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REVIEW

# Pedagogical transformation in medical imaging education: Simulation, active learning, and sustainability

## Transformación pedagógica en la enseñanza de la imagen médica: Simulación, aprendizaje activo y sostenibilidad

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**ABSTRACT**

**Introduction:** active learning methodologies are central to education in Medical Imaging and Radiotherapy (MIR), promoting student engagement, autonomy, and collaborative knowledge construction. Within this framework, the integration of simulators and specialised software has emerged as a relevant strategy to enhance training while supporting more sustainable academic practices. This review aimed to identify pedagogical approaches that improve learning outcomes and contribute to environmental and economic sustainability in MIR education.
**Method:** a narrative literature review was conducted, focusing on active learning methodologies used in radiology and related areas, with particular emphasis on computer-based simulation and software dedicated to technical training. The search encompassed PubMed and ScienceDirect and included studies addressing innovative practices applied to MIR teaching.
**Results:** the results demonstrate that laboratory-based practical training is significantly strengthened through the use of simulators applied to radiology, radiotherapy, and nuclear medicine. The incorporation of digital resources, demonstrative videos, scientific literature, and online assessment supports a more structured learning process. Furthermore, simulation reduces reliance on high-complexity clinical equipment, thereby decreasing financial costs, energy consumption, and $CO_2$ emissions.
systems, whose acquisition, operation and maintenance require substantial financial investment and are associated with high energy consumption and $CO_2$ emissions.
**Conclusions:** adoption of dedicated software and simulation systems fosters more active, safe and effective learning, enhancing pedagogical quality while reducing the environmental and financial impact associated with the use of clinical equipment. This approach therefore represents a promising pathway towards greater sustainability in MIR education.

**Keywords:** Environmental Sustainability; Teaching; Simulation Exercise; High Fidelity Simulation Training; Medical Imaging and Radiotherapy.

**RESUMEN**

**Introducción:** las metodologías de aprendizaje activo ocupan un papel central en la formación en Imagen Médica y Radioterapia (MIR), al promover participación, autonomía y construcción colaborativa del conocimiento. En este marco, la integración de simuladores y software especializado ha surgido como estrategia relevante para optimizar la formación y favorecer prácticas académicas sostenibles. Esta revisión tuvo como objetivo identificar enfoques pedagógicos que mejoren los resultados de aprendizaje y contribuyan a mayor sostenibilidad ambiental y económica.
**Métodos:** se llevó a cabo una revisión narrativa de la literatura, centrada en metodologías activas utilizadas en radiología y áreas afines, con especial énfasis en la simulación computacional y en software dedicado a la capacitación técnica. La búsqueda se realizó en bases de datos relevantes de ciencias de la salud e incluyó estudios que abordaran prácticas innovadoras aplicadas a la enseñanza de IMR.
**Resultados:** los resultados evidencian que la formación práctica en laboratorio se ve significativamente reforzada mediante simuladores aplicados a radiología, radioterapia y medicina nuclear. La incorporación de recursos digitales,

vídeos demostrativos, literatura científica y evaluación en línea favorece un aprendizaje más estructurado. Asimismo, la simulación reduce la dependencia de equipamiento clínico de alta complejidad, disminuyendo costes económicos, consumo energético y emisiones de $CO_2$

**Conclusiones:** adopción de software especializado y sistemas de simulación favorece un aprendizaje más activo, seguro y eficaz, fortaleciendo la calidad pedagógica y reduciendo el impacto ambiental y económico asociado al uso de equipamiento clínico real. Este enfoque representa, por tanto, una vía prometedora hacia una mayor sostenibilidad en la enseñanza de IMR.

**Palabras clave:** Sostenibilidad; Docencia; Ejercicio de simulación; Entrenamiento en simulación de alta fidelidad; Imagen Médica y Radioterapia.

## INTRODUCTION

Active learning methodologies have profoundly transformed the educational landscape of higher education in the health sciences, redefining the traditional role of students and positioning them as central agents in their own learning process. This emerging pedagogical paradigm, grounded in student-centred approaches, emphasises autonomy, active participation, and the development of higher-order cognitive skills such as critical thinking and problem solving. Among the innovative models most widely discussed in the literature, the flipped classroom and simulation stand out, as both have demonstrated significant gains in knowledge acquisition, student engagement and intrinsic motivation to learn.[1,2]

In the specific domain of Medical Imaging and Radiotherapy (MIR), these approaches acquire particular relevance due to the technical complexity of procedures, the need for precision, and the increasing incorporation of advanced digital technologies in clinical settings. The integration of specialised software, virtual reality simulators and digitally supported laboratory environments provides a training experience that combines safety, realism and progressive complexity. Following initial theoretical instruction, students can practise technical skills and clinical reasoning in a controlled environment, reducing the risk associated with error, strengthening pre-clinical preparation and facilitating the transition to supervised professional practice.[2,3]

In parallel, the use of simulation and other technological resources is increasingly associated with contemporary concerns regarding sustainability in health education. The transition towards technologically mediated pedagogical models helps reduce the consumption of disposable materials, the intensive use of real clinical equipment and the need for frequent travel, thereby aligning educational practice with principles of efficiency and environmental responsibility.[1,2,3] This framework is particularly relevant at a time when higher education institutions face growing challenges related to the adoption of ecological practices and the integration of the Sustainable Development Goals (SDGs) into their educational policies and strategies.

However, despite growing evidence on the pedagogical benefits of active methodologies and the transformative role of simulation in MIR training, the literature remains less clear regarding the intersections between pedagogical innovation and environmental sustainability. The identification of sustainable practices, the definition of impact metrics and the understanding of institutional and cultural barriers to implementation remain insufficiently explored areas. It is therefore essential to examine how emerging pedagogical models can integrate sustainability principles without compromising educational quality or the technical proficiency required in the training of highly qualified health professionals.[3,4]

In this context, the literature indicates a growing interest in integrating sustainability into health education; however, it remains limited and fragmented with regard to its operationalisation within Medical Imaging and Radiotherapy (MIR) programmes. In particular, there is a lack of systematised studies identifying concrete pedagogical strategies, structured curricular models, and evaluation indicators that enable the transversal and measurable integration of environmental sustainability principles into MIR education. Furthermore, empirical research examining the contribution of active learning methodologies to the simultaneous development of technical competencies, critical thinking, and ecological awareness in this specific context remains scarce.

Accordingly, this study aims to conduct a structured literature review that critically analyses how environmental sustainability has been conceptualised, implemented, and evaluated within MIR education, identifying the pedagogical approaches adopted, the curricular domains addressed, and the evidence regarding their educational impact. By delimiting these analytical dimensions, the review seeks to map existing gaps, systematise current practices, and provide evidence-informed recommendations to support the pedagogical integration of sustainability in MIR training.

## METHOD

A scoping review was conducted to map and synthesise the available evidence on active learning methodologies, simulation technologies, and environmentally sustainable practices in Medical Imaging and Radiotherapy (MIR) education. This methodological approach was selected because it enables a comprehensive exploration of a broad and emerging field, allowing the inclusion of diverse study designs and sources of evidence. In contrast to traditional systematic reviews focused on narrowly defined effectiveness questions, scoping reviews aim to identify key concepts, map the extent and nature of existing research, and highlight gaps in the literature.

### Search Strategy

The review was conducted in accordance with the Preferred Reporting Items for Systematic Reviews and Meta-Analyses extension for Scoping Reviews (PRISMA-ScR) guidelines, ensuring methodological transparency and reproducibility.

Was carried out in April 2025 in the PubMed and ScienceDirect databases, both considered relevant for the health sciences and health education fields. The following search terms were used: "sustainability", "education/teaching", "simulation", and "Medical Imaging and Radiotherapy" (including equivalent terms). These terms were combined using the Boolean operators AND and OR to broaden the scope of the search and ensure the identification of studies with diverse pedagogical and technological approaches, with Boolean expressions adapted to the specific search syntax and indexing characteristics of the databases consulted.The search was limited to scientific articles published between 2019 and 2025, ensuring the contemporaneity of the pedagogical practices identified, particularly in a period marked by rapid transition to digital environments and hybrid teaching models.

**Eligibility Criteria**

Eligibility criteria were defined in advance to ensure rigor and coherence in the selection of studies. The following were included: (1) original studies (quantitative, qualitative or mixed-methods); (2) published between 2019 and 2025; (3) written in English, Portuguese or Spanish; and (4) freely accessible. Only studies addressing: (1) active methodologies; (2) simulation; (3) digital teaching; and/or (4) sustainable practices within the MIR context were considered.

Opinion-based publications — such as letters to the editor, commentaries or technical notes — were excluded, as were abstracts without full-text availability. Articles inaccessible in full or focused exclusively on the technical performance of equipment, without direct relevance to the teaching–learning process, were also excluded. Finally, publications not aligned with the field of MIR were omitted.

**Selection Process**

The selection process consisted of two stages: (1) screening of titles and abstracts, carried out independently by each author, excluding studies that did not meet the eligibility criteria; and (2) full-text reading of potentially eligible articles, assessing relevance, methodological quality and contribution to the aims of the review. Any disagreement between authors was resolved through discussion and consensus, ensuring rigor in the eligibility process. The final selection reflected a joint evaluation, guaranteeing consistency and robustness in defining the documentary corpus. A total of 13 articles were included for narrative analysis, selected according to the PRISMA checklist (figure 1).

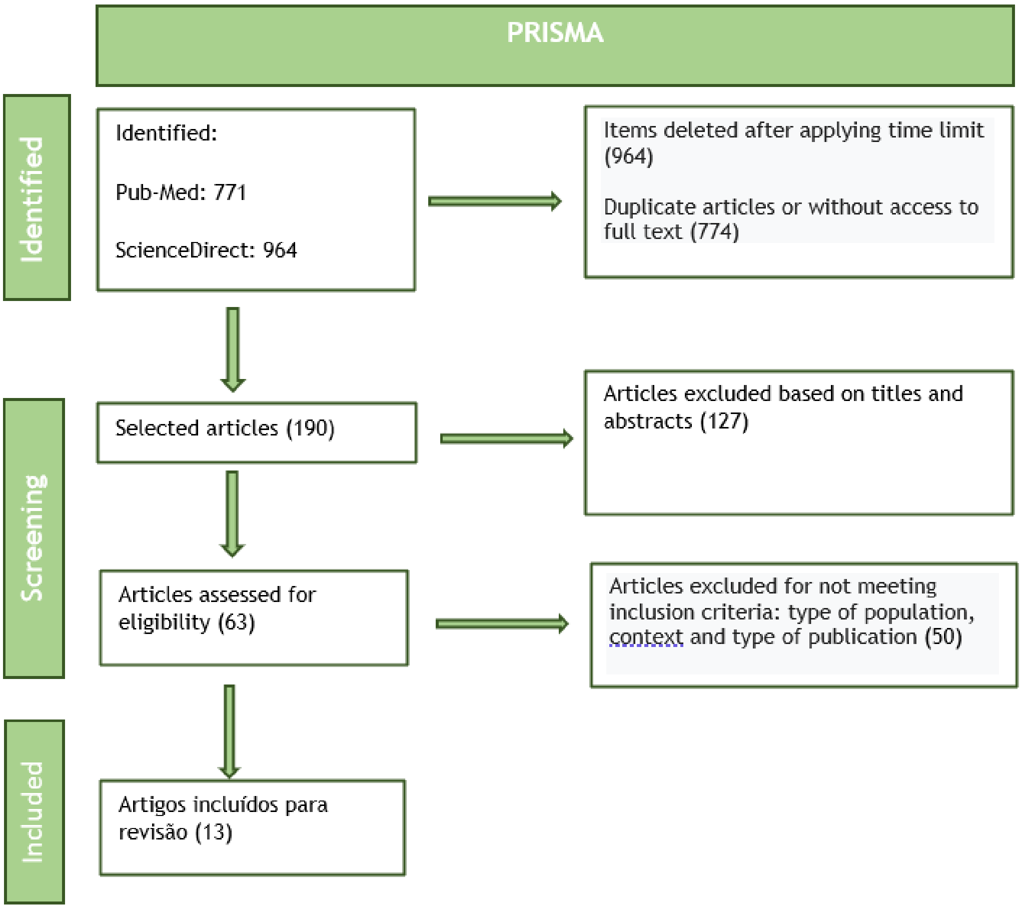


**Figure 1.** PRISMA Flowchart

**Data Extraction and Analysis**

The included studies were analysed according to the following elements: (1) study aim(s); (2) sample characteristics; (3) pedagogical methodologies or technologies employed; (4) contributions to active learning; (5) impact on sustainability (environmental, economic or pedagogical); and (6) limitations identified by the authors.

A narrative and thematic approach was used to organise the results, allowing the identification of patterns, convergences, gaps and opportunities for future research (table 1).

**Table 1.** Main Findings of the Analysed Articles

| Authors | Aim | Findings | Conclusions |
|---|---|---|---|
| Afzal et al.[1] | Flipped classroom model for teaching undergraduate students in radiology | Students prepare in advance, enabling classroom focus on higher-order cognitive skills. | Flipped classroom enhances knowledge and motivation. |
| Zhang et al.[2] | Flipped class based on micro-lecture in clinical imaging diagnosis | Integration of videos and digital theoretical resources improves learning. | Improved knowledge acquisition and motivation. |
| Faulkner et al.[3] | Simulation-based training for health service board members | Use of simulators complements theory and enhances practical experience. | Promotes learning optimisation and sustainability in education. |
| Beam et al.[4] | Simulation approach for evaluating safety behaviours | Simulation enables safe, interactive, and effective training. | Simulators support sustainable education systems. |
| Heye et al.[5] | Energy consumption of radiology: CT and MRI operation | Radiology contributes significantly to CO2 emissions. | Medical imaging has major environmental impact. |
| Sumner et al.[6] | Greening radiology: academic radiology | Simulation reduces equipment acquisition and energy consumption. | Clinical teaching can increasingly rely on simulators. |
| Anudjo et al.[7] | Environmental sustainability in radiology and radiotherapy practice | Reduced need for equipment lowers energy use and emissions. | Simulation supports greener educational practices. |
| Barloese et al.[8] | Sustainable healthcare imaging departments | Simulators allow safe and controlled training. | Imaging has substantial environmental impact. |
| Lingling et al.[9] | Flipped classroom vs traditional lectures | Improved theoretical and practical performance. | Higher satisfaction, teamwork, and self-directed learning. |
| Qi et al.[10] | Flipped classroom with small lectures in radiation practice | Shift to student-centred learning. | Improved short-term performance and practical skills. |
| Wang[11] | Flipped classroom under seminar teaching mode | Digital theoretical resources enhance sustainability and satisfaction. | Improved teamwork and satisfaction. |
| Xie et al.[12] | Flipped classroom combined with WeChat | Preparation in advance enhances higher-order skills. | Improved knowledge and motivation. |

### Ethical Considerations

Ethical approval was not required, as this is a secondary study based on a literature review and did not involve the collection of data from human participants. All studies included in the review were properly identified and cited in accordance with international scientific standards.

## RESULTS

### Conceptualisation of Environmental Sustainability in MIR Education

Environmental sustainability has emerged as a global priority and increasingly influences healthcare education systems. Within MIR education, sustainability is conceptualised as the integration of environmental responsibility into educational practices, institutional policies, and clinical training.[3,4]

The healthcare sector contributes significantly to global carbon emissions, accounting for approximately 4,4 % of total global $CO_2$ emissions across 36 analysed countries.[5,6,7,8] Consequently, several studies highlight the need to incorporate sustainability principles into healthcare curricula to prepare future professionals for environmentally responsible practice.

Across the literature, sustainability in MIR education is generally framed through three interrelated dimensions: environmental impact of imaging technologies, responsible resource management, and sustainability-oriented professional training.

### Institutional and Technological Strategies for Sustainable Imaging Education

Several studies describe institutional strategies aimed at reducing the environmental footprint of imaging education and clinical practice. These strategies primarily involve technological modernization, resource optimization, and the development of sustainability-focused institutional policies.

Medical imaging technologies, particularly MRI and CT systems, are recognized as major energy consumers due to their continuous operational requirements and complex support infrastructures. The replacement of obsolete imaging systems with next-generation technologies equipped with energy-efficient standby modes and optimized cooling systems is frequently identified as a key strategy to reduce energy consumption.[5,6,7,8]

Additionally, institutional initiatives promoting the rational use of imaging examinations, such as those aligned with the Choosing Wisely recommendations, aim to reduce unnecessary imaging procedures while improving clinical efficiency.

The management of digital infrastructures is also highlighted. Strategies including cloud-based storage, data compression technologies, and structured data retention policies are proposed to reduce the digital carbon footprint associated with large imaging data archives.[5]

### Sustainable Management of Consumables and Clinical Waste

Waste management represents a significant environmental challenge within imaging departments. The reviewed literature highlights that medical imaging generates diverse forms of waste, including sterile packaging, disposable accessories, and pharmacological substances such as iodinated and gadolinium-based contrast agents.[6,7,8]

Sustainability initiatives described in the literature include the implementation of waste segregation and recycling programs adapted to imaging environments. Additionally, the rational use of consumables and the prioritization of reusable materials, when clinically appropriate, are emphasized as strategies to reduce waste generation.

Environmental concerns related to the disposal of contrast agents are also increasingly recognized. Some studies advocate for improved collection and decontamination systems to reduce contamination of wastewater systems.

The promotion of environmental awareness among healthcare professionals and students is identified as a key component supporting sustainable waste management practices.

### Active Learning Methodologies and Educational Innovation

Active learning approaches are increasingly integrated into MIR education, often in combination with simulation-based training. The flipped classroom model is frequently described as an effective strategy for promoting student-centred learning while optimizing the use of educational resources.[9,10,11,12]

In this pedagogical model, students engage with theoretical material prior to classroom sessions through digital learning resources such as recorded lectures, educational videos, and scientific literature. Classroom time is then dedicated to simulation-based activities, case discussions, and problem-solving exercises.

Empirical evidence indicates improvements in academic performance associated with these methodologies. A study involving 2114 participants reported improvements in both theoretical knowledge and practical competencies, as well as higher levels of student satisfaction, teamwork, reflective capacity, and self-directed learning.[9]

### Simulation-Based Education as a Sustainable Pedagogical Strategy

Simulation technologies represent an important innovation in MIR education. These tools enable the development of technical competencies within controlled training environments while reducing dependence on physical equipment and clinical infrastructures.[3,4]

Simulation platforms include high-fidelity anatomical phantoms as well as advanced software capable of reproducing diagnostic imaging procedures and therapeutic planning processes. Imaging-specific simulators allow students to perform clinical case analyses, treatment planning exercises, and image interpretation using datasets that replicate realistic imaging conditions.[3,4]

The use of simulation technologies contributes to sustainability by reducing repeated use of imaging equipment during training and minimizing the need for physical teaching resources.

Recent developments also include immersive technologies such as virtual reality and augmented reality platforms, which enable three-dimensional exploration of radiological anatomy and interactive interpretation of complex imaging studies.[13,14,15]

### Educational Outcomes and Sustainability Implications

Simulation-based training also enables the development of complex clinical scenarios, particularly in emergency radiology contexts. Scenarios involving conditions such as intracranial haemorrhage, pulmonary embolism, or tension pneumothorax allow students to practice rapid diagnostic interpretation and decision-making in high-pressure environments.[13,14,15,16]

Structured debriefing sessions play a critical role in consolidating learning. These sessions involve guided reflective discussions in which students analyse decision-making processes, identify strengths and weaknesses, and develop strategies for improvement.

The literature consistently reports positive educational outcomes associated with simulation-based learning, including improved knowledge retention, enhanced practical skill development, and reduced error rates in clinical practice.

However, despite the strong evidence supporting educational benefits, relatively few studies provide objective metrics evaluating the environmental impact of these educational transformations. Indicators such as measurable reductions in energy consumption, waste production, or carbon emissions linked directly to pedagogical restructuring remain limited.

This finding highlights a gap between the conceptual discourse on sustainability in MIR education and the systematic evaluation of its environmental outcomes.

## CONCLUSIONS

The Medical Imaging sector is one of the healthcare areas with the greatest environmental impact, due to its high energy consumption, waste generation, and $CO_2$ emissions into the atmosphere.

Teaching methodologies that incorporate software and simulators specific to radiology, radiotherapy, and nuclear medicine provide students with increased interaction, opportunities to practice without risk to patients, and more active and effective learning experiences.

Simulation and immersive learning represent high-value pedagogical tools in Radiology education, addressing the limitations of traditional teaching approaches while aligning with the growing need for educational innovation in healthcare. Their curricular integration constitutes a fundamental step toward ensuring the development of more competent, confident, and patient-safety–centred professionals.

Simulation should be understood not only as a pedagogical innovation but also as a preventive and developmental strategy that enhances student training and simultaneously contributes to the construction of a more sustainable educational system.

## FINANCING

None.

## CONFLICT OF INTEREST

The authors declare that there is no conflict of interest.

## AUTHORSHIP CONTRIBUTION

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*Data curation:* Nélia Gaudêncio, Magda Ramos, António Abrantes.
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*Writing – original draft:* Nélia Gaudêncio, Magda Ramos, António Abrantes, Claudia Oliveira.
*Writing – review and editing:* Claudia Oliveira.

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