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Systematic Review

Considerations for environmental sustainability in clinical radiology and radiotherapy practice: A systematic literature review and recommendations for a greener practice

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ABSTRACT

Introduction: Environmental sustainability (ES) in healthcare is an important current challenge in the wider context of reducing the environmental impacts of human activity. Identifying key routes to making clinical radiology and radiotherapy (CRR) practice more environmentally sustainable will provide a framework for delivering greener clinical services. This study sought to explore and integrate current evidence regarding ES in CRR departments, to provide a comprehensive guide for greener practice, education, and research.
Methods: A systematic literature search and review of studies of diverse evidence including qualitative, quantitative, and mixed methods approach was completed across six databases. The Preferred Reporting Items for Systematic Review and Meta-Analysis (PRISMA) guidelines and the Quality Assessment Tool for Studies with Diverse Designs (QATSDD) was used to assess the included studies. A result-based convergent data synthesis approach was employed to integrate the study findings.
Results: A total of 162 articles were identified. After applying a predefined exclusion criterion, fourteen articles were eligible. Three themes emerged as potentially important areas of CRR practice that contribute to environmental footprint: energy consumption and data storage practices; usage of clinical consumables and waste management practices; and CRR activities related to staff and patient travel.
Conclusions: Key components of CRR practice that influence environmental impact were identified, which could serve as a framework for exploring greener practice interventions. Widening the scope of research, education and awareness is imperative to providing a holistic appreciation of the environmental burden of healthcare.
Implications for practice: Encouraging eco-friendly travelling options, leveraging artificial Intelligence (AI) and CRR specific policies to optimise utilisation of resources such as energy and radiopharmaceuticals are recommended for a greener practice.

Introduction

Climate change is of great concern globally due to its negative impact on public health[1–3] and wellbeing.[4] Anthropogenic climate change has become a global health threat, reported as a key indicator of health disparities, consequently, undermining efforts targeted at keeping individuals and populations' health.[4,5] The healthcare sector

Abbreviations: ES, Environmental Sustainability; CT, Computed Tomography; CRR, Clinical Radiology and Radiotherapy; MRI, Magnetic Resonance Imaging; PACS, Picture Archiving and Communication Systems; AI, Artificial Intelligence; IR, Interventional Radiology.

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generates about 4 million tonnes of waste annually worldwide, with most contributing to environmental pollution.[6,7] Recent evidence suggests that the environmental carbon footprint resulting from healthcare is significant[8,9] with approximately 10% of these attributed to clinical radiology and radiotherapy (CRR) waste, mainly from interventional procedures. A recognition of the contribution of healthcare to carbon emissions and other environmental costs, has led to a focus on reducing the environmental impact emanating from clinical service provision[9,10] by government bodies.[11,12]

CRR are central to modern medical practice for both disease diagnosis and management. However, their operations have been identified as major contributors to the sector's eco-footprint[9] and these have recently gained much attention as highlighted by a growing number of professional bodies, including the Intergovernmental Panel on Climate Change, Institute of Physics and Engineering in Medicine and the Radiotherapy Board.[13,14] These stem from the huge energy consumption by energy-intensive equipment systems,[15,16] large-data generation and storage,[17] radiotherapy treatment activities,[18] vehicular/air travel by service providers and users[19] and waste from clinical consumables such as gloves, single-use gowns, and radiopharmaceuticals.[10] In addition, emerging evidence highlighted increasing contamination of aquatic environments with radiological contrast media waste[10,20,21] mainly from the increased use of contrast-enhanced Computed Tomography (CT) and Magnetic Resonance Imaging (MRI) over the recent past decade. Although the toxicological effects of imaging contrast agents and radiopharmaceuticals from nuclear medicine and radiotherapy remain unclear,[22,23] some studies have shown that the transformed by-products of these agents persist overtime[24,25] and are potentially toxic to the ecosystem.[21,26–28]

As awareness of the contribution of the healthcare industry to climate change grows,[29–31] practitioners are encouraged to engage in sustainable, innovative, and greener CRR practices.[22–36] Given the diversified nature of CRR practice and the unique combination of resources for the efficient operation of departments, the corresponding eco-footprint might vary significantly across departments and sub-specialties globally. Thus, identifying key routes to reducing the carbon footprint and waste production across CRR is critical to promoting greener practice in healthcare. This study aims to systematically explore and integrate current evidence relating to considerations for environmental sustainability (ES) in CRR practice to provide a comprehensive guide for greener clinical practice, education, and research.

Methods

A systematic literature review of studies of diverse types of evidence, including qualitative, quantitative, and mixed methods approaches, was employed.[37] Seven key principles[38] underpinned this systematic review approach, including *transparency, clarity, integration, focus, equality, accessibility and coverage* to reduce selection, publication, and data extraction biases.[39] In addition, the Preferred Reporting Items for Systematic Review and Meta-Analysis (PRISMA) guidelines[40] was adopted and used in summarising the results from the literature search.

Inclusion & exclusion criteria

Peer reviewed primary studies published in English that explored concerns relating to ES issues in CRR practice were included. Thus, studies with similar goals as the current study were included, as recommended by Hornberger and Rangu.[41] Unpublished related research (i.e., abstracts, conference proceedings), literature reviews, opinion reports, editorials, grey literature, and studies outside the CRR domains were excluded.

Databases & search strategy

A systematic search strategy was adopted and refined together with an expert librarian to identify studies in each predefined database. The following databases: Science Direct, PubMed, Cumulative Index of Nursing and Allied Health Literature (CINAHL), SCOPUS, Medline, and Academic ultimate were searched for relevant articles. Medical Subject Headings (MeSH) were employed to identify and develop keywords for the literature search. The Boolean operators AND/OR/NOT were used together with the MeSH/keywords (sustainability, environment, medical imaging, radiotherapy, radiation oncology, radiology, diagnostic radiography, contrast, ecological footprints, greenhouse gas, climate change, lead hazards) for the literature search (Supplementary Table S1). To ensure coverage of all variations of related keywords, truncations/wildcards and symbols (***/?**) were employed. This approach helped to increase the sensitivity of the search across the selected databases. In keeping with good search practice,[41–43] a record of the search activities was documented.

An additional search was conducted manually on Google scholar for relevant publications. To ensure that no relevant research evidence was omitted, the reference lists of relevant literature were hand-searched for other published works on the subject. The literature search was initiated from July 2022 to August 2022 and updated in May 2023 for completeness.

Selection strategy & data extraction

The obtained articles were then exported to Mendeley (Elsevier, Netherlands) and duplicates were removed. Owing to the diverse nature of the study designs of the included studies, the Quality Assessment Tool for Studies with Diverse Designs (QATSDD)[42,43] was employed to assess the quality of the included studies and a score was computed. As done previously,[43] studies were categorised based on the scores as *high quality* if an aggregate score above 70% is achieved, *moderate quality* for those scoring between 50 and 70%, and *low quality* for those scored less than 50%. The aggregate quality scores were not a part of the article exclusion criteria. A data extraction template (see Table 1) with provisions for the following information: authors, year of publication, country/study setting, research discipline, aim of study, method/study design, key findings, and conclusions was used for the data extraction exercise. Briefly, the data extraction was first done by two authors (MNKA and WE) and was reconciled by the senior investigator (TNA) where necessary and generally in a consensus meeting with the research team.

Data analysis & synthesis

A result-based convergent data synthesis approach[53,54] was employed to integrate the findings from myriad studies for independent analyses and tabulation. This involves independently synthesising studies of similar designs and then integrating findings with all other included studies. A narrative synthesis[37,55] was then employed to integrate the independent data obtained from the literature search. The synthesis was a line-by-line review of the content of each study included, as suggested[37] and done previously.[43] The evaluative comments were labelled and integrated into a table of items and the commonly occurring items were then themed.

Results

The search returned 78 journal articles from the following databases: SCOPUS (n = 11), ScienceDirect (n = 22), Medline (n = 15), CINAHL (n = 23), Academic Ultimate (n = 7). Additional articles were identified through hand searching Google Scholar and other sources including relevant article reference lists (n = 17) (Fig. 1). After title and abstract screening, 19 articles were retained. Of these, 14 articles met the predefined study eligibility criteria (Table 1). The reasons for article exclusion are summarised in Fig. 1. All the included studies focused on activities relating to clinical radiology, with only one specifically focused on radiotherapy/radiation oncology (Table 1).

In relation to geographical distribution, half (n = 7, 50%) of the eligible studies were conducted in Europe, 42.86% (n = 6) from North America and the rest, 7.14% (n = 1) from Australia (Table 1). This suggests a continental imbalance in terms of ES research across the CRR domains. Similarly, the majority [n = 10 (71.43%)] of the studies focused on energy and the corresponding carbon cost, and [n = 2 (14.29%)] on travel and the rest [n = 2 (14.29%)] on consumables such as contrast and materials used in interventional radiology, thus, suggesting the need for attention on the other areas of practice of critical sustainability concern.

The quality evaluation and the assessment scoring of the included articles ranged from intermediate (61.90%) to high (100%), with an overall average quality score of 81.54% to indicate overall high quality (Supplementary Table S2).

Three broad themes emerged from the narrative synthesis: namely, Theme 1: energy consumption and data storage practices, Theme 2: usage of clinical consumables and waste management practices and Theme 3: travel activities related to CRR.

Discussion

This review explored the current ES considerations in CRR for greener practice. Key themes that emerged from the findings relate principally to energy consumption due to CRR equipment operations, use of clinical consumables and waste management, as well as related travel activities by both healthcare professionals and patients for their care management procedures and discussed.

Theme 1: Energy consumption and data storage practices

The normal energy consumption across radiology departments relate to energy-intensive equipment for diagnostic image acquisition and storage as well as a large number of relatively lower energy devices such as workstations for clinical reporting. The Canadian Coalition of Green Health reported on typical energy consumption per imaging equipment as follows: MRI-111000 kWh/yr, CT-41000 kWh/yr X-ray-9500 kWh/yr, ultrasound-760 kWh/yr.[31] Of all the imaging modalities, the magnitude of energy consumption appeared to be substantially high for MRI and then CT.

In line with these figures, Heye and colleagues[46] found the mean MRI energy consumption per year in the system-on state to be 82,174 kWh per MRI examination and 134,037 kWh for total consumption in their study. By comparison, they reported the total energy consumption of one CT scanner to be 26,226 kWh/yr. A particular concern is the energy waste associated with inefficient practice. For example, 2/3rds of the overall CT energy consumption emanated from energy consumed during the non-productive idle-state whereas, with MRI 1/3 of the consumption resulted from consumption during the system-off state owing to the need for helium cooling and cooling head operations.[46] Thus, suggesting the potential for significant energy savings during the idle state of imaging systems.

These studies provide a preliminary framework for comparing the potential environmental impact of various imaging modalities. Notwithstanding, modality-specific energy consumption trends reported[46] are consistent with the findings of the pilot study by Martin and colleagues[48] on the environmental impact of abdominal imaging involving ultrasound, CT and MRI. The equipment life cycle assessment[48] demonstrated that the energy consumption of MRI is highest followed by CT with the corresponding carbon footprint following a similar trend in magnitude.[50,51] This implies that energy consumption and the corresponding CO_2 emission varies with the type of imaging modality such that the higher the energy consumed the greater the CO_2 emission and the potential environmental impact. Similar observations were made by Marwick and Buonocore[56] in their study focused on cardiac imaging.

With regards to other equipment-related energy consumptions such as workstations, Hainc et al.[20] reported an overall normal energy consumption of 32 radiology workstations to be 53,170 KWh/yr. Although, the energy consumption by workstations and monitors may be considered insignificant compared to other imaging devices, there is potential for waste during out of hours when the systems are left on while unused. For example, evidence shows that turning off workstations after core working hours reduced total energy consumption by about 5.6%, corresponding to an extrapolated saving of 3.2 tons in CO_2 emissions.[6]

In CRR departments across varied settings, huge energy losses are reported during out of hours' periods (Table 1). Energy wastage was estimated in four independent Irish CRR departments and this ranged between 6656 KWh and 27,452 KWh per year.[44] Of note, these relate to energy consumption associated with ancillary devices and observable lighting of the department during out of hours periods. It was therefore concluded that Irish radiology departments were energy inefficient, with recommendations to suggest the overarching role of radiographers in ensuring ES via energy efficiency[44,57] which, including employing optimised technical imaging approaches that require relatively lower energy consumption. Energy wastage in CRR departments is mostly associated with ancillary equipment, lights, workstations, PACS left on when the departments are closed. McCarthy and colleagues[57] reported in their observational study that at one point 67.4% and 92.6% of desktops and PACS reporting workstations were left switched on after the radiology department had closed. These revelations are indicative of poor attention to energy sustainability and its environmental and economic repercussions and more importantly, represent huge opportunities for greening radiology and radiotherapy practice.

In radiotherapy, the linear particle accelerators (LINACs) use significant energy during treatment procedures resulting in high carbon emissions.[58,49] Shenker et al.[49] reported estimates of CO_2 emissions from four most common cancer treatment procedures using LINAC-external beam radiotherapy treatment (EBRT). The corresponding CO_2 emissions per case ranked in order of magnitude from highest to lowest were: conventional treatment for prostate cancer (17.34 kg CO_2), conventional EBRT for lung cancer (14.42 kg CO_2), long-course rectal cancer (11.32 kg CO_2), and 15-fx breast cancer (7.19 kg CO_2), respectively, to suggest that the amount of power consumption and the corresponding carbon footprint may be related to the type of examination/treatment procedure.[49] This also implies that power consumption in radiotherapy may also be significant compared to high energy-consuming diagnostic imaging technologies and might amount to far reaching environmental consequences.

CRR practices involve the generation of large data, most of which require secure storage for clinical management. Radiological data generation and storage contributes to the ecological footprint of CRR due to energy usage.[17] Unfortunately, radiological data storage is largely disregarded when assessing the environmental impact of radiology.[17] The environmental repercussions of radiological data management stems from energy consumption in data transfer and storage (this includes redundant and duplicate data)

Table 1
Details of relevant primary articles included for the study.

Article No.	Study Reference & Journal	Methods				Study aim(s)	Study outcomes		Study quality Grading
		Country/Continent of study	Sample/Study area characteristics	Study design & analysis approach	Study period & duration or operational details of centres		Key findings	Key conclusions	
1	Yakar & Kwee 2020[19] European Journal of Radiology	USA, North America	Total number (n) of Radiologists per State: California (n = 1426), New York (n = 1.066), Texas (n = 879), Florida (n = 771), Pennsylvania (n = 640) Online survey Total sample size (n = 4782)	Quantitative research design. Quantitative analysis	26 Nov.–1 Dec. 2017	To ascertain the airplane travel-related carbon footprint of the Radiological Society of North America (RSNA) yearly meeting, the associated health burden, and the costs to offset these greenhouse gas emissions (i.e., compensation of emissions by funding an equivalent Carbon dioxide saving).	The estimated airplane travel-related CO_2-equivalent emissions of 11,223 attendees from the USA and 10,684 from other nations were 7,067,618 kg and 32,438,420 kg, totalling 39,506,038 kg. This caused an estimated 51.4–79.0 DALYs. The calculated amount of Total CO_2 offset costs were calculated to be $474,072, which corresponds to $6001–9223 per DALY averted	The airplane travel-related carbon footprint of the RSNA yearly meeting and the associated health burden are substantial, hence, stakeholders should take measures to overcome this undesired side effect. Offsetting this carbon footprint is cost-effective and this initiative should be taken by the radiological community	High
2	Burke & Stowe 2015[44] Radiography	Republic of Ireland, Europe	Radiography departments (n = 4)	Out-of-hours-end-use energy Surveys Quantitative analysis approach	Data collection took place on Friday evenings but duration variable and not indicated.	To present an Irish perspective of radiology energy efficiency and more specifically the radiography department- a department primarily staffed by radiographers.	A range of equipment: desktop and workstation display, computers and CR plate readers are left on in closed departments. Lighting is not powered off in radiography departments, notably within X-ray suites and changing rooms. Estimated annual savings in individual radiography departments ranges from 6656 kWh to 27,542 kWh and V1095.58-V4533.41 (£865.50 e £3581.39).	Irish radiography departments are energy inefficient and radiographers, as the key staffers, have a role in promoting improved radiology energy efficiency. This study focused on radiography departments, but improvements are also likely to be attainable in the wider hospital.	Intermediate

3	Büttner et al. 2021[6] European Journal of Radiology	Germany, Europe	Radiology workstations (n = 3)	Quantitative observational design Descriptive statistical analysis.	1 year	To investigate if turning off workstations after core working hours can reduce energy consumption in light of both ecological and economical aspects	Turning off workstations after core working hours decreased energy consumption by approximately 5.6%, corresponding to an extrapolated savings of 3.2 tons in carbon dioxide (CO_2) emissions and 2100.70 USD/year in electricity costs for 227 workstations. Theoretical computations show that consistent auto-shutdown after core working hours could potentially reduce total energy consumption by 38.6%, equalling 22.2 tons of CO_2 and 14,388.28 USD/year. However, staff costs resulting from waiting times after manually restarting workstations would amount to 36,280.02 USD/year	Turning off workstations after core working hours can decrease energy consumption and costs but varies with user adherence. Costs by waiting time after manually starting up workstations is greater than energy savings by far. Thus, an energy-saving approach with auto-shutdown/restart apart from enabling an energy-saving mode would be the most beneficial.	High
4	Chua et al. 2021[7] Journal of Vascular and Interventional Radiology	USA, North America	An Interventional Radiology (IR) department at a tertiary care medical centre. Number of IR procedures during the study period (n = 98)	Prospective and retrospective design. Quantitative analysis using life cycle assessment (LCA) approach	19–25 June 2019 5 consecutive working days between 7:00 AM and 7:00 PM each day	To compute the volume of GHG produced by a hospital-based interventional radiology department (IR).	98 IR procedures were performed on 97 patients with drainages being (30), placement and removal of venous access (21), and CT guided biopsy (13). Carbon footprint estimated during the procedure was 23,500 kg CO_2e. Sources of CO_2 emissions in descending order: are indoor climate control (11,600 kg CO_2e), production and transportation of disposable surgical materials (9640 kg CO_2e), electrical plug load	The practice of IR produces significant amount of GHS, a majority of which come from energy used for climate control followed by emissions related to the production and transportation of single use supplies. Efforts to reduce energy consumption and the use of disposable supplies may decrease GHG emissions and IR's contribution to climate change	High

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Table 1 (*continued*)

Article No.	Study Reference & Journal	Methods				Study aim(s)	Study outcomes		Study quality Grading
		Country/Continent of study	Sample/Study area characteristics	Study design & analysis approach	Study period & duration or operational details of centres		Key findings	Key conclusions	
							for radiography, non-Imaging, and lighting equipment (1060 kg CO_2e), staff transportation (524 kg CO_2e), waste disposal (426 kg CO_2e), production and laundering of linens (279 kg CO_2e), and gas anaesthetics (19.3 kg CO_2e).		
5	Dekker et al. 2022[10] Insights into imaging	Netherlands, Europe	Rhine River at Lobith: Germany–Netherlands. Number of observations per contrast agent: Iopamerol = 13 Iopromide = 13 Iopamidol = 13 Diatrizoic acid = 13 Iohexol = 13	Retrospective design. Trend analysis using quantitative data analysis	2010–2019 Total duration = 9 years	To make health professionals aware of the opportunity to take the lead now in more conscious decisions concerning use of contrast media (CM) and overview of the different perspectives for action	Statistical analysis of the trend of the CM concentrations between 2010 and 2019 at the German-Dutch border crossing indicates that the load of Diatrizoic acid reduced with 2.7% per annum, while Iohexol increased by 3.1% and Iopromide by 2.4%. The load of Iomeprol and Iopamidol did not show a significant trend. The reason for the decrease for Diatrizoic acid is anchored in the fact that this oral CM is in the process of being phased out as water or barium-sulphate is now preferred.	Although, CMs have an inherently low toxicity, it is however, evident that their transformed by-products in wastewater or treatment plants may pose problems to the water ecosystem. To tackle the problem of CM in the water system holistically, it is necessary for all parties involved to cooperate, from the producer of CM to the consumer of drinking water.	Intermediate
6	Gendy et al. 2022[45] Journal of Clinical Radiology	United Kingdom, Europe	25 questions administered to all Radiology staff at Merseyside and few other regions in the UK. 242 responses received.	Online survey (mixed method). Mixed method data analysis	Not indicated	To assess attitudes towards the climate change among radiology staff and to identify present practices that may impact the National Health Service (NHS) net zero target.	242 responses received from respondents. The analysis shows elevated levels of worry about the climate emergency among the respondents. Active travel accounts for	There is huge potential for reducing the carbon footprint of radiology services by reducing travel, both for work and for radiology education. The potential for large	High

							a small proportion of commuting related to provision of radiological services. Some energy-saving approaches are implemented generally in radiology departments, but these are likely to account for only a small proportion of energy use within a department	savings related to energy-saving measures were discussed.	
7	Hainc et al. 2019[20] Journal of Academic Radiology	Switzerland, Europe	radiology workstations (n = 36)	Experimental research design Quantitative analysis	194 days	To quantify the power consumption of reporting workstations in a radiology department and to consider a hypothetical scenario to reduce energy waste.	The overall power consumption of 32 reporting stations out of 36 was 53,170 kWh/a, equivalent to 12 family households (4500 kWh/a per household in Switzerland in 2014) or 97.2 barrels of oil. Three main power consumption patterns of the reporting stations were identified: mainly off, mainly on, and always off. The on-mode consumption per annum was 40,763 kWh/a, the stand-by consumption was 10,010 kWh/a, and the off-mode consumption was 2397 kWh/a. The reporting stations spent half of their on-mode time awaiting the initiation of stand-by, resulting in a wait-time consumption of 18,243 kWh/a. The hypothetical scenario, achieved an energy saving of 23,692 kWh/a, a	The power consumption of the reporting stations is not negligible. Reducing energy waste in the radiology department is attainable via simple changes in device configuration which will simultaneously promote energy-wise habits.	High

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Table 1 (*continued*)

Article No.	Study Reference & Journal	Methods				Study aim(s)	Study outcomes		Study quality Grading
		Country/Continent of study	Sample/Study area characteristics	Study design & analysis approach	Study period & duration or operational details of centres		Key findings	Key conclusions	
							reduction of about 45% of the initial energy consumption, equivalent to 5 households or 40.8 barrels of oil consumed		
8	Heye et al. 2020[46] Health Policy and Practice	Switzerland, Europe	Imaging modalities (CT, n = 3; MRI, n = 4) and cooling systems (unspecified number) in a Radiology department of a University Hospital	Quantitative research design Quantitative data analysis	2015 (1 year)	To measure the energy consumption of CT and MRI scanners in a university hospital radiology department and to estimate energy- and cost-saving potential during clinical operation	The aggregated energy consumption imaging 40,276 patients amounted to 614,825 kWh, dedicated cooling systems to 492,624 kWh, representing 44.5% of the combined consumption of 1,107,450 kWh (at a cost of U.S. $199,341). This is equivalent to the usage in a town of 852 people constituting 4.0% of the total yearly energy consumption at the authors' hospital	CT and MRI energy consumption is considerably high. However, there is considerable energy and cost saving opportunities during non-productive hours. Realization of this could potentially reduce cost while increasing energy efficiency.	High
9	McAlister et al. 2022[47] The Lancet Regional Health-Western Pacific	Australia, Australia	Two Australian University-Affiliated Health services. Imaging modalities considered (CT, US, CXR, MCXR, MRI) [(n = 5)]	Prospective quantitative design. Process-based attributional and consequential life cycle assessment analysis	10 February 2021 –30 August 2021	To estimate the carbon footprints of diagnostic imaging at 2 University-affiliated hospitals	Average CO_2e emissions: 17¢5 kg/scan for MRI; 9¢2 kg/scan for CT; 0¢8 kg/scan for CXR; 0¢5 kg/scan for MCXR; and 0¢5 kg/scan for US. Emissions from scanners in standby mode were significant. When expressed as emissions per additional scan impacts were lower: 1¢1 kg/scan for MRI; 1¢1 kg/scan for CT; 0¢6 kg/scan for CXR; 0¢	Stakeholders can reduce carbon emissions from diagnostic imaging, firstly by reducing the request of unnecessary examinations, or by ordering low-impact imaging (X-ray and US) in place of high-impact MRI and CT when clinically suitable. Secondly, whenever possible, scanners should be switched off to reduce emissions from standby	High

							1 kg/scan for MCXR; and 0¢1 kg/ scan for US, due to emissions from standby power being excluded	power. Thirdly, ensuring high utilisation rates for scanners both reduces the time they spend in standby, and apportions the impacts of the reduced standby power of a greater number of scans. This therefore reduces the impact on any individual scan, maximising resource efficiency.	
10	Martin et al. 2018[48] Journal of the American College of Radiology	USA, North America	Used prototypes of MRI, CT, and Ultrasound equipment at the University of Michigan Medical Centre. Number of imaging equipment (n = 3)	Quantitative study design approach using convenient sampling. Multiparametric analysis using life cycle Assessment (LCA)	24 h	To estimate multifactorial environmental impact of MRI, CT and Ultrasound using streamlined LCA	Ultrasound consumed less energy in both production and use phases (7.8 and 10.3 MJ/ examination, respectively) compared to CT (58.9 and 41.1 MJ/ examination) and MRI (93.2 and 216 MJ/examination). Similarly, Ultrasound emitted less CO_2 equivalents in production and use phases (0.5 and 0.65 kg/ examination) compared to CT (4.0 and 2.61 kg/ examination) or MRI (6.0 and 13.72 kg/ examination). Accordingly, potential human health effects from pollutant emissions were found to be least with ultrasound in both production and use phases.	The environmental impact ranking among the three imaging modalities found ultrasound to have the least environmental impact, by one or more orders of scale in various domains. Essentially, this analysis provides a preliminary framework for comparing environmental impacts across imaging modalities, which may provide useful inputs for cost-effectiveness analyses and policymaking	High
11	Shenker et al. 2022[49] Advances in Radiation Oncology	USA, North America	Identified patients with the 4 most common cancer types treated with External Beam	Power in kilowatt per hour (kWh) converted to CO_2 equivalence.	January 2021 to June 2022	To estimate the CO_2 emission associated with energy usage from linear accelerator	From the study, carbon emissions per course, on average, in order of magnitude ranging	In conclusion, “Standby” mode of a LINAC according to the findings uses the most energy	High

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Table 1 (*continued*)

Article No.	Study Reference & Journal	Methods				Study aim(s)	Study outcomes		Study quality Grading
		Country/Continent of study	Sample/Study area characteristics	Study design & analysis approach	Study period & duration or operational details of centres		Key findings	Key conclusions	
			Radiotherapy Treatment (EBRT), Carbon footprint for this treatment was calculated using the US' Environmental Protection Agency GHG equivalencies calculator.			(LINAC)-EBRT for most common cancers.	from lowest to highest was prostate SBRT (2.18 kg CO_2; interquartile range, 1.92–2.30) and conventional treatment for prostate cancer (17.34 kg CO_2; interquartile range, 10.26–23.79); corresponding to CO_2-equivalent emissions of driving an average of 5.4 miles and 41.2 miles in a standard vehicle, respectively. Additionally, "Standby" mode for a LINAC TrueBeam and Clinac IX uses 112 kWh and 64.8 kWh per day, respectively.	per day. However, comprehensive research are warranted to reduce the environmental impact of health and cancer care.	
12	Brown et al. 2023[50] Canadian Association of Radiologists' Journal	Canada, North America	Assess the energy and cost saving in CT when shutdown overnight and Sundays compared to when left on for the same period.	Quantitative design approach.	9 Weeks (April–June 2022)	To evaluate energy and cost savings associated with a CT scanner when shutdown overnight during non-operational hours compared with when the CT scanner is left on or partially shutdown.	Shutting down the CT system overnight and Sunday compared to system ON mode has shown to save approximately 14,000 kWh over one year with a 95% confidence interval of (13,899 kWh, 14,464 kWh) as computed by the electrical power provider.	In conclusion, Energy consumed by a CT scanner can be significantly reduced via system shutdown when the unit is non-operational, saving emissions and cost. Additionally, with respect to cost and energy savings, this study emphasises the relevance of clinician leadership in convening interdisciplinary teams outside of usual healthcare silos to rethink how we purposefully use energy and reduce waste.	High

13	Woolen et al. 2023[51] Radiology	North America	The study involved four 3 T MRI units	Numerical Power readings were collected with power meter and power monitoring software	Duration of data collection: 29th September 2022—1st November 2022 and 13th—17th January 2023	The study evaluated the power and energy consumptions of the MRI systems.	Projected energy consumption per annum per scanner ranged from 82.7 to 171.1 MW-hours, with 72%—91% defined as non-productive. Turning off the MRI unit overnight for 12 h during unproductive hours yields energy savings of 25%—33% and the power save mode also reduces consumption by 22%—28% compared to the off mode.	Turning off MRI units made radiology departments more energy efficient and showed huge sustainability and cost benefits.	High
14	de Reeder et al. 2023[52] CVIR Endovascular	Netherlands, Europe	Survey was distributed to 272 IR members. 83.7% of the respondents indicate awareness of the negative impact of IR services on the environment	A mixed method approach: Used surveys and interviews among interventional radiologists. Thematic analysis was done	Each interview lasted 24—37 min.	The study explored the current state of sustainability within Interventional Radiologists specialists in the Netherlands	The study shows that there is awareness of sustainability and willingness to be sustainable however, there is no action, lack of leadership and sustainability not priority.	Despite the existence of barriers, IR departments can implement several improvements. An important factor is that sustainability should not lead to inconvenience for employees, which can be ensured by an adequately designed waste infrastructure and behavioural changes. Additionally, there is an opportunity for more collaboration between IR departments in knowledge sharing and open innovation towards sustainability.	High

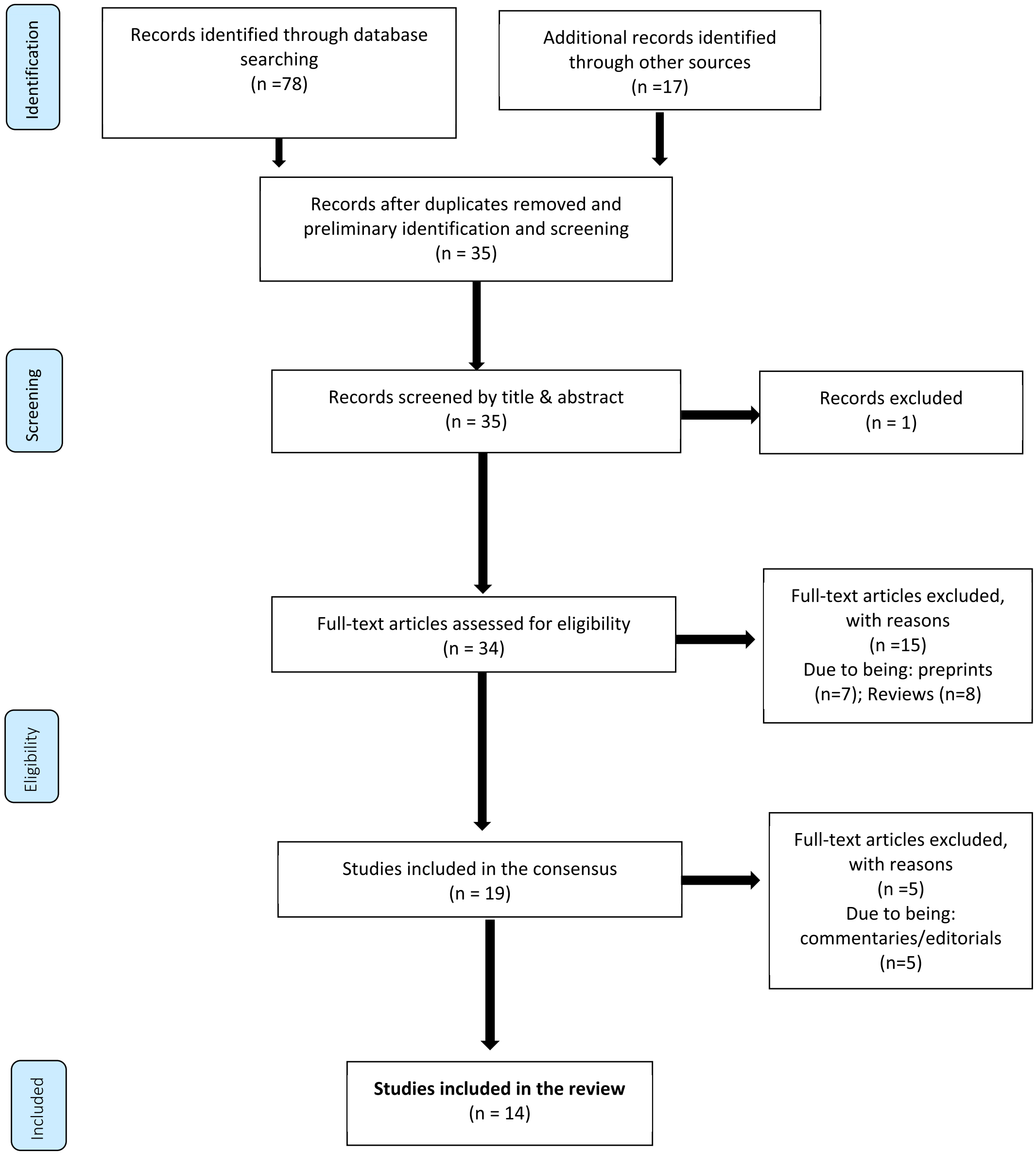

Figure 1. PRISMA flow diagram – search strategy.

and management of cooling systems for servers which account for approximately 86% of energy transmitted to radiology departments.[17,59] Additionally, radiological data centres consume high volumes of water, and recent estimates indicate that about 626 billion gallons of water per annum is consumed for operations.[59] The estimates are projected to increase with the increasing adoption and dominance of artificial intelligence (AI) applications in CRR[57,60–62] which have a high computational load.[63,60–62]

Theme 2: Usage of clinical consumables and waste management practices

Environmental pollutants in this context relate to compounds released into the ecosystem, which threaten the health of living things.[64] Approximately 10% of the total carbon emissions are attributed to the healthcare sector, of these, a large proportion is attributed to CRR due to waste from interventional procedures (IR) and the operation of high energy intensity equipment.[7,31,64] Woolen and colleagues[31] attributed this to the high number of short procedures involving primarily high volume of single-use products including syringes, coils, wires, catheters, sheaths, multiple ancillary devices, sterile drapes and towels. An audit of greenhouse gas in an IR department over a 5-day period observed a minimum carbon emission estimate to be 23,500 kg CO_2.[7]

Similar reports from Germany and Australia showed that the carbon footprint of CRR practice is substantial, thus, further highlighting the considerable contributions of CRR to the environmental footprints.[6,47] In radiotherapy, thermoplastic shells are used, most of which are biodegradable.[58] However, the mould rooms use lots of plastics and non-degradable materials. In low-income countries, cobalt-60 radiotherapy systems are more common.[65] Though meant to be a 'greener' source of energy, the disposal of radioactive and nuclear medicine waste/pollution is much a challenge.

The potential ecotoxicology of radiopharmaceuticals such as iodinated contrast agents and gadolinium-based contrast agents has attracted scrutiny in recent times, owing to the nonselective treatment of water.[66] The increasing pollution of the aquatic environment by radiopharmaceuticals is attributed to the increasing number of contrast-enhanced radiological procedures performed globally over the past two decades.[10] Contamination of water sources from radiopharmaceuticals used in CRR is concerning as these chemicals end up in water bodies via patients voiding post examination. Dekker and colleagues[10] reported increasing contamination of water sources by iodinated contrast media. Similarly, Hofmann and Brünjes reported high concentrations of gadolinium contrast medium in various water sources.[24] The potentially toxic nature of the by-products of the transformed elements of these agents is a critical concern due to depletion of aquatic ecosystems and the increasing cost of freshwater treatment.[24,26,67] Globally, approximately 300 million CT examinations are performed annually, involving an estimated volume of 10 million litres of iodinated contrast media (ICM) agents.[68] These ICM agents end up in the aquatic ecosystem and finally in drinking water.[10] Of note, urgent and critical sustainable approaches to retrieving ICM and gadolinium post-contrast enhanced radiological examinations are required to preserve the ecosystem, while reducing the cost of water purification and making water safe for human consumption. Preliminary suggestions include patients waiting in CRR departments for their urine to be collected after CM examinations for contrast extraction.[10] Possible challenges would be the cooperation of stakeholders, time, and the additional financial and material resources this would require. Additionally, leftover contrast media could be collected within departments and returned to manufacturers for recycling in accordance with circular economy principles.[69]

Theme 3: Travel activities related to radiology and radiotherapy/radiation oncology

Two studies, from the United Kingdom[45] and North America[19] specifically explored the environmental impact associated with travelling activities related to CRR practice. Even though these studies were undertaken in two different continents and therefore differ in scope, method, and context, they demonstrated similar opportunities to reduce ecological footprint while adopting sustainable and greener travelling options and virtual consultations where possible. Yakar and Kwee[19] investigated the carbon cost emanating from air travel to the Radiological Society of North America (RSNA) conference to be substantial; estimated to be 39,506,038 kg translating into an equivalent cost of $474,072.[16] This implies that, if the conference were to be held remotely via a virtual platform, these carbon costs would have been saved. Similar observations were made by Leochico et al.[70] in their scoping review focused on scientific conferences external to radiology/radiotherapy and recommended the need for climate change awareness creation among stakeholders towards conducting “green and sustainable conferences”.

In the United Kingdom survey by Gendy and colleagues,[45] although 92% of respondents were concerned about the climate emergency crisis, only 23% of the radiology staff use active transport to commute some or all the time for professional and personal activities. Opportunities for use of active travel options could be explored and encouraged including travel schemes, use of electric vehicles, cycle to work schemes should be considered. Additionally, some of the adaptive approaches to healthcare delivery which were employed during the COVID-19 pandemic[43] could be adopted by the CRR community to reduce travel-related environmental impacts. For example, some therapeutic radiographers were completing their contouring assignments remotely[43] and radiologists and reporting radiographers are increasingly working remotely. In relation to patient travel, a UK study[11] has revealed the potential for CO_2 savings from delivering targeted intraoperative radiotherapy (TARGIT) instead of external beam radiotherapy treatment (EBRT) approach which involves travelling several times to the treatment facility. Thus, if TARGIT services are widely available for eligible patients, an estimated 5 million miles of travel corresponding to 1200 tonnes of CO_2 savings per year could be achieved according to the authors.[71] Additionally, smarter patient scheduling options could be employed to support green patient travel options.

Recommendations for greener CRR practice

Possible strategies to deliver ES in CRR practice range from easy-to-implement changes to changes on a larger scale and longer-term requiring a multidisciplinary stakeholder involvement (Fig. 2).[4] As such, championing education and active participation of practitioners, and other stakeholders is imperative to attaining a greener clinical practice.[72]

i. ***Controlled use of resources***: Chawla and colleagues[73] proposed a four-step principle for a greener CRR practice and include less energy and water utilisation, less waste generation, usage of biodegradable materials and proper waste disposal or recycling. Energy efficiency is possible via incorporation of auto-shutdown functions in imaging and their auxiliary equipment.[23,74] Utilising motion-sensitive light and light emitting diodes was suggested as they potentially save about 75% of energy[23,74] compared to incandescent bulbs.[73] Turning off equipment when not in use has proven beneficial in saving power/CO_2 and cost[50,51] and by extension a potent approach to greening CRR practice.[75]

In addition, reduction of unnecessary radiological requests/examinations,[47] proper disposal of waste, implementation of circular economy principles including recycling and reuse of equipment parts, and promotion of paperless CRR practice. Equipment manufacturers and service engineers should adopt remote equipment servicing which promises to be of great benefit as it will save physical travel-related carbon emissions. Another key strategy is embracing the use of AI in CRR systems such as the integration of advanced reconstruction algorithms into new CT scanners to reduce overall energy emission per scanning case and to help eliminate the need for repeat scans.[76–78,61]

ii. ***Periodic performance auditing***: Resource conservation and energy efficiency audits should be conducted periodically within CRR departments to ensure that resource/energy usage is within acceptable predefined limits. By expressing the carbon cost for each CRR procedure, it would be easy to track performance and identify any lapses for implementation of appropriate preventive measures. Similarly, radiopharmaceutical dosages for CRR procedures should be streamlined to ensure that waste is managed efficiently.

iii. ***Policy formulation and formation of ES working groups***: Policy makers and the international CRR community and related professional bodies should incorporate ES in departmental policies and protocols, and to ensure these are enforced. Commitment towards environmental friendliness be reinforced through resource allocation for audits and research. For example, de Reeder and colleagues[52] reported that there is lack of action stemming from lack of leadership and prioritisation of sustainability concerns in clinical radiology practice. Policy formulation and formation of discipline-specific working groups would therefore provide the required leadership to promote the sustainability agenda through creation of new roles such as sustainability leads/champions/ambassadors within CRR departments. Other

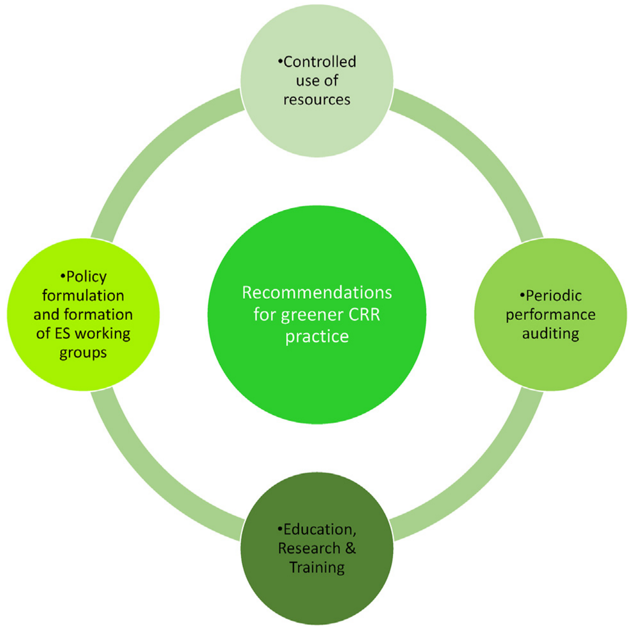

Figure 2. Summary of recommendations for greener CRR practice.

approaches to consider under this recommendation are environmental impact justifications as part of clinical vetting and referrals for CRR procedures as part of the clinical decision making. Additionally, research funding organisations should require ES outcomes from all funded activities to ensure researchers commit to employing imaging techniques of optimal energy intensity, planting trees at the end of their project among others. Finally, the international CRR community may adopt committee-based or working group-based approaches to monitor and ensure that departments within sub-regions across the globe adopt and implement best practices that promote greener practice together with equipment manufacturers.

vi. ***Education, Research, and training***: ES should be incorporated into clinical radiology and radiography education and training curriculum including continuous professional development (CPD) activities to create awareness among the practitioners.[79,80,60] Specialist CPD activities geared towards sustainability behavioural changes, practice reformations will be necessary to increase focus on efficient energy utilisation within departments by all staff. Sustainability in healthcare and its related research activities should be prioritised and supported with specialised funding quota schemes.

Limitations

Only articles published in English were included and thus, we acknowledge the possibility of omitting relevant literature published in other languages. However, findings of key opinion articles and other editorials were included in the discussion to provide completeness of the existing perspectives on the topic. Secondly, no studies were found from some continents (i.e., Africa and Asia), potentially limiting geographic applicability of our findings. Likewise, primary research on radiotherapy-related ES is very limited (only n = 1, included in this study); hence, the ecological contribution of the sub-discipline remains unclear, however, our recommendations are broadly applicable to radiotherapy and other CRR sub-disciplines including nuclear medicine. Reports of the energy sources to CRR operations are limited and future research could focus on this area to provide clarity to greener sourcing of energy.

Conclusion

Healthcare is an important contributor to ecotoxicology and global emissions. The contribution of various sectors within the healthcare value chain differs in scope and quantum, with CRR being considered as a major contributor due to its resource intensiveness and corresponding carbon footprint. The major causes of environmental pollution from CRR include the generation of greenhouse gases resulting from huge energy consumption, travel activities, and waste, including the excretion of by-products of radiopharmaceuticals into the aquatic ecosystem. There are many opportunities to improve the ES of CRR departments, but these have not been widely prioritised due to lack of discipline-specific ES policies, legislations, education, and research. Thus, widening the scope of research and awareness creation is imperative to providing a more holistic and better appreciation of the environmental burden of CRR.

Conflict of interest statement

All authors have no conflicts of interests to declare. Of note, TNA and AH are both members of the editorial board but were blinded to the decision making process.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.radi.2023.09.006.

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