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Towards a Greener Radiology: A Comprehensive Life Cycle Assessment Framework for Diagnostic Imaging

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***Abstract* – The increasing focus on environmental sustainability is becoming essential in the radiology sector, which is accredited for about 10 % of the healthcare industry's carbon footprint. A multitude of research initiatives investigated the environmental impacts of diagnostic imaging. Life Cycle Assessment (LCA) stands as a prominent method for structural assessment of environmental impacts, offering a tool for examining the environmental consequences of specific processes. The aim of this study includes analysing existing LCA approaches in the literature to identify their limitations and to suggest a comprehensive LCA framework for diagnostic imaging. Of the original articles on environmental sustainability in radiology published since 2014, five have described an LCA approach. About the boundaries of their systems, all studies considered the electricity consumption of imaging equipment. Usage of consumables was included in 80 % (4/5) of the studies, as well as energy consumption of auxiliary equipment and Heating, Ventilation and Air Conditioning (HVAC) systems. Only 40 % (2/5) of articles considered waste generation, cleaning and disposal of products used during imaging activities. The articles also varied in their LCA approach, with different life cycle assessment methods. Insights from this analysis led to the identification of differences in LCA methodological approaches in imaging found in the literature. In addition, a new LCA framework designed to overcome the limitations observed in existing research was proposed, offering a more comprehensive analysis. The objective may be the development of more targeted strategies to reduce Greenhouse Gas (GHG) emissions associated with diagnostic procedures.**

***Keywords* – Electricity consumption; Environmental sustainability; Greenhouse Gas (GHG) emissions; Healthcare sector; Radiology; Research methodology.**

1. INTRODUCTION

The increasing focus on environmental sustainability within the diagnostic imaging sector reflects a broader understanding of healthcare's significant environmental footprint [1]. This sector, which includes technologies such as X-ray, Magnetic Resonance Imaging (MRI), Computer Tomography (CT) and ultrasound scanners, is recognized for contributing about 10 % to the healthcare industry's overall carbon footprint [2], [3]. This awareness has

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stimulated numerous research initiatives aimed at comprehensively understanding and mitigating the environmental impacts associated with diagnostic imaging [4].

These impacts are multifaceted. One of the primary concerns is the substantial electricity consumption required to power the equipment used in diagnostic imaging. The operation of MRI, CT scanners, and other imaging technologies demands significant energy, contributing indirectly to the sector's carbon emissions [5]–[10]. This energy consumption not only exacerbates the healthcare industry's carbon footprint but also increases operational costs, pushing for more energy-efficient innovations in medical technology [11]. Furthermore, the environmental impact associated with the electricity used differs depending on the country in which the equipment is located, as it is necessary to consider the emission factors for electricity consumption which varies from country to country [12].

Another critical environmental issue is the carbon emissions resulting from the use of diagnostic imaging. These emissions are not only associated with the energy used during the operation of the equipment but also with the lifecycle of the imaging technologies, including their manufacture, transportation, maintenance, repair operations and disposal [13]. The healthcare sector's reliance on fossil fuels for energy contributes significantly to its carbon emissions, highlighting the need for a shift towards renewable energy sources and more sustainable practices within the sector.

Waste generation is also a significant concern. Diagnostic imaging procedures can produce a variety of wastes, including single-use plastics, contrast media and the disposal of obsolete or outdated equipment [13], [14]. The management and disposal of this waste present challenges in terms of both environmental sustainability and public health as underlined in different studies [15]–[19].

In response to these challenges, there is a growing push in the diagnostic imaging industry towards studying the environmental impact of radiological activities and proposing greener practices [11]. This includes efforts to reduce energy consumption during equipment idle-period [6], the choice of diagnostic examinations with less environmental impact for the same clinical utility [20], and initiatives to reduce waste and promote recycling and resource recovery [21]. In addition, there is a growing interest in assessing the full environmental impact of diagnostic imaging procedures through life cycle assessment (LCA) studies, already used in other areas of the healthcare system [22]. LCA is a method used to assess the environmental consequences associated with all the stages of a product's life from raw material extraction through materials processing, manufacture, distribution, use, repair and maintenance, and disposal or recycling [23]. These methods help identify key areas where improvements can be made, promoting a more sustainable approach to healthcare.

When evaluating the environmental impact of a diagnostic imaging activity through LCA, it is essential to consider various aspects that span the entire diagnostic pathway of a patient. These aspects also align with the three scopes outlined in the GHG Emissions Protocol Corporate Standard (Fig. 1) [24].

The main purpose of this study was to establish a novel framework for quantifying the environmental impact of diagnostic imaging processes through an LCA study. This involved a thorough review of existing literature to identify previously employed methodologies, comparing these approaches to highlight their merits and limitations. Through an analysis of these studies, the research aimed to identify the strengths and gaps in the current literature.

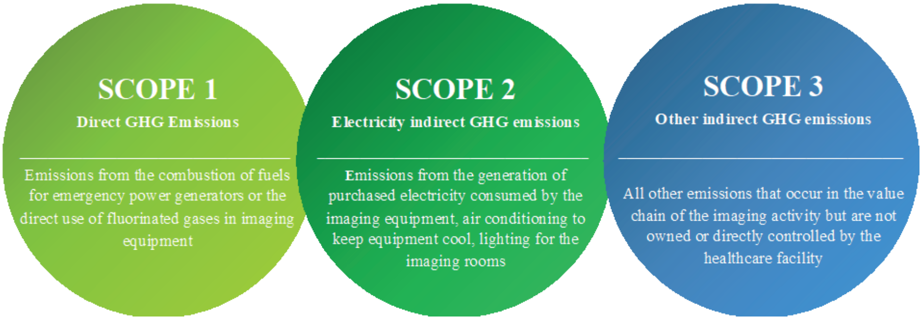

Fig. 1. Scope 1, 2 and 3 emissions in diagnostic imaging department according to the GHG protocol.

2. Methods and Methodology

The study was structured in two distinct segments. Initially, a literature review was conducted to analyse existing publications on environmental sustainability in the field of radiology. The aim was to identify articles that addressed LCA specifically. The search was limited to original studies written in English, published in peer-reviewed journals, with an available abstract.

In the subsequent phase of the study, the focus shifted towards developing a detailed framework designed for the application of LCA within medical imaging practices. This segment sought to bridge the gap between theoretical sustainability concepts and practical application in radiology, emphasising how LCA can be effectively integrated to assess and minimise the environmental footprint of imaging technologies and procedures. It proposed a systematic approach to evaluate the entire lifecycle of imaging equipment – from manufacture and daily use to disposal and recycling – thereby providing insights into potential environmental impacts and offering guidelines to implement these practices effectively. No ethics committee approval was needed to perform this study.

2.1. Literature review and data extraction

In February 2024, a literature review was conducted on Medline (PubMed), Embase (Elsevier) and Web of Science to find original articles on environmental sustainability in diagnostic imaging. Initially, a preliminary review of the collected articles was conducted, during which reviews, case reports, and studies solely relying on automated computer analysis were omitted. Following this, for all studies that passed this initial phase, the complete texts were acquired for further examination. Lastly, a manual search of the references within the selected articles and reviews was performed to identify any further studies that met the eligibility criteria.

Studies were excluded if: 1) focused on hospitals in general or in a setting different from diagnostic imaging department, 2) reviews, editorials, and viewpoints; 3) Abstracts or conference proceedings.

Studies were included in the final analysis if they were focused on the LCA approach on diagnostic imaging.

For all articles included at the final selection, a data extraction was performed. For each study the extracted data (when present) were: year of publication; country of publication; aim of the study; diagnostic imaging technique considered; functional unit of the analysis; LCA methods; LCA software; LCA characteristics.

2.2. Framework design

Through the results of the literature review, a comprehensive framework for a new LCA methodology adapted to imaging technologies was proposed. This framework was created to address shortcomings identified in previous studies by providing a more holistic assessment. By drawing on examples from various sectors beyond healthcare, this new approach improves the methodological foundations.

The key to improving the LCA framework is the identification of all imaging steps with a substantial environmental impact. This allows the associated carbon emissions to be accurately calculated, ensuring a more accurate and complete environmental assessment.

3. RESULTS

3.1. Literature Review

3.1.1. Study selection

From a search conducted on Medline, Embase, and Web of Science, a total of 17 original research articles focused on environmental sustainability within the field of radiology, published from 2014 onwards, were identified. Among these, only 5 articles, which represent 29.4 % of the total, described a LCA approach in the context of diagnostic imaging.

3.1.2. Characteristics of the included articles

Baseline characteristics of articles are summarised in Table 1.

TABLE 1. BASELINE CHARACTERISTICS OF ARTICLES

Study	Year	Country	Imaging technique	Aim/objective
Leapman [25]	2023	USA	MRI, Ultrasound	Estimate the environmental impact associated with prostate MRI examinations and prostate biopsy
McAlister [26]	2022	Australia	Chest X-ray, Mobile Chest X-ray, CT, MRI, Ultrasound	Estimate the carbon footprint of five different diagnostic imaging modalities
Esmaeili [27]	2018	USA	MRI	Estimate the environmental impact of MRI examinations
Martin [28]	2018	USA	CT, MRI, Ultrasound	Estimate environmental impacts of various abdominal imaging examinations
Esmaeili [29]	2015	USA	CT	Estimate the environmental impact of CT examinations

Four articles originated from the United States and one from Australia. The imaging techniques evaluated across the articles include MRI, which was analysed in all articles, CT and Ultrasound, each discussed in 3/5 articles, and Chest X-ray as well as Mobile Chest X-ray, each mentioned in 1/5 articles. Regarding the aims of the identified studies, three articles were focused on assessing the environmental impact of diagnostic imaging broadly, without specifying the clinical inquiries being addressed [26], [27], [29]. Conversely, two studies concentrated on evaluating the environmental footprint of diagnostic imaging tailored to specific anatomical regions, specifically targeting the abdomen [28] and prostate [25]. The study on prostate imaging also encompassed the environmental considerations of an associated interventional procedure, namely a biopsy.

3.1.3. Characteristics of Life Cycle Assessments

The specific characteristics regarding the Life Cycle Assessment method of the articles are described in Table 2.

In the studies reviewed, 3/5 articles adopt the complete patient examination, defined as the sequence of scans necessary for a diagnostic evaluation, as the functional unit for study, correlating it with a specific carbon footprint [25], [27], [28]. Conversely, 2/5 articles focus on the environmental impact of individual scans, treating each scan as the functional unit for analysis [26], [29].

Among the system boundaries adopted, one study exclusively adopted a Cradle-to-grave approach [28], two studies adopted a Gate-to-gate approach for energy consumed by imaging equipment and a Cradle-to-gate approach for consumable use [27], [29], two studies set Cradle-to-grave system boundaries [25], [26]. Two articles specified the use of life cycle inventory database *Ecoinvent* [25], [26]. Life Cycle impact assessment model also varied: two studies [25], [28] utilised the Tool for the Reduction and Assessment of Chemical and other environmental Impact (TRACI) 2.1, while one study utilised *ReCiPe* 2016 model [25].

TABLE 2. SPECIFIC CHARACTERISTICS OF LCA

Study	**Functional Unit**	**System boundary**	**LC inventory database**	**LC Impact assessment model**
Leapman [25]	Examination	Cradle-to-grave	*Ecoinvent* 3.3	TRACI 2.1 version 1.04
McAlister [26]	Scan	Cradle-to-grave	*Ecoinvent* 3.5	*ReCiPe* 2016
Esmaeili [27]	Examination	Gate-to-gate Cradle-to-gate	n/a	n/a
Martin [28]	Examination	Cradle-to-gate	n/a	TRACI 2.1 version 1.03
Esmaeili [29]	Scan	Gate-to-gate Cradle-to-gate	n/a	n/a

An LCA analysis considers various processes associated with a specific production activity in their system boundaries. The same can apply to healthcare and diagnostic activities as well. In the selected articles, in addition to different types of LCA, various processes that contribute to a diagnostic activity were considered. The processes considered by the selected articles for their respective LCA analyses are described in Table 3.

Seven processes that contribute to the ecological footprint associated with diagnostic imaging procedures are considered in the selected articles:

- Energy consumption of auxiliary equipment, such as contrast media injectors, computers and workstations;
- Electricity consumption of imaging equipment;
- Heating, ventilation and air conditioning (HVAC) systems;
- Manufacture of capital equipment, including imaging devices;
- Staff and patient travel to and from the healthcare facility;
- Usage of consumables, such as paper towel, gloves, contrast agent;
- Waste generation, cleaning, disposal of all products and equipment used during diagnostic activities.

All selected studies [25]–[29] considered the energy consumption of imaging equipment in their LCA analysis, related to the amount of carbon emissions (CO_2-eq). In this analysis, all phases of energy consumption for the radiological equipment were considered, including the production phase, the idle-period (when the device is on but not in use), the standby phase, and the periods when the equipment is switched off.

The energy consumption of auxiliary equipment was considered in 4/5 studies, [25]–[29], counting the energy consumption associated with the contrast medium injectors and computer stations required to perform the diagnostic examination and produce the report, as well as heating, ventilation and air conditioning systems [25], [27]–[29], and usage of consumables [25]–[27], [29], such as paper towel, gloves, contrast agent and syringes. Waste generation, cleaning and disposal were analysed in 2/5 studies [25], [26]. Factors like manufacture of capital equipment and staff and patient travel to and from the healthcare facility, were each covered in only 20 % of the studies.

TABLE 3. PROCESSES INCLUDED IN SYSTEM BOUNDARIES

Study	**Energy consumption of auxiliary equipment**	**Electricity consumption of imaging equipment**	**Heating, ventilation and air conditioning**	**Manufacture of capital equipment**	**Staff and patient travel**	**Usage of consumables**	**Waste generation, cleaning, disposal**
Leapman [25]	Yes	Yes	Yes	–	Yes	Yes	Yes
McAlister [26]	Yes	Yes	–	–	–	Yes	Yes
Esmaeili [27]	Yes	Yes	Yes	–	–	Yes	–
Martin [28]	–	Yes	Yes	Yes	–	–	–
Esmaeili [29]	Yes	Yes	Yes	–	–	Yes	–

3.2. LCA Framework

Through the results of the literature review, the LCA framework, depicted in Fig. 2, was designed to overcome the limitations of the studies currently in the literature by covering all aspects that can be included in the three phases: preclinical, clinical, post-clinical.

- Preclinical Phase: The production and transportation of imaging equipment and consumables, including the manufacture of components and the delivery of contrast agents or radioactive materials used in diagnostic tests.
- Clinical Phase: The patients and staff travel to and from healthcare facilities [30], which includes emissions from transportation. It can also consider the use of disposable items during the imaging process, such as gowns or syringes for contrast administration.
- Post-clinical Phase: The disposal, maintenance and repair operations of imaging equipment, the disposal or recycling of consumables, management of hazardous waste (like used contrast materials or radioactive waste), and data storage and management for the images produced

The next stage in the sustainability assessment framework is the system approach. Only two articles considered a Cradle-to-grave system approach. This reveals that there are currently no studies that have outlined a comprehensive LCA framework in diagnostic imaging. When analysing LCA interface software, Life Cycle inventory database and Life Cycle impact assessment model, not in all articles are specified. For example, only two articles specify which inventory database was used (*Ecoinvent*). There is no common approach in using the LC impact assessment model, where two studies utilised the TRACI 2.1, while one study utilised *ReCiPe* 2016 model. Therefore, it becomes evident that there is a need for a common inclusive LCA framework within diagnostic imaging. Such a framework should integrate the attributes of existing studies in the literature and aim to cover in the system boundary, as comprehensively as possible, all factors contributing to the carbon footprint associated with diagnostic imaging practices.

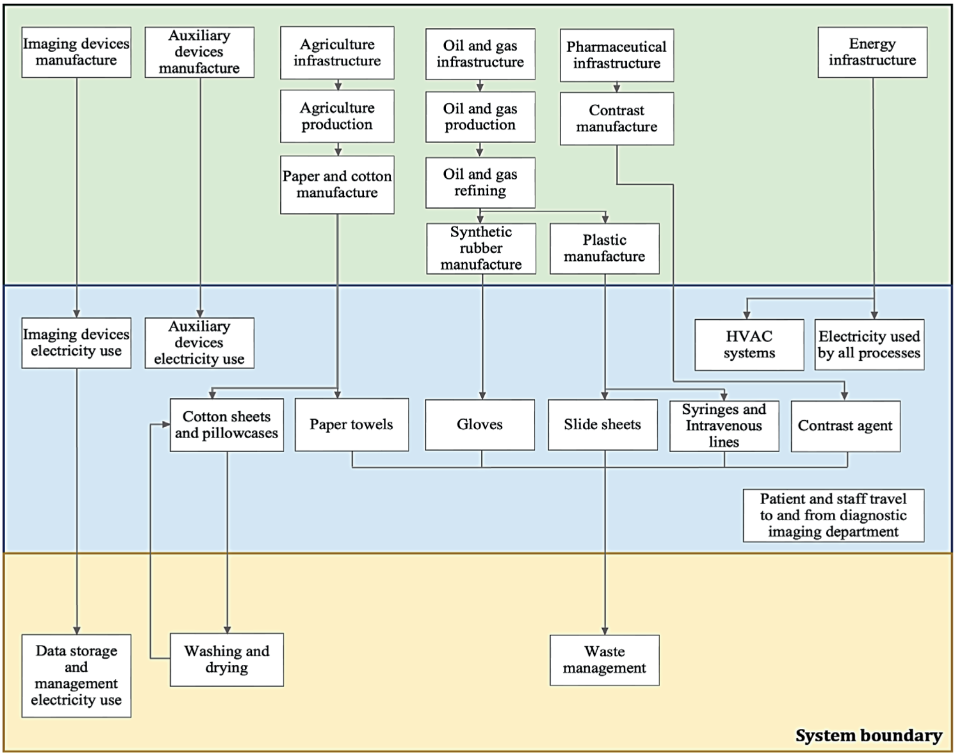

Fig. 2. Comprehensive Life Cycle Assessment Framework for Diagnostic Imaging.

The choice of methodology can be determined according to the geographical location of the study. Finally, in the interpretation phase, the results of the LCA are analysed, particularly regarding inherent uncertainty. To understand the impact of uncertainty on the results, sensitivity analysis can be used to discover the impact that variations in parameter values may have on the results of the study. The use of this model to implement an LCA methodology may make it possible to overcome the limitations of LCA studies implemented in the radiological area and to follow the characteristics of other models described in other scientific areas [31]–[34].

The feasibility of implementing the proposed framework in real healthcare settings depends on various factors such as the existing technological infrastructure, the skills of the staff and the availability of financial resources. The main challenges include data collection, protection of patient privacy, and the need for training and awareness-raising of healthcare personnel.

3.3. Study limitations

Despite the valuable insights provided by the considered studies, this proposal for a new Life Cycle Assessment framework for diagnostic imaging is also based on data collected during the literature review. This literature review has some limitations that should be considered. Firstly, the scope of this review is limited to the studies available within the selected timeframe and databases. Although efforts were made to include a wide range of articles, it is possible that some relevant studies were inadvertently excluded, including those not published in the English language. Secondly, the generalizability of the findings from the included studies may be limited due to variability in study designs, contexts, and geographic locations. The included studies were conducted in various countries, with variations in healthcare systems, infrastructures and energy sources. These contextual factors can influence energy consumption patterns and practices in diagnostic imaging departments, making it difficult to draw universal conclusions. Furthermore, the heterogeneity of the data collected across studies poses a challenge for direct comparisons and synthesis.

4. Conclusion

This literature review offers an in-depth examination of various studies focused on employing LCA methodology to assess the environmental impact of diagnostic imaging procedures routinely conducted by healthcare facilities in different countries. The findings from this research have culminated in the creation of a comprehensive framework for a novel LCA methodology designed for diagnostic imaging in radiology. This new approach aims to address and overcome the limitations identified in literature by providing a complete analysis that takes the entirety of the environmental footprint of imaging modalities, including CT, MRI, and ultrasound procedures. By refining the LCA framework, it will be possible to identify the phases in diagnostic imaging that have the most substantial environmental impact. Consequently, this enables the formulation of precise strategies aimed at minimising the greenhouse gas emissions linked to diagnostic imaging processes.

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