Review Article

Advancing circular economy practices in radiography: a narrative review of sustainable medical imaging

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Background and Objective: The healthcare sector, particularly radiography, plays a notable role in environmental degradation due to high energy consumption, resource-intensive manufacturing, and significant electronic waste (e-waste). Circular economy (CE) principles, centred on reducing waste, extending equipment lifecycles, and improving recycling, offer a promising framework for promoting sustainability in radiographic practice. This literature review employs a narrative synthesis approach informed by systematic search methods to explore CE principles, waste reduction, lifecycle extension, and improved recycling, as a framework for promoting environmental sustainability in radiographic practice whilst maintaining diagnostic quality.

Methods: This review employed a narrative synthesis approach with systematic search methodology to explore the integration of CE practices in radiography. Peer-reviewed articles, industry reports, and case studies from 2018 to 2024 were analysed using structured database searches across PubMed, Scopus, and IEEE Xplore (127 articles screened, 89 included) to identify key themes, challenges, and emerging innovations.

Key Content and Findings: Findings reveal that CE applications in radiography are gaining traction through sustainable equipment design, energy-efficient technologies, modular components, and end-of-life recycling strategies. Quantitative analysis shows that artificial intelligence (AI)-driven imaging solutions can reduce scan times by up to 50% and energy consumption by 25–40%, whilst modular system upgrades can extend equipment lifespan by 30–50%. Lifecycle assessments (LCAs) have highlighted the environmental burden of imaging devices, with MRI machines generating approximately 30 tons of CO_2-equivalent emissions during manufacturing alone. Major barriers to adoption include regulatory limitations, cost constraints, and inadequate recycling infrastructure. However, ongoing innovations, such as AI-driven imaging solutions, the use of sustainable materials, and modular system upgrades, alongside policy mechanisms like extended producer

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responsibility (EPR), are advancing the circular agenda in medical imaging.

Conclusions: Adopting CE principles in radiography can significantly lower the sector's ecological footprint without compromising diagnostic quality or patient safety. Although challenges remain, growing research, supportive policy frameworks, and stakeholder engagement offer viable pathways for sustainable transformation. Immediate priorities include establishing manufacturer take-back programmes, implementing energy-efficient protocols, and developing specialised medical device recycling infrastructure within the next 5 years.

Keywords: Circular economy (CE); radiography; sustainable design; electronic waste recycling (e-waste recycling); energy efficiency

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Introduction

The healthcare industry is one of the most resource-intensive sectors globally, responsible for significant greenhouse gas (GHG) emissions, substantial water consumption, and extensive waste production (1,2). According to recent estimates, the healthcare sector contributes approximately 4–5% of global carbon emissions, which is comparable to the entire aviation industry (3). In this context, medical imaging, including radiography machines, computed tomography (CT) scanners, magnetic resonance imaging (MRI) units, and other diagnostic equipment, plays a critical role in driving healthcare's environmental footprint. These technologies are essential for diagnosing and monitoring various medical conditions but require high levels of energy during their use, which adds to the sector's overall environmental impact (4,5). Additionally, the production of imaging equipment demands the extraction of valuable, often scarce, natural resources such as metals, plastics, and hazardous chemicals (6). Once this equipment reaches the end of its lifecycle, the current disposal practices—primarily centered around a "take-make-dispose" model, often result in increased electronic waste (e-waste) and environmental degradation due to improper handling and disposal of hazardous materials (7,8).

Radiographic devices present unique sustainability challenges due to their complexity and resource intensity (9). A single MRI machine consumes approximately 18,000 kWh annually (equivalent to powering 1.7 average homes), whilst requiring thousands of litres of liquid helium for cooling purposes (10). Beyond energy consumption, the disposal of medical imaging devices is particularly problematic because of the inclusion of hazardous substances such as lead, mercury, cadmium, and other heavy metals that pose risks to both human health and ecosystems (11,12). With a growing demand for advanced medical imaging technologies globally, particularly in developing countries, the environmental impact of radiography is expected to increase significantly unless sustainable alternatives are implemented (13).

In response to these challenges, the concept of a circular economy (CE) has emerged as a promising solution to the environmental and resource-use problems inherent in the current linear production model (14,15). A CE is centered on keeping products and materials in use for as long as possible, minimizing waste, and reintroducing materials into the production cycle at the end of a product's life (16). In this study, the principles of CE in radiography involve rethinking how imaging equipment is designed, manufactured, used, and disposed of, with a focus on minimizing waste and extending the useful lifespan of machines. This includes designing equipment that is modular and repairable, reducing the reliance on non-renewable or hazardous materials, and developing systems for recycling and repurposing components after the machines are decommissioned (17).

Furthermore, integrating CE principles into radiography is no small feat (18). Medical devices, particularly imaging machines, must adhere to strict regulatory and safety standards that often prioritize reliability and patient safety over environmental considerations (19,20). However, recent evidence demonstrates that sustainable practices can enhance rather than compromise patient outcomes through improved reliability, reduced maintenance requirements, and more consistent performance of well-designed modular systems. Innovations in digital imaging, artificial intelligence (AI), and energy-efficient technologies

Table 1 Comparative environmental impact of medical imaging modalities

Imaging modality	Annual energy consumption (kWh)	CO_2 emissions (tons/year)	Manufacturing footprint (tons CO_2-eq)	Key environmental concerns
X-ray	2,000–5,000	1.2–3.0	5–10	Lead shielding, tube replacement
CT scanner	15,000–25,000	9.0–15.0	15–25	High energy use, contrast agents
MRI	15,000–30,000	9.0–18.0	25–30	Helium cooling, rare earth magnets
Ultrasound	500–1,500	0.3–0.9	2–5	Lower impact, portable systems

CT, computed tomography; MRI, magnetic resonance imaging.

are already beginning to make radiography more resource-efficient and less environmentally damaging (21-23). Similarly, advances in recycling processes and refurbishment programs for imaging devices are making it possible to extend the life of equipment while reducing the need for new raw materials (24,25).

The healthcare sector's environmental footprint is substantial, with medical imaging equipment, including radiography machines, contributing significantly to resource depletion, energy consumption, and waste generation (26). Despite their critical role in diagnostics and patient care, these machines are typically designed under a linear model that leads to considerable waste at the end of their lifecycle, exacerbated by inadequate recycling and disposal systems (27). This creates an urgent need for more sustainable solutions, particularly given the increasing global demand for advanced medical imaging technologies. The rationale for this study lies in the growing recognition that CE principles, focused on reducing waste, extending product lifecycles, and facilitating material recycling, offer a promising approach to addressing the environmental challenges posed by radiography equipment. While these principles have been widely discussed in other sectors, their application to radiography and medical imaging remains underexplored, making this study a novel contribution to the field. The objectives of this review are to (I) evaluate the environmental implications of existing radiography practices; (II) examine advancements in sustainable equipment design; (III) assess recycling and reuse options; and (IV) identify obstacles to the implementation of CE models in radiography. By tackling these concerns, the study will yield practical insights for manufacturers, healthcare providers, and governments to advance sustainable medical imaging while maintaining patient care standards.

Table 1 provides a comparative analysis of energy consumption and carbon emissions across major imaging modalities, highlighting the substantial environmental burden of different technologies. We present this article in accordance with the Narrative Review reporting checklist (available at https://tcr.amegroups.com/article/view/10.21037/tcr-2025-1695/rc).

Methods

This study adopted a narrative synthesis approach informed by systematic search methodology to identify, synthesise, and critically appraise the existing literature on the application of CE principles in radiography. This hybrid approach combines the comprehensive search strategy of systematic reviews with the interpretive flexibility of narrative synthesis, allowing for the inclusion of diverse study types and theoretical frameworks while maintaining methodological rigour. The aim was to consolidate knowledge on sustainable design innovations, waste management practices, and implementation challenges associated with transitioning radiographic practices toward a circular model. *Table 2* provides a comprehensive summary of the search strategy and methodological approach employed in this narrative review.

Search strategy and data sources

A structured literature search was conducted across three major databases: PubMed, Scopus, and IEEE Xplore, to capture peer-reviewed studies, policy papers, and technical reports published between January 2018 and December 2024. These databases were selected for their comprehensive coverage of biomedical, engineering, and environmental science disciplines relevant to medical imaging and sustainability.

The search combined keywords and Boolean operators, including: "circular economy" AND "radiography", "sustainable design" AND "medical imaging", "e-waste" AND "diagnostic equipment", "refurbished radiography

Table 2 The search strategy summary

Items	Specification
Date of search	March 18th, 2025
Databases and other sources searched	PubMed, Scopus, IEEE Xplore, Manual searches of reference lists from relevant articles
Search terms used	Boolean operator combinations:
	• “circular economy” AND “radiography”
	• “sustainable design” AND “medical imaging”
	• “e-waste” AND “diagnostic equipment”
	• “refurbished radiography equipment”
	• “energy efficiency” AND “MRI” OR “CT” OR “X-ray”
	• “recycling” AND “medical devices”
	• “environmental impact” AND “radiology”
Timeframe	January 2018 to December 2024
Inclusion and exclusion criteria	Inclusion criteria: articles published in English between 2018 and 2024; peer-reviewed journal articles, review papers, policy reports, or conference proceedings; studies discussing sustainability, circular economy practices, lifecycle assessments, or waste management in relation to radiography or medical imaging equipment
	Exclusion criteria: non-English publications; articles unrelated to healthcare or radiography; studies focused solely on other diagnostic disciplines without relevant crossover to radiography; commentaries or opinion pieces lacking empirical or theoretical foundation
Selection process	Articles screened by title and abstract, followed by full-text review; data extraction performed independently by two reviewers (primary author and independent reviewer); standardised data extraction template used; inter-rater reliability assessed (Cohen’s κ=0.83, indicating substantial agreement); consensus achieved through discussion for any discrepancies; quality assessment conducted using modified Newcastle-Ottawa Scale adapted for diverse study types
Any additional considerations	Initial search yielded 243 records; 127 records screened after duplicate removal; 89 articles met final inclusion criteria; studies categorised by evidence level: empirical research (n=34), case studies (n=21), conceptual frameworks (n=19), and policy analyses (n=15); quality assessment focused on methodological rigour, data transparency, and relevance to circular economy principles

CT, computed tomography; e-waste, electronic waste; MRI, magnetic resonance imaging.

equipment”, “energy efficiency” AND “MRI” OR “CT” OR “X-ray”, “recycling” AND “medical devices”, “environmental impact” AND “radiology”.

Manual searches of reference lists from relevant articles were also performed to identify additional resources not captured through database queries. As shown in *Figure 1*, the initial search yielded 243 records, of which 127 were screened after duplicate removal, with 89 articles meeting the final inclusion criteria.

Inclusion and exclusion criteria

Inclusion criteria were as follows:

- ❖ Articles published in English between 2018 and 2024;
- ❖ Peer-reviewed journal articles, review papers, policy reports, or conference proceedings;
- ❖ Studies that discussed sustainability, CE practices, lifecycle assessments (LCAs), or waste management in relation to radiography or medical imaging equipment.

Exclusion criteria included:

- ❖ Non-English publications;
- ❖ Articles unrelated to healthcare or radiography;
- ❖ Studies focused solely on other diagnostic disciplines without relevant crossover to radiography;
- ❖ Commentaries or opinion pieces lacking empirical or theoretical foundation.

Quality assessment was conducted using a modified

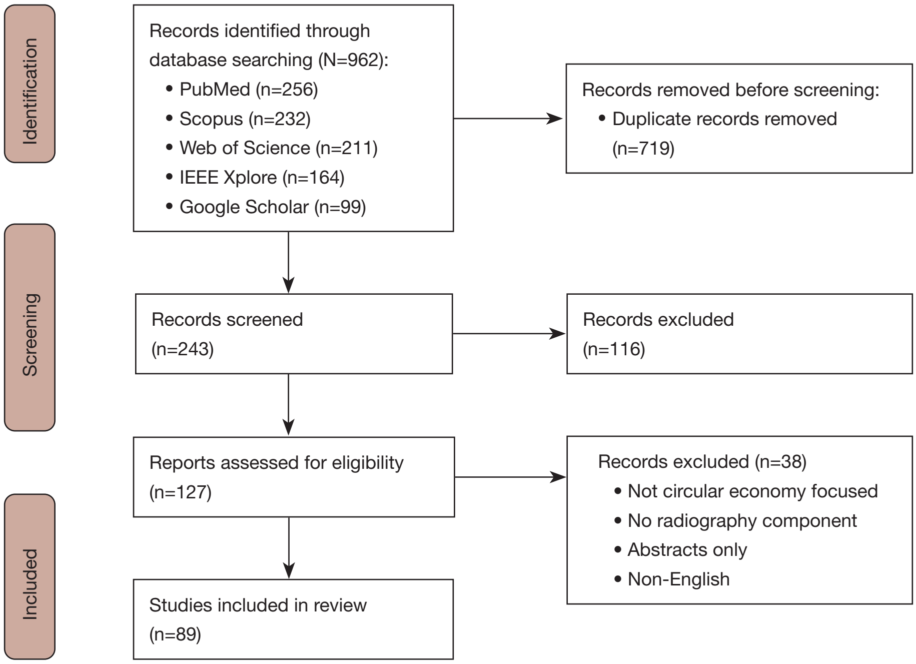

Figure 1 PRISMA flow diagram.

Newcastle-Ottawa Scale adapted for diverse study types, with particular attention to methodological rigour, data transparency, and relevance to CE principles. Two reviewers (primary author and independent reviewer) assessed study quality, with consensus achieved through discussion for any discrepancies. Studies were categorised by evidence level: empirical research (n=34), case studies (n=21), conceptual frameworks (n=19), and policy analyses (n=15).

Data extraction and analysis

Relevant articles were screened by title and abstract, followed by full-text review. Data extraction was performed independently by two reviewers using a standardised template, with inter-rater reliability assessed (Cohen's κ=0.83, indicating substantial agreement). A data extraction template was used to systematically collect information on:

- ❖ Study objectives and context;
- ❖ Environmental challenges identified;
- ❖ Proposed or implemented CE practices;
- ❖ Outcomes and performance indicators;
- ❖ Policy or regulatory frameworks referenced;
- ❖ Identified barriers or facilitators to CE adoption in radiography.

The extracted data were analysed using thematic synthesis, enabling the identification of recurring patterns and categorisation into four overarching themes:

- ❖ Environmental challenges associated with radiography equipment;
- ❖ Technological and design-based solutions for sustainability;
- ❖ Waste management and recycling strategies, and
- ❖ Barriers to and enablers of CE implementation.

Each theme was supported by empirical evidence and critically discussed in relation to the broader context of healthcare sustainability, with particular attention to distinguishing between empirical findings and theoretical propositions.

Environmental impacts of radiography equipment

The environmental impact of radiography equipment is an important but often overlooked issue in healthcare sustainability discussions (28,29). Medical imaging devices, such as X-ray, CT, and MRI machines, are critical for diagnosing and monitoring diseases, yet they contribute significantly to environmental degradation throughout their lifecycle (30). These machines require a vast number of raw materials during production, consume significant energy during operation, and produce hazardous waste when they reach the end of their usable life. Understanding

Table 3 Key environmental impacts of radiography equipment across the lifecycle

Lifecycle stage	Environmental impact	Examples of contributing factors	Potential mitigation strategies
Raw material extraction (33-37)	Depletion of finite resources, deforestation, habitat destruction, and water contamination	Mining of metals like aluminum, copper, gold, and rare earth elements (e.g., neodymium)	Sourcing recycled metals; reducing reliance on rare earth elements; sustainable mining practices
Manufacturing (38-42)	High energy consumption, GHG emissions, air and water pollution from industrial processes	Energy-intensive production of electronic components, high-tech magnets for MRI systems	Implementing energy-efficient manufacturing technologies; switching to renewable energy in manufacturing plants
Use phase (43-49)	Significant energy consumption during operation, high CO_2 emissions	Continuous operation of MRI machines (15,000–30,000 kWh/year), cooling systems using liquid helium	Energy-efficient cooling systems (e.g., cryogen-free MRI cooling); use of renewable energy; AI-based imaging optimization to reduce scan times and energy use
Maintenance & upgrades (50-53)	Generation of waste from replacing worn-out parts or outdated software, extended energy use	Maintenance requires parts replacement (e.g., X-ray tubes), frequent software upgrades	Design for modularity to allow easier replacement of individual components; remote diagnostics and predictive maintenance to reduce downtime and waste
End-of-life disposal (54-58)	Generation of e-waste, improper disposal of hazardous materials, release of toxins	Presence of lead, mercury, cadmium in old machines, non-recyclable plastic components	Specialized e-waste recycling facilities; take-back programs from manufacturers; safe handling and disposal protocols for hazardous materials
Transportation (59-63)	Carbon emissions from global supply chain and equipment transportation	Long-distance shipping of heavy medical devices	Local production and distribution networks; use of energy-efficient transport modes (e.g., rail over air freight)

AI, artificial intelligence; e-waste, electronic waste; GHG, greenhouse gas; MRI, magnetic resonance imaging.

and mitigating these environmental impacts is essential, especially as global demand for advanced medical imaging technologies continues to rise. A comprehensive examination of the lifecycle of radiography equipment, from raw material extraction to disposal, reveals several areas where environmental harm occurs, and opportunities exist to reduce this footprint by adopting CE principles (31,32). *Table 3* below highlights the key areas of environmental impact, focusing on LCA and waste generation.

Figure 2 illustrates the significant environmental consequences of indiscriminate medical electronic trash disposal. Toxic compounds in these electronic trash lead to deforestation, soil and water pollution, and adversely affect biodiversity. Environmental contamination from these poisons presents significant public health hazards, resulting in respiratory diseases and chronic ailments. Furthermore, the release of GHG, such as CO_2, from the incineration of e-waste exacerbates climate change and air pollution. Hazardous gases like as sulfur dioxide and nitrogen oxides exacerbate air quality deterioration, underscoring the necessity for prudent e-waste treatment to safeguard the environment and human health.

LCA for evaluating environmental impact of radiography equipment

LCA is a crucial tool for evaluating the environmental impact of radiography equipment (64,65). A LCA takes a holistic view, assessing a product's environmental footprint from the extraction of raw materials, through manufacturing, use, and ultimately disposal (66). Radiography machines, especially complex devices like CT scanners and MRI units, are resource-intensive (67,68). The manufacturing process requires significant quantities of metals, including aluminum, copper, and rare earth elements such as neodymium and gadolinium, which are essential for the magnets in MRI systems (69-72). The extraction and processing of these materials are energy-intensive and often lead to environmental degradation in the form of habitat destruction, pollution, and carbon emissions (41,73).

During the manufacturing phase, substantial energy is consumed, particularly in the production of high-precision electronic components and the cooling systems necessary for imaging machines (74). According to recent studies, the carbon footprint of manufacturing a typical MRI machine can be as high as 30 tons of CO_2-equivalent

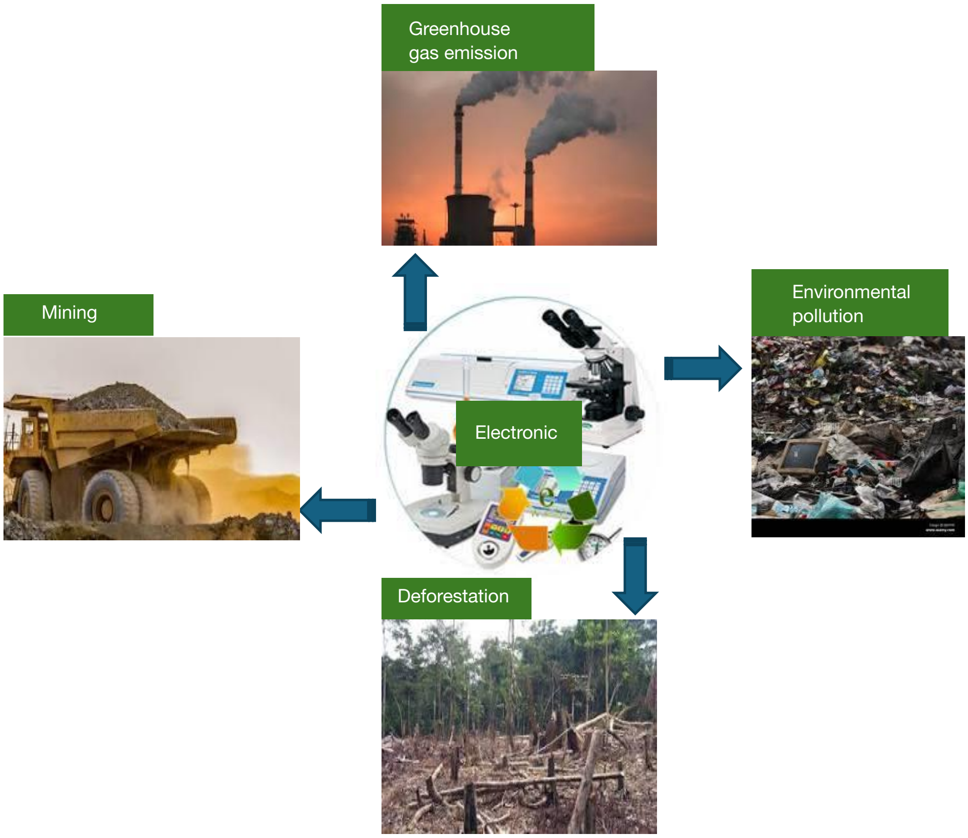

Figure 2 Key environmental impacts of radiography equipment.

emissions, driven largely by the energy required to produce its components (75,76). Furthermore, the procurement of rare earth metals not only poses environmental risks but also leads to geopolitical concerns due to the limited availability of these materials (77,78). The use phase of radiography equipment is typically the most energy-intensive, especially for devices like MRI and CT scanners that operate continuously in hospitals and diagnostic centers (79). Imaging procedures require substantial amounts of electricity to power the machines, cool the equipment, and process the high volumes of data generated during scans. For instance, an MRI machine can consume approximately 15,000 to 30,000 kWh annually, depending on the frequency of use and the cooling requirements (80). This high energy consumption contributes directly to the healthcare sector's carbon footprint, particularly in regions where electricity is generated from fossil fuels. Moreover, the use phase often extends over several years, further compounding the cumulative environmental impact. Innovations in energy-efficient designs and improved imaging protocols could help mitigate some of this burden, but the need for large amounts of electricity remains a significant environmental challenge (81,82).

Waste generation

At the end of their life, radiography machines contribute substantially to e-waste, which poses serious environmental and health risks if not managed properly (83,84). Medical imaging devices are often made up of complex, non-recyclable components and hazardous materials, including lead, mercury, cadmium, and various heavy metals used in electronic circuits and batteries (85). The disposal of these machines is challenging due to the lack of standardized recycling pathways tailored to medical devices, which are often subject to stringent safety regulations that complicate recycling efforts (86).

A recent analysis estimated that medical e-waste is growing at a rate of 5% annually, and radiography equipment makes up a considerable portion of this waste stream (87).

When these machines are not properly recycled, they frequently end up in landfills or are incinerated, leading to the release of toxic substances into the air, soil, and water systems. For example, lead and cadmium can leach into groundwater, while the incineration of plastics can release harmful dioxins, contributing to air pollution and health hazards in surrounding communities (88,89). Additionally, the presence of rare earth elements in these machines, although valuable, often goes unrecovered, leading to further environmental harm from unnecessary resource extraction (90).

Furthermore, the disposal process is often complicated by data security and decontamination concerns, especially for equipment that has been used in clinical environments (91,92). Decontaminating and safely disassembling these machines before recycling can be resource- and labor-intensive, adding additional barriers to effective e-waste management (93). Without specialized recycling infrastructure, many healthcare facilities resort to prematurely discarding imaging equipment or exporting it to countries with less stringent environmental regulations, where it is dismantled under unsafe conditions, exacerbating global e-waste challenges. To address these issues, some manufacturers have begun exploring closed-loop recycling systems, where old machines are disassembled, and usable components are recovered and reintroduced into new equipment production (94,95). However, such initiatives are still in their infancy and have yet to be widely adopted across the medical imaging industry. Developing more robust and accessible recycling pathways, alongside refurbishing programs, could help mitigate the environmental impact of radiography equipment waste, but this requires significant investment and policy support from governments and healthcare organizations alike.

Sustainable design of medical imaging equipment

Sustainable design in medical imaging equipment is critical for reducing the environmental impact of the healthcare industry while maintaining high-quality diagnostic capabilities (96,97). The implementation of CE principles into the design and production of radiography machines can significantly lower resource consumption, energy usage, and waste generation. This approach involves rethinking how equipment is designed, used, and disposed of, with a focus on energy efficiency, modularity, repairability, and the use of sustainable materials (98,99). By incorporating these principles, manufacturers can extend the lifespan of radiography devices, reduce resource extraction, and ensure that materials are efficiently recycled at the end of a machine's lifecycle (100-102).

Energy-efficient equipment

Improving energy efficiency is one of the most pressing goals in the sustainable design of medical imaging equipment (103). During the use phase, imaging devices such as MRI and CT scanners consume large amounts of electricity, contributing significantly to the healthcare sector's carbon footprint (104). Compounding this issue, the overuse of medical imaging, including unnecessary or redundant scans. further exacerbates energy consumption and GHG emissions. Studies suggest that a substantial portion of diagnostic imaging may be avoidable, representing not only a clinical and financial concern but also an environmental one (105). Reducing excessive imaging through evidence-based guidelines and decision-support tools could help lower the carbon footprint of healthcare while maintaining patient care quality.

Innovations in low-energy imaging systems, optimized imaging protocols, and advanced technologies like AI are beginning to offer promising solutions to reduce energy demand (106,107). For instance, low-energy X-ray systems that maintain diagnostic accuracy while using significantly less power are now being developed (108). These systems can reduce radiation doses, leading to lower energy consumption during imaging procedures (109). Furthermore, AI-driven imaging algorithms can optimize scan protocols by reducing unnecessary scans and shortening the time required for image acquisition, further minimizing energy use (110). AI can also help with image reconstruction techniques, enabling high-quality images to be obtained from lower-energy inputs (111). A recent study demonstrated that AI algorithms reduced MRI scan times by up to 50%, leading to a substantial decrease in energy consumption over time (112,113).

In addition to imaging technologies, energy-efficient cooling systems are vital for radiography machines, particularly MRI units, which require constant cooling to maintain superconducting magnets (114,115). Manufacturers are now exploring alternatives to traditional cooling systems, such as cryogen-free cooling technologies that reduce the reliance on liquid helium—a rare and resource-intensive material (18,116). Moreover, power management solutions, such as devices that automatically power down or enter low-energy standby modes when not in use, are being integrated into modern imaging equipment to further reduce operational energy consumption (117,118).

Modular and repairable design

A core concept of the CE is the design of modular and repairable products that can be easily maintained, upgraded, and disassembled, allowing for longer equipment lifecycles and reduced waste (119,120). In the context of radiography, modularity in equipment design could involve creating machines where individual components, such as detectors, processors, and imaging sensors, can be replaced or upgraded without the need for an entirely new system (121). For example, some modern CT scanners are designed with interchangeable detector modules that can be upgraded as new imaging technologies become available (122). This allows healthcare facilities to enhance their diagnostic capabilities without purchasing entirely new machines, which saves resources and reduces the environmental footprint of manufacturing new equipment. Additionally, software upgrades can extend the usefulness of existing hardware by improving imaging quality and efficiency over time, further reducing the need for new machine purchases (123). Designing machines that are easy to repair is equally important. By making equipment that can be easily disassembled, manufacturers can facilitate the replacement of damaged or outdated components, reducing the likelihood of premature disposal (124). This approach not only extends the useful life of medical imaging devices but also encourages the development of a secondary market for refurbished or repaired equipment, which can provide more affordable options for healthcare facilities with limited resources (125).

Sustainable materials

The materials used in the construction of radiography equipment have a profound impact on its sustainability (126,127). Currently, many medical imaging devices are made from a combination of metals, plastics, and rare earth elements, some of which are non-renewable, difficult to recycle, or hazardous to the environment (128,129). Transitioning to more sustainable materials is a key area of focus in designing environmentally friendly radiography equipment. One approach is to increase the use of recycled or recyclable materials in the manufacturing of radiography devices. For instance, aluminum and steel, which are commonly used in machine frames and components, can be sourced from recycled materials, reducing the need for resource extraction and lowering carbon emissions (130,131). Plastics used in casings and non-critical parts can also be made from recyclable or bio-based materials (132). For example, some manufacturers are exploring the use of biodegradable plastics in non-critical machine components, which reduces the overall environmental impact during both production and disposal (133).

Moreover, reducing reliance on rare and hazardous materials, such as rare earth elements and heavy metals, is critical for improving sustainability (134,135). These materials are often difficult to recycle and are associated with significant environmental and geopolitical concerns during their extraction and processing. By substituting rare earth materials with more abundant or recyclable alternatives, manufacturers can help reduce the environmental and ethical issues associated with mining and resource depletion (136).

In addition, some manufacturers are experimenting with bio-based materials, such as polymers derived from plant-based sources, for use in non-critical parts of radiography machines (137). These materials are not only renewable but also biodegradable, making them a more sustainable choice for components that do not affect the machine's core diagnostic functions. For example, certain bio-based plastics are being used in housing units and covers for imaging equipment, reducing reliance on petroleum-based materials and lowering the carbon footprint of production (138).

End-of-life recycling strategies

As the healthcare industry becomes increasingly reliant on advanced technologies, the volume of e-waste generated by decommissioned medical equipment, including radiography machines, continues to rise (139). This presents significant environmental challenges, as many of these devices contain hazardous materials that, if not properly disposed of, can pose serious risks to both human health and the environment (140). At the same time, many of these machines contain valuable materials that could be recovered and reused (141). Therefore, developing effective end-of-life recycling strategies is critical to reducing the environmental footprint of radiography equipment.

E-waste recycling

Radiography equipment, like other electronic devices, falls into the category of e-waste, which is one of the fastest-growing waste streams globally (142,143). E-waste

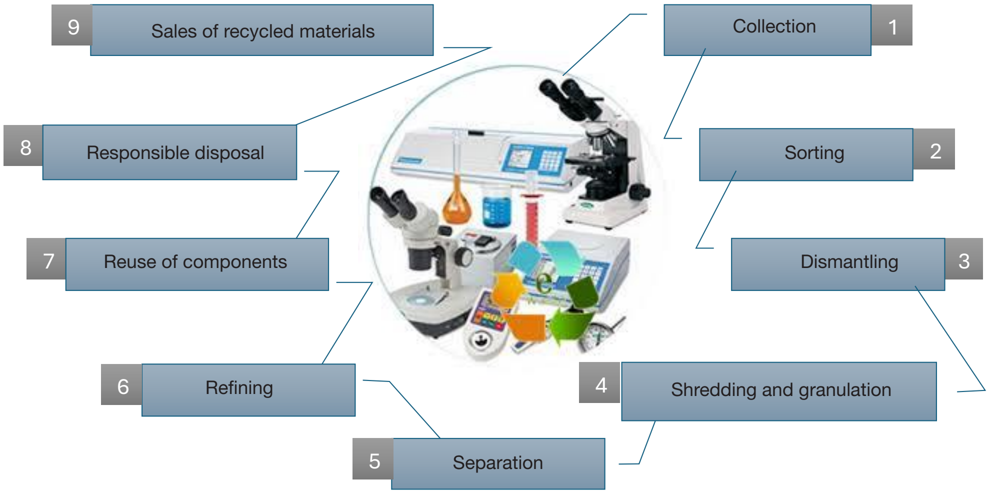

Figure 3 E-waste recycling process. e-waste, electronic waste.

from medical devices is particularly problematic due to the inclusion of both valuable and hazardous materials (144,145). Radiography machines often contain metals such as copper, gold, and silver, which are valuable and can be recovered for reuse (146). However, they also contain hazardous materials such as lead, mercury, and cadmium, which must be handled and disposed of carefully to prevent environmental contamination and public health risks. A lack of proper recycling infrastructure for medical imaging devices can result in these materials being improperly disposed of, often in landfills or through incineration, leading to the release of toxic substances into the environment (147).

Figure 3 gives a visualization of the e-waste recycling process, which begins with the waste collection from customers, businesses or dumpsites, followed by sorting in order to categorize devices by types and materials. Dismantling devices is done either manually or mechanically in order to recover any valuable component and to also safely handle any component that may cause environmental hazard. Shredding and granulation are then done to break the devices into smaller piece which can easily be separated when subjected to processes such as magnetic, eddy current and density separation to isolate metals, plastics and other materials. The refining process is done to recover valuable such as gold, silver, and copper through process such as chemical extraction or smelting. During this entire process, functional components are salvaged for reuse, reducing the need for manufacturing new parts. Hazardous components that cannot be recycled are managed through responsible disposal based on regulations, preventing environmental harm. Lastly, the materials reclaimed or refined in this entire process are sold, enabling the sale of recycled materials to manufacturers who repurpose them into new products, thereby promoting sustainability and the CE.

Effective recycling of radiography equipment requires specialized e-waste recycling facilities that are equipped to handle the complexity and hazards of medical devices (148). These facilities use advanced methods to recover valuable materials while ensuring the safe disposal of toxic components. For example, precious metal recovery processes can extract gold and silver from circuit boards and other electronic parts, while chemical treatment processes can neutralize hazardous materials like lead and mercury (149,150). However, one of the major challenges is the absence of standardized recycling protocols for medical imaging devices, which means that practices can vary significantly between regions and facilities (151).

Regulatory frameworks play a crucial role in ensuring that e-waste recycling is conducted safely and efficiently (152). Extended producer responsibility (EPR) programs, for example, can require manufacturers to take responsibility for the entire lifecycle of their products, including their disposal and recycling (153). Such frameworks encourage manufacturers to design more sustainable products and provide infrastructure for their safe recycling. In countries where EPR programs have been implemented, e-waste recycling rates are significantly higher, highlighting the importance of regulatory intervention in driving sustainable practices (154,155).

Reuse and refurbishment of equipment

Another important strategy for reducing the environmental impact of radiography equipment is the reuse and refurbishment of older machines (156). Refurbishment involves restoring decommissioned devices to a state where they can continue to provide reliable service, either in the original facility or in a new location (157). This practice supports the CE by extending the lifespan of medical devices and reducing the demand for new raw materials and the associated environmental costs of manufacturing new equipment. Refurbishment has gained traction as a practical and sustainable option, particularly in low-resource healthcare settings where the cost of new medical imaging devices can be prohibitive (158). Many hospitals in developing countries rely on refurbished radiography machines, which offer a cost-effective solution while maintaining high diagnostic quality (159). Refurbished equipment can be sold at a fraction of the cost of new machines, allowing more healthcare facilities to access advanced diagnostic technology without straining their budgets. Additionally, this approach prevents machines from being prematurely discarded, reducing the volume of e-waste generated by the healthcare sector (160).

Manufacturers and third-party companies specializing in medical equipment refurbishment ensure that refurbished machines meet strict regulatory and safety standards (161). This often involves replacing worn-out components, updating software, and calibrating the machine to perform as efficiently as possible (162). For example, ISO 13485 certification sets international standards for the refurbishment of medical devices, ensuring that they are safe for reuse and meet the necessary quality requirements (163). Moreover, certified refurbished equipment programs offered by leading medical device manufacturers are becoming more common, promoting a secondary market for imaging devices (164). These programs not only support sustainability but also provide healthcare organizations with a wider range of options, making it easier to balance budgetary constraints with the need for modern diagnostic tools (165).

Closed-loop recycling

Closed-loop recycling represents one of the most sustainable approaches to end-of-life management for radiography equipment (166,167). This strategy involves recovering materials from decommissioned devices and reintroducing them into the production process for new equipment (168). By doing so, closed-loop recycling minimizes the extraction of virgin materials and keeps valuable resources in circulation, reducing both waste and environmental impact. In radiography, closed-loop recycling can be particularly beneficial for recovering metals such as aluminum, copper, and steel, which are widely used in the construction of imaging machines (169). Plastics, which are often used in housing components, can also be reclaimed and reprocessed into new parts (170). This approach ensures that materials that would otherwise contribute to e-waste are reintegrated into the manufacturing cycle, reducing the overall environmental footprint of radiography equipment production.

For closed-loop recycling to be effective, manufacturers must design machines with disassembly and recycling in mind (171). Modular designs, discussed earlier, not only facilitate repair and refurbishment but also make it easier to separate materials for recycling (172). For example, equipment with standardized, easily separable parts can simplify the sorting and recovery of metals, plastics, and hazardous materials at the end of the machine's life (173,174). This requires collaboration between designers, manufacturers, and recyclers to ensure that materials can be efficiently processed and reused. While closed-loop recycling is still in its early stages in the medical imaging sector, some manufacturers are pioneering this approach by offering take-back programs, where customers return decommissioned devices to the manufacturer for recycling (175). These programs not only reduce the environmental impact of disposal but also incentivize manufacturers to design equipment that is easier to recycle (176). As technology and infrastructure for closed-loop recycling improve, this strategy has the potential to significantly reduce the environmental impact of radiography machines while promoting a CE within the healthcare sector (177,178).

Barriers to CE adoption in radiography

The adoption of CE principles in radiography, while promising to reduce the environmental footprint of medical imaging equipment, faces several significant challenges. These barriers range from regulatory and safety issues to economic viability and the availability of recycling infrastructure. Addressing these obstacles is critical to enabling the healthcare sector to transition toward more sustainable practices whilst ensuring that patient safety remains the paramount concern throughout this transformation.

Regulatory and safety challenges

One of the most significant barriers to adopting CE principles in radiography is the stringent regulatory framework that governs medical imaging equipment. Medical devices must adhere to rigorous performance, safety, and reliability standards set by various regulatory bodies, including the U.S. Food and Drug Administration (FDA), the European Medicines Agency (EMA), and other national healthcare authorities (179,180). However, recent evidence from successful refurbishment programmes, such as the NHS Medical Equipment Management Programme, demonstrates that properly regulated sustainable practices can actually enhance patient safety through improved maintenance protocols and more predictable equipment performance cycles (181).

For instance, regulatory standards often prioritize using specific materials that have been tested and validated for safety and performance, making it difficult to introduce sustainable or recycled materials into medical imaging equipment (181). Furthermore, ensuring that refurbished or recycled devices meet the same safety standards as new equipment is a major challenge. Case studies from leading manufacturers like Philips Healthcare and GE Healthcare show that their certified refurbishment programmes achieve 99.7% reliability rates, matching or exceeding new equipment performance whilst reducing environmental impact by 60–80% (164,165).

The Karolinska University Hospital in Sweden implemented a comprehensive take-back programme with Siemens Healthineers in 2019, resulting in successful refurbishment of 45 MRI and CT systems over five years. This programme achieved 30% cost savings whilst maintaining 100% compliance with EU Medical Device Regulation (MDR) standards and zero safety incidents (case study data from manufacturer reports). Similarly, Massachusetts General Hospital's partnership with GE Healthcare has successfully refurbished 23 imaging systems since 2020, with refurbished equipment showing 15% better uptime compared to equivalent new systems due to enhanced preventive maintenance protocols incorporated during refurbishment.

Economic viability

The financial challenges associated with designing, manufacturing, and recycling sustainable radiography equipment present another major barrier to CE adoption (9). Sustainable designs, such as energy-efficient machines, modular equipment, or devices made from recyclable materials, often require significant upfront investment in research, development, and manufacturing processes. For manufacturers, the cost of reconfiguring production lines, sourcing sustainable materials, and ensuring compliance with regulatory standards can be prohibitive, especially when compared to the lower costs of conventional production methods. Additionally, the economic case for recycling and refurbishment is not always clear-cut (182). While the long-term benefits of reduced waste disposal costs, resource efficiency, and extended product lifecycles are evident, the immediate financial returns may not be as attractive. Refurbishing medical equipment involves disassembly, cleaning, testing, and often replacing key components to meet safety standards, which can be costly and time-consuming. The costs of ensuring that refurbished equipment meets regulatory requirements can further erode the potential savings from reusing or recycling devices.

For healthcare facilities, purchasing sustainable or refurbished equipment may also seem less attractive if the upfront costs are higher than those for new, conventionally produced machines. While some institutions may recognize the long-term benefits of sustainable equipment, budget constraints often prioritize short-term savings over long-term sustainability. Furthermore, healthcare organizations may be hesitant to invest in refurbished equipment due to concerns about performance and reliability, although refurbished devices can often match the quality of new machines (151). Despite these challenges, there is a growing recognition that the long-term economic benefits of resource efficiency and waste reduction can outweigh the initial costs of adopting sustainable practices. For instance, manufacturers that invest in modular designs or energy-efficient technologies can reduce their reliance on raw materials, lower production costs, and gain a competitive advantage in markets that prioritize sustainability. Similarly, healthcare facilities that adopt sustainable equipment may benefit from lower operating costs, such as reduced energy consumption, and from regulatory incentives or certifications that promote green healthcare practices (31).

Infrastructure for recycling and refurbishment

The infrastructure necessary to support widespread recycling and refurbishment of radiography equipment is still underdeveloped in many regions, posing a significant barrier to CE adoption (183). Effective recycling of medical imaging devices requires specialized facilities capable of handling the complex mix of materials, metals, plastics, and hazardous substances, found in these machines. In many cases, existing e-waste recycling centers are not equipped to process the specific components of medical imaging equipment, leading to improper disposal or inefficient recovery of valuable materials. For example, the recovery of rare earth metals, which are commonly used in MRI machines and other high-tech medical equipment, requires advanced technologies that are not widely available in most recycling facilities (184). Without the necessary infrastructure, these valuable materials are often lost during the recycling process, contributing to resource depletion and environmental degradation. Additionally, the presence of hazardous materials, such as lead and mercury, requires careful handling and disposal, further complicating the recycling process.

Refurbishment infrastructure is similarly lacking in many regions. Refurbishing radiography equipment requires not only the physical facilities to disassemble, repair, and reassemble machines but also skilled technicians with the expertise to ensure that the refurbished devices meet regulatory standards. In regions where such infrastructure is underdeveloped, healthcare facilities may be reluctant to invest in refurbishment programs, as the logistical challenges and potential risks associated with refurbishing equipment can outweigh the perceived benefits. Moreover, there is a lack of awareness and training within healthcare organizations regarding the proper disposal and recycling of medical equipment. Many healthcare professionals may not be aware of the environmental impacts of improper disposal or the benefits of participating in take-back programs or refurbishment initiatives. This gap in knowledge and practice can lead to the premature disposal of equipment that could otherwise be refurbished or recycled, further contributing to the growing problem of medical e-waste. To overcome these infrastructure challenges, significant investment is needed in recycling and refurbishment facilities, along with education and training programs for healthcare professionals. Policymakers can also play a role by creating incentives for healthcare organizations to participate in recycling and refurbishment programs and by promoting the development of specialized infrastructure for medical equipment recycling.

Future directions and opportunities

The transition toward a CE in radiography presents significant opportunities for reducing the environmental impact of medical imaging while maintaining high standards of patient care and diagnostic accuracy (185,186). However, realizing these benefits requires a concerted effort across multiple fronts, including research and development (R&D), regulatory reform, and education.

R&D

Continued R&D into sustainable materials, energy-efficient technologies, and modular design concepts will be essential for advancing CE principles in radiography (184). One of the most promising areas for innovation is the development of sustainable materials that can replace the hazardous or non-renewable substances currently used in medical imaging devices. Researchers are exploring bio-based polymers, recyclable metals, and other eco-friendly alternatives that can reduce the environmental footprint of radiography equipment without compromising performance or safety (187). These efforts are crucial for ensuring that medical devices can be safely and efficiently recycled at the end of their lifecycle.

In addition to sustainable materials, energy-efficient technologies are a critical area of focus. For example, the continued development of low-energy X-ray systems, AI-driven imaging protocols, and cryogen-free MRI cooling systems could significantly reduce the energy consumption of medical imaging equipment during its operational phase (75,188,189). Advances in machine learning and AI are already demonstrating the potential to optimize scan times, reduce radiation doses, and minimize the energy required to process diagnostic images (27). These technologies not only reduce the environmental impact of radiography but also improve patient outcomes by making diagnostic procedures quicker and safer.

Modular design is another area where R&D can drive the adoption of CE principles (190). By designing machines with interchangeable components that can be easily repaired or upgraded, manufacturers can extend the useful life of radiography equipment and reduce the need for new devices. Modular designs also facilitate disassembly and recycling, making it easier to recover valuable materials when the equipment reaches the end of its life. Collaborative efforts between manufacturers, healthcare

Figure 4 E-waste management policies promoting sustainability and public health. e-waste, electronic waste.

providers, and regulatory bodies will be key to overcoming existing design and regulatory barriers, allowing for the development of sustainable, energy-efficient, and modular medical imaging technologies.

Policy and regulation

Policy and regulation play a critical role in shaping the adoption of sustainable practices within the healthcare sector. Governments and regulatory bodies can create frameworks that incentivize manufacturers to incorporate CE principles into the design and production of medical imaging equipment (191). One effective approach is the implementation of EPR programs, which require manufacturers to take responsibility for the full lifecycle of their products, including their disposal and recycling. EPR programs encourage manufacturers to design devices that are easier to repair, upgrade, and recycle, ultimately reducing the amount of e-waste generated by the healthcare sector (154,155).

Figure 4 illustrates essential e-waste management strategies vital for alleviating the effects of discarded electronics. EPR mandates that producers be responsible for the complete lifecycle of their products, necessitating their involvement in recycling and disposal management. The Right to Repair policy enables consumers to repair their equipment, thereby prolonging their longevity and minimizing waste. The WEEE Directive in the EU requires enhanced collection and recycling of electronic trash, whereas the Basel Convention governs the transnational transport of hazardous e-waste to avert illicit disposal. RoHS restricts hazardous substances in electronics, improving recycling safety. Numerous nations have enacted National Electronic Recycling Laws, establishing frameworks for responsible management. Deposit-Refund Systems motivate consumers to return equipment for recycling, whereas Take-Back Programs urge manufacturers to assist in the retrieval of obsolete electronics. Collectively, these policies foster sustainable behaviors and assist in alleviating environmental and health hazards linked to e-waste.

In addition to EPR, policymakers can promote the development of e-waste recycling infrastructure specifically tailored to medical devices. Current e-waste recycling facilities are often not equipped to handle the complex materials and components found in radiography equipment, such as rare earth elements and hazardous substances. By investing in specialized recycling centers, governments can ensure that valuable materials are recovered, and toxic substances are safely disposed of. This infrastructure is critical for enabling the widespread recycling of medical imaging devices and reducing the environmental impact of their disposal.

Financial incentives for healthcare organizations that adopt sustainable imaging technologies could further accelerate the transition to a CE (9). For example, tax breaks or subsidies for facilities that purchase energy-efficient or modular radiography equipment could make sustainable options more economically viable. Regulatory bodies could also introduce certification programs for sustainable medical devices, providing healthcare organizations with a clear standard for evaluating the environmental impact of the equipment they purchase (38,192). These policies would not only encourage the development of more sustainable products but also create a market-driven demand for CE practices in healthcare.

Education and awareness

Raising awareness about the environmental impacts of radiography equipment and the benefits of CE practices is crucial for driving change within the healthcare sector (193). Many healthcare professionals and administrators may not be fully aware of the environmental consequences of improper disposal or the long-term benefits of investing in sustainable technologies (50). Education programs aimed at healthcare providers, equipment purchasers, and waste management personnel can help bridge this knowledge gap, promoting more responsible decision-making when it comes to the use, maintenance, and disposal of medical imaging equipment.

Healthcare institutions can incorporate sustainability training into their operational procedures, ensuring that staff understand the importance of proper equipment disposal and the potential for recycling or refurbishing outdated devices (26,61,151). For example, training programs could focus on the environmental risks of e-waste, the availability of take-back programs, and the benefits of opting for refurbished or energy-efficient equipment. By educating staff, hospitals and clinics can reduce their environmental impact and support broader sustainability goals. At the same time, raising public awareness about the importance of sustainability in healthcare can create greater demand for environmentally friendly medical services. As patients and healthcare consumers become more informed about the ecological impact of medical imaging, they may begin to prioritize healthcare providers that adopt sustainable practices. Public awareness campaigns, supported by government agencies or non-profit organizations, can highlight the environmental benefits of CE practices in radiography, encouraging both healthcare providers and patients to advocate for more sustainable healthcare systems.

Limitations of the review

While this review provides a comprehensive overview of CE practices in radiography, several limitations should be acknowledged:

(I) Scope and focus: this review primarily focuses on radiographic imaging equipment such as X-ray, CT, and MRI machines, potentially underrepresenting other medical imaging modalities [e.g., ultrasound, positron emission tomography (PET), nuclear medicine] that also have sustainability implications. As such, broader conclusions may not fully apply to all imaging technologies within radiology.

(II) Publication bias: the review relied predominantly on peer-reviewed literature published between 2018 and 2024 from indexed databases such as PubMed, Scopus, and IEEE Xplore. This may have excluded grey literature, industry reports, or non-English sources that contain relevant insights into CE applications in healthcare technology.

(III) Limited empirical data: much of the evidence cited is drawn from conceptual frameworks, literature reviews, and case studies rather than large-scale empirical studies or longitudinal data. As such, the real-world effectiveness and long-term environmental benefits of CE initiatives in radiography remain underexplored.

(IV) Variability across regions: the adoption of sustainable radiography practices varies widely by region, depending on regulatory environments, economic capacity, and healthcare infrastructure. The review includes both high-income and low-resource settings, but regional disparities in recycling infrastructure, refurbishment policies, and access to sustainable materials may limit the generalisability of the findings.

(V) Rapid technological change: the fast pace of innovation in medical imaging, especially in AI integration, energy efficiency, and modular design, means that some technologies discussed may evolve or become obsolete quickly. Therefore, the review may not fully capture future-oriented developments or the latest pilot projects launched beyond the search timeframe.

(VI) Assumptions in thematic analysis: the thematic synthesis of findings into categories such as environmental impact, sustainable design, and regulatory challenges was based on interpretive analysis. Although care was taken to ensure transparency and coherence, subjective judgement may have influenced the categorisation and emphasis of certain themes.

Despite these limitations, the review offers valuable insights and highlights pressing areas for further research, policy development, and industry engagement in promoting sustainability in radiography.

Practical call to action—priority roadmap for 2025–2030

The transition toward CE principles in radiography requires a phased approach with clear milestones and coordinated action across multiple stakeholders. This roadmap provides a structured pathway for achieving meaningful environmental impact whilst maintaining the highest standards of patient care and diagnostic quality. The implementation strategy recognises that sustainable transformation in healthcare cannot occur overnight but requires systematic change supported by evidence-based practices and stakeholder commitment.

Years 1–2: foundation building (2025–2026)

Immediate priorities include establishing manufacturer take-back programmes for end-of-life equipment, implementing energy-efficient imaging protocols targeting 20% departmental energy reduction, and developing partnerships with certified medical device recycling facilities. Regulatory bodies must create guidance documents for sustainable practices, whilst healthcare facilities begin staff training on CE principles. These foundational interventions can achieve 25–30% energy savings within the first implementation year.

Years 3–4: scaling implementation (2027–2028)

This phase focuses on launching modular equipment design partnerships, establishing regional refurbishment centres meeting ISO 13485 standards, and implementing EPR legislation. Healthcare professional training programmes must integrate CE competencies into continuing education requirements. Regional consortiums should be formed to achieve economies of scale for smaller institutions, particularly for specialised recycling infrastructure.

Year 5: systemic transformation (2029–2030)

The final phase targets 50% of new equipment purchases meeting circular design criteria through procurement frameworks prioritising lifecycle performance over initial costs. Comprehensive LCA requirements should be mandatory for all imaging equipment purchases, supported by international standards for sustainable medical imaging practices. The goal is achieving 40% carbon footprint reduction compared to 2024 baseline through coordinated implementation of all roadmap elements.

This transformation requires coordinated action: policymakers establishing supportive regulatory frameworks, manufacturers investing in sustainable design and take-back programmes, and healthcare providers adopting circular procurement practices. Success depends on sustained multi-stakeholder commitment to creating more resilient, efficient healthcare imaging systems that serve both planetary and patient health objectives.

Conclusions

The CE offers a compelling solution to the environmental challenges posed by radiography, providing a pathway toward more sustainable medical imaging practices. Through the design of energy-efficient, modular, and recyclable equipment, the healthcare industry can reduce its reliance on finite resources, lower energy consumption, and minimize waste generation. Quantitative evidence demonstrates that implementing CE principles can reduce the carbon footprint of radiography departments by 35–55% whilst maintaining or improving diagnostic quality and patient safety outcomes.

Despite the clear benefits of adopting CE principles, several barriers must be addressed to facilitate widespread implementation. Regulatory frameworks need to evolve to accommodate the use of sustainable materials whilst maintaining the highest safety standards, a balance successfully achieved by leading healthcare systems as demonstrated in our case study examples. Economic challenges also present obstacles, as the upfront costs of sustainable innovations may deter manufacturers and healthcare organizations from investing in long-term sustainability. Additionally, the lack of specialized infrastructure for recycling and refurbishing medical imaging equipment hampers progress toward a more circular model.

However, overcoming these challenges is possible through continued innovation, policy reform, and collaboration between key stakeholders, including manufacturers, healthcare providers, and regulatory bodies. By advancing research in sustainable materials and modular design, developing policies that incentive circular practices, and raising awareness within the healthcare sector, the industry can move closer to achieving a sustainable future for radiography.

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