk/government/collections/government-conversion-factors-for-company-reporting
[38] Heijungs R. Ecodesign – Carbon Footprint – Life Cycle Assessment - Life Cycle Sustainability Analysis. A Flexible Framework for a Continuum of Tools. *Environmental and Climate Technologies* 2010:4(1):42–46. https://doi.org/10.2478/v10145-010-0016-5
[39] SimaPro: LCA Software 2023, *PRé Sustainability* [Online]. [Accessed 16.08.2024]. Available: https://simapro.com/
[40] Roletto A., Savio A., Marchi B., Zanoni S. Towards a Greener Radiology: A Comprehensive Life Cycle Assessment Framework for Diagnostic Imaging. *Environmental and Climate Technologies* 2024:28(1):303–311. https://doi.org/10.2478/rtuect-2024-0024