Environmentally sustainable health care: the opportunities and challenges of life cycle assessments

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The health-care sector is a substantial contributor to climate change. To address this global issue, more than 120 countries committed to creating environmentally sustainable health systems at the COP28 UN Climate Change Conference held in November, 2023. Sustainability is thus becoming increasingly important for clinical practice. Life cycle assessments quantify the environmental sustainability of systems, products, and processes such as medical interventions. In this Personal View, we explain the fundamental concepts and principles of the methodology in the context of health care, intended for readers new to the field. The opportunities and challenges of applying this methodology to the delivery of health care are also discussed, as sustainability will become an important consideration in clinical decision making.

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Introduction

The health-care sector is estimated to be responsible for 4·6% of global greenhouse gas emissions, making the sector a substantial contributor to climate change.[1] In November, 2023, more than 120 countries pledged to develop environmentally sustainable health systems at the COP28 UN Climate Change Conference.[2] Three main principles for developing sustainable health systems have been presented in the current literature.[3] First, the demand for health-care services should be reduced through disease prevention. Second, health-care provision should be appropriate, avoiding unnecessary investigations and treatments. Third, if health-care services are necessary, efforts should be made to minimise the greenhouse gas emissions associated with them, including reducing the environmental impact of health-care infrastructure. This Personal View focuses on the third principle of improving the environmental sustainability of health services.

National health systems are estimated to contribute between 1·5% and 9·8% of national greenhouse gas emissions.[4] The health-care supply chain, which includes clinical products and medicines used for health services, is estimated to account for 50% to 75% of the carbon emissions produced by health systems.[5] Health professionals are, therefore, requesting guidance on making the health services they provide more sustainable.[6]

Implementing sustainability improvements in health care on the basis of findings from environmental sustainability assessments is challenging without understanding how the figures are generated and without gaining insights into the opportunities and challenges of quantifying sustainability. Health professionals seeking to integrate environmental sustainability into clinical research, guidelines, or procurement should understand the fundamental concepts of the life cycle assessment (LCA) methodology, which is an important approach for assessing environmental sustainability.

Global standards define the LCA methodology,[7,8] which can be applied to systems and products to quantify their environmental impact numerically. The method is characterised by its life cycle perspective in which all parts of a system's or product's life cycle are assessed, from the extraction of raw materials to production, use, and end-of-life disposal. The life cycle perspective reduces the risk of transferring an environmental issue from one stage of the life cycle to another. The method can be used to quantify a broad range of environmental issues, such as global warming, human toxicity, and water consumption. Addressing multiple environmental impacts additionally lessens the possibility of improving one environmental issue while inadvertently worsening another, described as problem shifting.[9]

In this Personal View, we aim to introduce the fundamental concepts and principles of the LCA methodology in the context of health care for health professionals and health-care administrators who are new to the field. We discuss some of the opportunities and challenges that can arise when applying this methodology to the delivery of health-care services. Key concepts and definitions discussed in this Personal View are detailed in the panel. According to the framework from the global LCA standards, an LCA should follow four phases (figure 1), as described in the following sections.[7,8]

Phase 1: goal and scope definition

Establishing the goal in a clinical LCA study

Defining the goal and scope is the first phase of the LCA framework. For LCA studies in health care, the goal often includes an environmental hotspot analysis to identify targets for improvements in terms of sustainability.[10] Examples of global warming hotspots identified in LCA studies of national health systems include the procurement of medical goods and pharmaceuticals.[11–13] A well defined goal is the foundation on which the scope of an LCA is defined, including the intended functionality and the boundaries of the studied product or system.

The functional unit

The functional unit provides a quantitative definition of the function of the investigated product or system.[7,8] In the context of an LCA study assessing the environmental

Panel: Key concepts and definitions

This list does not include all terminology relevant to life cycle assessment (LCA) and only includes the key terms and concepts covered in this Personal View.

Bottom-up LCA
A widely used description for process-based LCA. For more details, please refer to the section on process-based LCA.

Carbon dioxide equivalents (CO_{2e})
The total climate change contribution associated with the emission of various types of greenhouse gases, expressed as an equivalent emission of the greenhouse gas CO_2.

Carbon footprint
An environmental impact assessment reporting the amount of greenhouse gases released into the environment throughout the life cycle of the studied activity, expressed in CO_{2e}; please refer to the section on CO_{2e}.

Cutoff level
A percentage value of the overall environmental impact, such as less than 1%, which is considered negligible. This cutoff level is defined in the goal and scope phase of an LCA. The cutoff level is used to identify when the contribution of a process or product is so small or minor that further investment in data quality optimisation is unnecessary. Additionally, the cutoff value can be used to identify activities that can be excluded from the product system, as their influence on the overall results is considered negligible.

Endpoints
A collective term for the damage caused by the environmental impacts (midpoint), which can be quantified in terms of damage to human health, the environment, and the economy.

Environmentally extended multiregional input–output LCA
A term for an LCA using an input–output database, such as EXIOBASE, to model the life cycle inventory (LCI) on the basis of the economic flows between the involved societal sectors and convert consumption in an economic sector into environmental impacts.

Functional unit
A quantitative definition of the service or function delivered by a product, process, or system.

Greenhouse gas
A collective term for gases with potential to cause global warming, including methane, nitrous oxide, and carbon dioxide.

LCA
A quantitative environmental impact assessment method that can be applied to products and systems to assess their environmental impact throughout their entire life cycle (from raw material extraction to waste disposal). This method allows for the examination of several environmental impacts and is defined by global standards (ISO 14040:2006 and 14044:2006).

Life cycle impact assessment
The conversion of the large numbers of emissions released and the resources used from the activities covered in the product system into environmental impact scores (midpoints); please refer to the section on midpoints.

LCI analysis
The conversion of inventory data measured in physical flows into emissions released and resources used from the activities covered in the product system.

LCI database
Database that contains information regarding the emissions released and the resources used for different activities (materials, products, and processes), such as ecoinvent.

Midpoints
Environmental impact scores derived from LCI results. The midpoint scores represent the environmental impacts from the activities covered in the product system.

Process-based LCA
A form of LCA in which physical flows, such as weight, volume, and energy usage, are measured in the LCI analysis. An inventory database such as ecoinvent can be used; please refer to the section on LCI databases.

Product system
The system of processes needed to obtain the functionality that is described in the functional unit of an LCA. The product system is typically divided into life cycle stages of the activities that are included within the system boundaries and often illustrated as a simplified flow chart.

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Sensitivity analysis
Identifying the key figures and assumptions of the product system modelling and testing the robustness of LCA results by examining how different scenarios for the data assumptions might affect the overall results.

System boundaries
The processes and their grouping into life cycle stages examined in the LCA, which can include the entire life cycle from raw material extraction to waste disposal (cradle to grave) or parts of the life cycle, such as raw material to product manufacturing (cradle to gate).

Top-down LCA
A widely used description for environmentally extended multiregional input–output LCA. For more details, please refer to the section on environmentally extended multiregional input–output LCA.

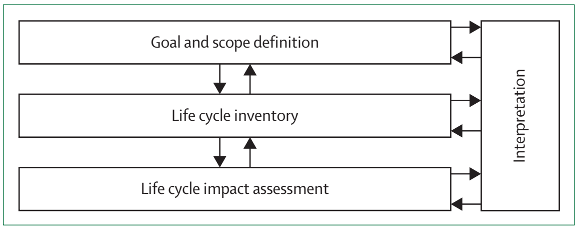

Figure 1: **The life cycle assessment framework (adopted from ISO 14040:2006)[8]**

impact of a medical treatment, the functional unit could be framed as: one patient undergoing a specific medical intervention with a specific treatment outcome for a specific diagnosis at a specific study site within a specified timeframe. Specifying the study site implies that the findings pertain to the site, recognising that the medical treatment could vary between sites. Examples of functional units from published LCA studies include: the treatment of one patient with septic shock in the intensive care unit, the birth of one baby, and one hysterectomy.[14–16]

Basing comparative LCA studies on a well defined functional unit is important to ensure that the compared alternatives are functionally equivalent and, thereby, that the environmental comparison is meaningful and relevant.[9] The functional unit has important implications for the system boundaries and product system, as described in the following section.

The system boundaries and product system

The system boundaries describe and delimit the life cycle stages covered in a study. An LCA will be classified as a gate-to-gate study when the study covers the raw material extraction and manufacturing stage without considering the use and end-of-life stages. A study that covers the entire life cycle is called a cradle-to-grave LCA.

The product system, in simple terms, is a network tree that contains all the processes needed to obtain the functional unit. The processes are normally grouped within life cycle stages of the product or system of the LCA study. For instance, in the case of a cradle-to-grave LCA of a peripheral intravenous catheter (PIVC), the product system includes all stages from sourcing the raw materials to managing the product as waste when discarded after use. The product system also includes the life cycle stages of the medical device factory, with its machinery used for producing the PIVC. Such inclusion substantially increases the complexity of the product system. The international standard operates with cutoff criteria in the identification of the system boundaries. Processes that contribute less than this criterion to the overall environmental impacts of the product system could be omitted from the analysis, which could help to reduce the complexity of the product system.

To summarise, the first step of the LCA framework involves establishing the goal and scope, including the functional unit, system boundaries, and product system. The iterative approach of the LCA methodology enables modelling the complexity of the product system.

Phase 2: life cycle inventory (LCI)

Top-down and bottom-up inventory data

The second phase in the LCA framework is the LCI analysis, which involves collecting data regarding all the stages and processes of a product's or system's life cycle that fall within the study's defined boundaries. Two primary approaches exist for modelling inventory data: top-down and bottom-up.

In the top-down approach, known as environmentally extended multiregional input–output LCA, the inventory data are based on national economic trade and consumption statistics linked to associated environmental impacts.[17] In practical terms, this approach involves reviewing the financial records of the medical facility and assigning expenses to top-down categories such as human health services, pharmaceuticals and chemicals, and medical instruments.[13]

In contrast, the bottom-up approach, known as process-based LCA, relies on a detailed understanding of the concrete product system and its measurable physical flows. In this approach, the volume, mass, area, or energy use of the products and processes within the scope of the study are quantified. For example, applying a bottom-up approach to a PIVC involves measuring the weight of all components, specifying material types (polypropylene, polythene, steel, or aluminium), and drawing data from LCA databases to identify the resources used and emissions released during their production. If the top-down approach were applied instead, the amount of money spent on the PIVC would be assigned to an appropriate top-down category, such as medical instruments, and the environmental impact would be derived from the average data for this category.

In this Personal View, we have used a PIVC as an example to illustrate the difference between the two primary approaches to modelling inventory data to simplify the explanation of these complex methods. However, assessing the environmental impact of health services typically extends beyond assessing individual products. Health services include areas such as clinical procedures, interventions, and diagnostics tests, which often require previous medical consultations and recovery and rehabilitation periods, which could also be considered.

When analysing the carbon footprint of large-scale systems such as the health-care sector at national and global levels, a top-down approach is typically used.[18] Applying the bottom-up approach (which relies on measurable physical units and a detailed study of the product system) to health systems would be complex, given the vast number of products and processes involved, and in this case, the sectoral averaging implied by the top-down approach is less of a problem.[10] Although a top-down approach is useful for assessing carbon footprints, modest coverage of emissions other than greenhouse gases makes the approach inadequate to evaluate most of the other environmental impacts.[9]

A bottom-up approach is the preferred choice for small-scale systems such as clinical procedures, interventions, products, and diagnostic tests owing to the enhanced representativeness of the results.[10] Sometimes, a bottom-up LCA is complemented by a top-down LCA for some parts of the product system in what is termed a hybrid LCA.

From inventory data to inventory results

Once the inventory data are collected on the basis of the product system, the information is converted into numerical LCI results. These numerical LCI results represent the natural resources used (inputs) and the pollutants released into land, air, and water (outputs) for the functional unit of the study. These LCI results can include emission of substances such as carbon dioxide, mercury, and nitrous oxide. For a bottom-up LCA, the LCI results typically comprise hundreds to thousands of different substance emissions, even for simple products such as the previous example of a PIVC.

To perform the inventory analysis, LCA software such as SimaPro, openLCA, and Brightway are used, which link the inventory data to international LCI databases. Databases that apply the top-down approach, such as EXIOBASE, contain top-down categories for more than 150 societal sectors and products.[19] Databases that use the bottom-up approach, such as ecoinvent and the country-specific US Life Cycle Inventory Database, could contain bottom-up datasets for more than 18 000 processes covering the environmental inputs and outputs of materials, products, and activities.[20] The LCA practitioner uses the LCA software to assemble the bottom-up datasets and the top-down categories as puzzle pieces to form the product system.

For more on **US Life Cycle Inventory Database**, see https://www.nrel.gov/analysis/lci

The top-down and bottom-up inventory databases are extensive but also have limitations. First, some specific datasets required to model the complete life cycle of health services, products, and medicines can be missing from the databases. As a result, similar processes or materials might need to be used as proxies. Additionally, these databases can become outdated. For instance, the top-down database EXIOBASE version 3.9.5, which was released in February, 2025, is based on data from 2020, with some estimates extending to 2022.[21] Since EXIOBASE is frequently used to assess the carbon footprint of health systems, the results might not reflect the current situation since energy systems are fairly rapidly decarbonised in many countries. The same issue can apply to bottom-up datasets. For example, datasets concerning electricity can rely on the composition of a country's electricity grid mix from 4 to 5 years ago. If the grid mix has changed since, possibly incorporating more or less renewable energy, this difference could affect the results of the LCA. Therefore, the global LCA standards require such limitations to be taken into account.[7,8]

To summarise, the LCA software enables the easy conversion of complex inventory data into numerical LCI results on the basis of the top-down or bottom-up approach, which forms the second phase of the LCA framework, known as the LCI. However, interpreting the environmental impact on the basis of the LCI alone can be challenging, as LCI contains a large number of numerical values for the resources used and the pollutants released. This stage is at which the third phase of the LCA framework comes in, interpreting the LCI information into indicators of environmental impact.

Phase 3: life cycle impact assessment

From inventory results to environmental impact

The third phase of the LCA framework is the life cycle impact assessment (LCIA). In this phase, the results obtained from the LCI are converted into a specific number of environmental impact scores, known as midpoints. The midpoints could include global warming, stratospheric ozone depletion, ionising radiation, ozone and fine particulate matter formation, terrestrial acidification and ecotoxicity, freshwater and marine eutrophication and ecotoxicity, human toxicity, land use, mineral and fossil resource scarcity, and water consumption.[22] To detect potential problem shifting from one midpoint to another, the LCIA should include all relevant impacts from the studied product system. The LCIA simplifies and qualifies the interpretation and identification of environmental hotspots.

The LCI results are converted into midpoint scores using the LCA software, which supports the use of various LCIA models, some of which include up to 18 midpoints.[22] The first step in the conversion process is assigning conversion factors to the LCI results, which allows the results to be

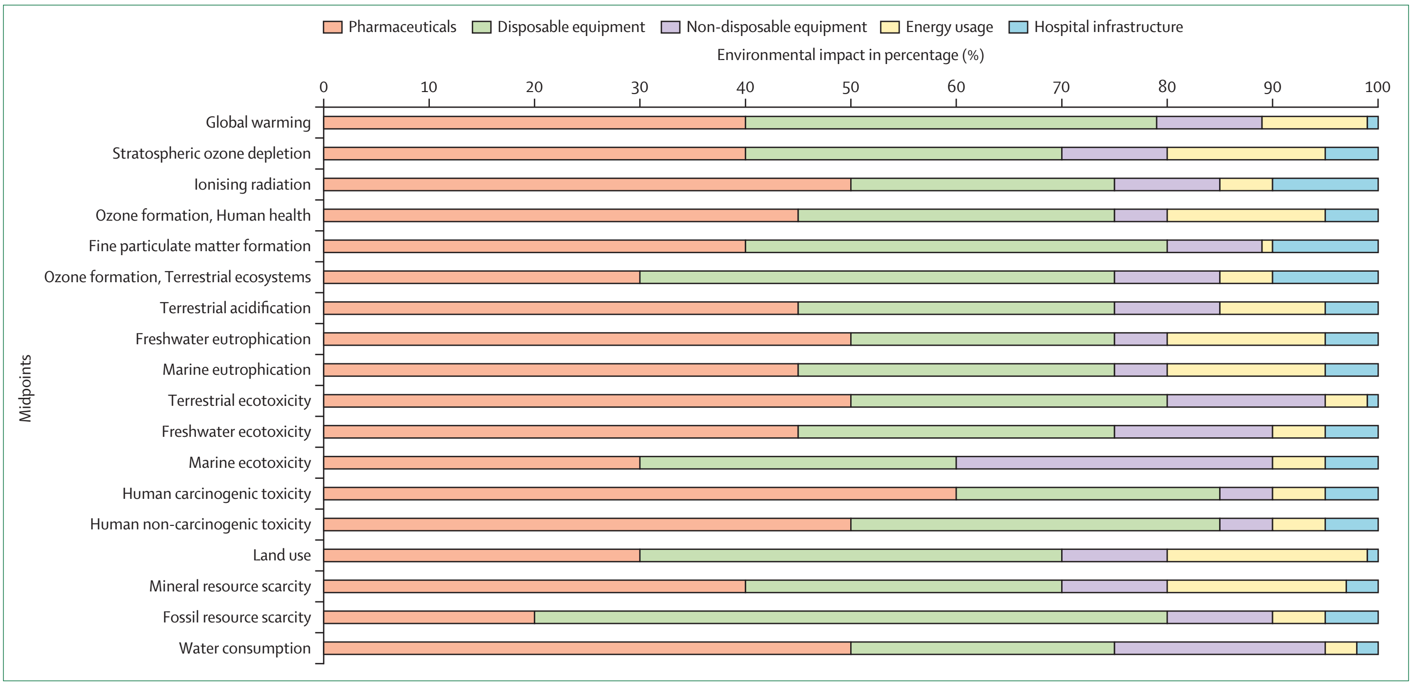

Figure 2: **A fictional example of the midpoint scores for a medical intervention**
This figure presents a fictional example of the environmental impact scores (midpoints) for a medical intervention. The figure has been created to show how potential environmental hotspots can be identified and presented. Of note, this figure is solely for illustrative purposes in this Personal View and does not represent any actual medical intervention (although the pattern that can be seen with dominance from pharmaceuticals and disposable equipment for most of the midpoints has been observed in several other studies).[10] The 18 midpoints are based on the life cycle impact assessment model ReCiPe.[22] Each midpoint is normalised to a scale of 100%, which means that comparing the magnitudes across midpoints is not possible. Such a figure should be accompanied by a table that provides the absolute values of the midpoints, along with their corresponding units.

expressed in standard units of measurement, such as carbon dioxide equivalents (CO_{2e}) used for greenhouse gases. All greenhouse gases, including methane, carbon dioxide, and nitrous oxide, contribute to the midpoint for global warming, but they have different global warming potentials. The global warming potential of nitrous oxide, for instance, which is used for sedation and pain relief, is 289 times greater than that of carbon dioxide.[23] Therefore, the conversion factor for nitrous oxide is 289 kg CO_{2e}/kg N_2O. The conversion is performed for all the LCI results until they have been assigned to a relevant midpoint with the same standard unit of measure, translating the LCI information into a profile of environmental midpoint scores.

Environmental hotspot analysis

To identify potential environmental hotspots in the life cycle, the midpoints can be presented in a stacked bar diagram, distinguishing the impacts from the different processes or stages of the life cycle. The majority of existing LCA studies of medical interventions only show results for the midpoint of global warming.[10] A fictional medical intervention is used in figure 2 to show how the environmental hotspot analysis covering additional midpoints could be presented. For transparency, this diagram should be accompanied by a table with the absolute values of the midpoints to comply with the requirements of the LCA standards.[7,8]

To review the environmental damages and simplify interpretation further, the midpoints can be converted into three endpoints, representing the damage to human health, ecosystems, and natural resources. Again, a conversion factor is used for each midpoint to transform the midpoint scores into endpoint scores. The endpoint scores can also be presented in stacked bar diagrams, as illustrated in figure 3 for the same fictional medical intervention.

In summary, the LCIA not only compiles the LCI results but also identifies environmental hotspots. The environmental damages can be reviewed by converting midpoints to endpoints, which weigh the midpoint scores with their relative severity. The endpoint scores can ease interpretation further, but they are also accompanied by additional uncertainty owing to the additional modelling needed.

The LCA framework follows an iterative approach, in which these three phases are repeated, as explained in the following section.

Phase 4: interpretation of the results

In the interpretation phase, the results of the LCIA are interpreted in relation to the goal of the LCA to answer the question initially posed. To manage the complexity of the product system and improve the reliability and validity of

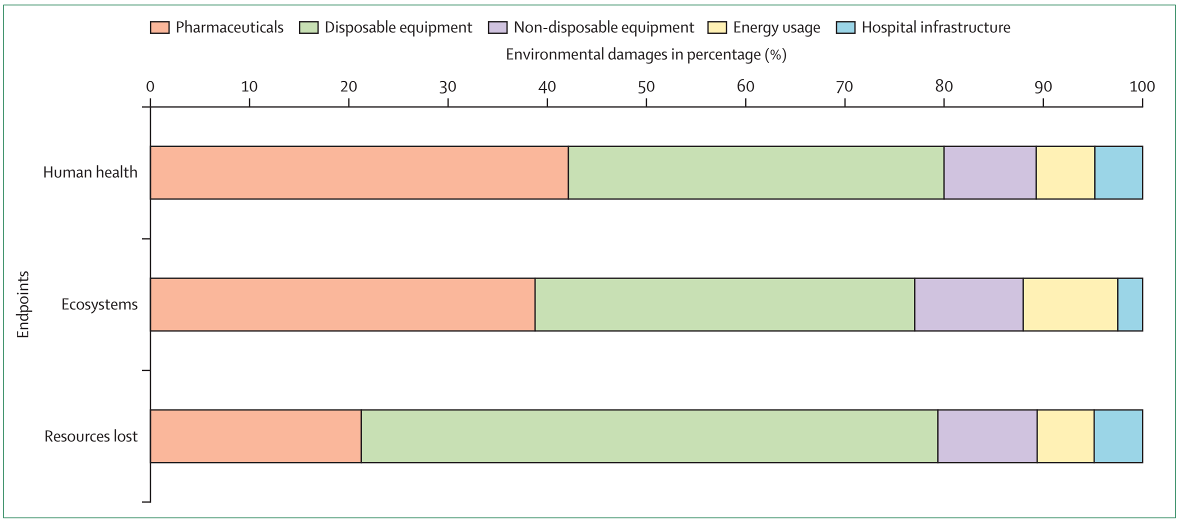

Figure 3: **A fictional example of the endpoint scores for a medical intervention**
This figure presents a fictional example of the environmental damage scores (endpoints) for a medical intervention. Similar to figure 2, this figure also has been created to illustrate the identification and presentation of potential environmental hotspots. Of note, this figure only serves as an example in this Personal View and does not reflect any real medical intervention (although the pattern that can be seen with dominance from pharmaceuticals and disposable equipment for most of the midpoints has been observed in several other studies).[10] The three endpoints are based on the life cycle impact assessment model ReCiPe.[22] Each endpoint is normalised to a scale of 100%, which means that comparing the magnitudes across endpoints is not possible. Such a figure should be accompanied by a table that provides the absolute values of the endpoints, along with their corresponding units.

the results in a time-effective way, sensitivity analysis is typically applied in an iterative approach.

In the first iteration, all processes and products in the product system should be identified and modelled, which would usually be done using the LCA software. The initial iteration typically requires using datasets resembling the products and processes in the product system as proxies owing to incomplete inventory databases. Additionally, data could be missing in some instances, such as when identifying the material composition of a product or measuring the electricity consumed for various processes is difficult. Consequently, the initial iteration often relies on assumptions derived from literature or estimates provided by experts to fill in missing data. The iterative approach helps to identify areas at which data quality might need to be improved, as only a few processes or activities in the life cycle are commonly responsible for the majority of the environmental impact. In subsequent iterations, the focus is directed towards improving the data quality for these major contributors,[9] as even minor improvements in these areas can have a substantial influence on the overall results. Time can be wasted when spent on improving the data quality of minor contributors, as even major data improvements in these areas have little influence on the overall results.

Improving the data quality of substantial contributors might not always be feasible. However, conducting a sensitivity analysis can help to assess the robustness of the assumptions made by examining various scenarios. For instance, a medical device manufacturer might not disclose the exact weight ratio and material composition of their products. By testing various scenarios that explore how changes in the assumed weight ratio and material composition might influence the results of the overall environmental impact, we gain a better understanding of how the assumptions made influence the LCA results.

To summarise, the interpretation phase typically involves repeating the methodological phases of the LCA framework multiple times with focus on the main drivers of the overall environmental impacts from the product system. This iteration increases data precision for the dominating processes until the results are of sufficient precision to answer the question posed in the LCA. The iterative approach helps to manage the complexities of the LCA framework and improves the results in an effective manner.

Opportunities and challenges to the application of LCA to health care

Examining sustainability quantitatively and applying a life cycle perspective makes LCA a valuable tool for medical decision makers. LCA studies that comply with global LCA standards can support clinical decision making and provide an opportunity to make informed decisions on what to target to improve the environmental impact. However, applying the LCA methodology to health care can be challenging.

A review of health-care LCAs reported that the methodology differed among the studies.[10] In addition, the carbon footprint of different clinical procedures, interventions, and diagnostic tests had been estimated in 29 studies, of which only 11 included at least one midpoint other than global warming. A carbon footprint analysis will often be insufficient to draw conclusions on the overall environmental impact, and more midpoints need to be included to avoid problem shifting.[9]

The 29 studies on clinical activities varied in their scope,[10] sometimes including activities before and after the investigated medical intervention and the transport of staff and patients. The inclusion of specific activities in LCAs depends on the definition of the goal and scope. If the focus is solely on the environmental impact specific to the medical intervention itself, related activities or transportation could be excluded. However, using such a narrow goal and scope might overlook other substantial environmental impacts associated with the intervention, some of which could fall outside the control of health professionals and require attention from health-care leadership or policy changes. Defining the goal and scope of an LCA can be challenging and might need revisions throughout the iterative LCA process.

Top-down, bottom-up, and hybrid approaches have all been applied in LCA studies in health care.[10] A top-down approach has predominately been applied to health systems at national and international levels.[10] This approach is particularly useful for gauging the carbon footprint of large systems but less so for other midpoints,[9] which has been the case in some studies.[12,24–26] The top-down approach has also been applied to small-scale system analysis such as medical interventions, including the treatment of acute decompensated heart failure and type 2 diabetes,[27,28] which can be a problem owing to the low resolution of the approach. The top-down approach will thus always show that an expensive pharmaceutical has a greater environmental impact than a less expensive drug because the impact is estimated on the basis of financial spending in the pharmaceutical sector without any further distinction.

The bottom-up and hybrid approaches are predominantly used in LCA studies of clinical procedures, interventions, and diagnostic tests.[10] In hybrid LCAs of medical interventions and procedures for which bottom-up data were considered too difficult to obtain, the top-down approach has been applied, particularly in the case of pharmaceuticals and medical equipment.[14,16,29] The low resolution of the results of these hybrid studies can be problematic. Few studies have examined the environmental impact of health-care infrastructure and facility operations,[10] highlighting the need for additional research in this area.

The objective of this Personal View has been to introduce the fundamental concepts and principles of LCA in relation to health-care delivery, without requiring previous LCA experience, as the interest in applying this methodology to health care is growing.[10] Health professionals planning to gain a deeper understanding of LCA or to perform LCA studies are advised to consult with experienced LCA practitioners or to seek further information in the literature or both.[9] The free online platform HealthcareLCA is also a valuable resource for health professionals exploring published health-care LCA studies.

A more standardised and transparent approach is needed for applying LCA to medical interventions.[10] Such an approach can help to integrate environmental sustainability into clinical decision making. Collaboration between the medical and technical sciences is central in developing this approach. Health professionals are aware of the safety and effectiveness of medical treatments. By taking these considerations into account, sustainability can be promoted while avoiding medical complications, benefiting both the patient and the environment. A guideline for conducting LCAs in health care is currently being developed and is registered with the Enhancing the Quality and Transparency of Health Research (EQUATOR) Network. The guideline covers various disciplines within health-care delivery and could help to standardise the application and reporting of LCAs in health care in the future.

For more on the **ECoHealth guideline,** see https://www.equator-network.org/library/reporting-guidelines-under-development/reporting-guidelines-under-development-for-other-study-designs/#ECO

Conclusions

This Personal View introduces the fundamental concepts of the LCA methodology in the context of health care. LCA is used to quantify environmental sustainability through a life cycle perspective. The standardised LCA framework includes four iterative phases, which can be made operational by the use of different types of LCA software. Studies that adhere to this framework can guide targeted environmental improvements and support clinical decision making. A more standardised approach is needed for applying the methodology to medical interventions, which requires collaboration between the medical and technical sciences.

Contributors

All authors were involved in the study conceptualisation. ARR wrote the original draft under the supervision of SB and MZH.

Declaration of interests

We declare no competing interests.

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For more on **HealthcareLCA**, see www.healthcarelca.com

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