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Sustainable Practices in Diagnostic Imaging: A Systematic Review of Environmental Initiatives and Resource Management in Saudi Radiology Departments

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Abstract: Diagnostic imaging services represent significant contributors to healthcare's environmental footprint through energy consumption, waste generation, and resource utilization. This systematic review examines sustainable practices implemented in Saudi Arabian radiology departments with a focus on environmental initiatives and resource management strategies. Following PRISMA guidelines, comprehensive database searches identified 37 eligible studies published between 2010-2023 that documented sustainable interventions in Saudi radiological settings. The review identified four primary domains of sustainable practice: energy efficiency interventions, waste reduction strategies, water conservation approaches, and resource optimization initiatives. Implementation of Picture Archiving and Communication Systems (PACS) demonstrated significant impacts on environmental sustainability with documented reductions in chemical waste (82-97%), physical storage requirements (94%), and energy utilization (43-71%) across multiple facilities. Energy efficiency interventions, including equipment power management protocols and facility design modifications, achieved energy consumption reductions of 17-35% in participating departments. Waste management strategies incorporating tailored segregation protocols and staff education programs demonstrated reductions in hazardous waste generation of 23-41%. Implementation challenges consistently identified included initial capital requirements, staff resistance to workflow changes, technical integration difficulties, and administrative barriers. The review highlights significant gaps in current research, particularly regarding standardized assessment methodologies, cost-effectiveness evaluations, and studies addressing smaller facilities outside major urban centers. These findings provide a comprehensive evidence base to inform policy development, resource allocation, and future research to advance sustainable radiological practices within Saudi healthcare systems.

1. Introduction

Healthcare delivery systems generate substantial environmental impacts through energy consumption, waste production, resource utilization, and greenhouse gas emissions. Within this sector, diagnostic imaging departments represent particularly resource-intensive operations due to their reliance on sophisticated equipment, chemical processes, specialized materials, and continuous power requirements (Weidman et al., 2020). As healthcare facilities globally face increasing pressure to reduce their environmental footprint while maintaining quality service delivery, sustainable practices in diagnostic imaging have emerged as an important focus area for environmental initiatives and resource management (Gould & Hoyt, 2022).

The healthcare sector in Saudi Arabia has undergone significant expansion and technological advancement in recent decades, with substantial investments in diagnostic imaging capabilities across the Kingdom. This expansion, while enhancing healthcare accessibility and quality, has created corresponding environmental challenges related to energy consumption, waste management, and resource utilization within radiological services (Alsultan et al., 2019). The Saudi Vision 2030 framework, which guides national development efforts, includes sustainability as a core component, with specific goals addressing environmental protection, resource conservation, and sustainable development across sectors, including healthcare (Vision 2030, 2016).

Within this context, radiology departments face unique sustainability challenges stemming from their technological requirements, operational characteristics, and material utilization patterns. Traditional film-based radiography generates chemical waste and requires substantial physical storage space, while advanced imaging modalities such as computed tomography (CT) and magnetic resonance imaging (MRI) have significant energy consumption profiles (Chua et al., 2021). Additionally, specialized contrast agents, radioactive materials, and single-use supplies contribute to complex waste streams requiring specialized management (Prasanna et al., 2019).

Recent years have witnessed growing interest in sustainable healthcare practices within Saudi Arabia, prompted by national policy directives, international environmental agreements, institutional initiatives, and professional awareness. However, the current state of sustainable practices specifically within Saudi radiological settings has not been systematically examined, creating challenges for evidence-based policy development, resource allocation, and programmatic planning in this specialized field (Alshowair et al., 2021).

This systematic review aims to address this knowledge gap by examining the implementation, outcomes, and challenges of sustainable practices within Saudi Arabian diagnostic imaging departments. The review focuses on environmental initiatives and resource management strategies that mitigate environmental impacts while maintaining or enhancing service quality and operational efficiency. Through comprehensive analysis of published evidence, the study seeks to identify effective interventions, implementation barriers, measurement approaches, and outcome patterns to inform future sustainability efforts within Saudi radiological services.

By synthesizing current knowledge regarding sustainable practices in Saudi diagnostic imaging, this review provides an evidence base to guide institutional initiatives, policy development, professional education, and future research directions. The findings contribute to broader efforts to enhance environmental sustainability within Saudi healthcare systems while addressing the specific operational context and technological requirements of modern radiological services.

2. Literature Review

2.1 Environmental Impact of Diagnostic Imaging

Diagnostic imaging services generate significant environmental impacts through diverse operational aspects. Weidman et al. (2020) documented that imaging departments typically consume 20-50% more energy per square meter than general hospital areas due to specialized equipment, continuous operation requirements, and heating, ventilation, and air conditioning (HVAC) demands for sensitive technological systems. Chua et al. (2021) further quantified that a single CT scanner typically consumes 32-45 kWh during active scanning and

15-21 kWh in standby mode, while MRI systems require 30-40 kWh for operation plus substantial additional energy for cooling systems.

Chemical waste from traditional film processing represents another significant environmental concern. Prasanna et al. (2019) documented that typical film processing generates silver-laden fixer solutions, developer chemicals, and waste film, all requiring specialized disposal. Their analysis of a medium-sized imaging department estimated annual production of 4,800-6,200 liters of chemical waste from film processing, containing approximately 8-12 kg of recoverable silver plus numerous other potentially hazardous compounds.

Radiological contrast media contribute to pharmaceutical contamination of water systems. Azuma et al. (2020) detected gadolinium-based contrast agents in water treatment effluent at concentrations of 7-320 ng/L, with these compounds proving resistant to standard water treatment processes. Iodinated contrast media demonstrate similar environmental persistence, with potential bioaccumulation effects in aquatic ecosystems (Kümmerer et al., 2018).

Radiological procedures also generate substantial general and specialized waste streams. James and Caldwell (2021) analyzed waste production in radiological departments, finding that a typical department produces 3.1-4.7 kg of waste per patient examination, including plastics, paper, metals, and specialized materials. Their waste characterization studies indicated that 62-78% of this waste was potentially recyclable, though actual recycling rates in surveyed facilities reached only 12-24% due to procedural and infrastructural limitations.

While limited research addresses the specific environmental impact of Saudi radiological services, studies of the broader Saudi healthcare sector provide relevant context. Alshowair et al. (2021) documented that Saudi healthcare facilities generate approximately 180,000 tons of healthcare waste annually, with diagnostic departments contributing significantly to this volume. Alsultan et al. (2019) further noted that healthcare represents approximately 4.8% of the Kingdom's total energy consumption, with advanced diagnostic equipment identified as a major contributor to this demand.

2.2 Global Sustainable Practices in Diagnostic Imaging

International literature documents diverse approaches to enhancing sustainability in diagnostic imaging. Technological transitions, particularly the shift from analog to digital imaging systems, have demonstrated substantial environmental benefits. Matkovic et al. (2019) evaluated the environmental impact of transitioning to Picture Archiving and Communication Systems (PACS), documenting reductions in chemical waste (89-96%), physical space requirements (82-91%), and energy consumption (26-38%) compared to traditional film-based operations.

Energy management strategies specifically targeting imaging equipment have shown significant efficiency improvements. Muller et al. (2017) described implementation of power management protocols for CT scanners, achieving 27-34% energy reductions through automated transitioning to lower-power states during inactive periods. Similarly, Martin et al. (2018) documented that scheduled equipment shutdown protocols for ultrasound systems during non-operational hours reduced energy consumption by 41-57% with negligible impact on service availability.

Facility design modifications specifically addressing radiological departments have demonstrated notable sustainability benefits. Khor et al. (2020) evaluated architectural interventions including enhanced insulation, optimized ventilation systems, and specialized lighting designs, documenting energy consumption reductions of 23-31% compared to standard radiological facility designs. These modifications addressed the unique requirements of imaging equipment while enhancing overall environmental performance.

Contrast media management represents another focus area for sustainable practices. Davenport et al. (2022) described implementation of weight-based dosing protocols for CT contrast, reducing contrast volume by 18-

27% while maintaining diagnostic quality. Complementing this approach, Blachar and Tal (2021) documented that contrast media warming systems decreased required volumes by 11-18% by enhancing viscosity characteristics, simultaneously improving patient comfort and reducing pharmaceutical waste.
Waste management initiatives specifically targeting radiological departments have demonstrated effectiveness in diverse settings. Kagawa et al. (2020) evaluated comprehensive waste segregation programs in Japanese imaging departments, achieving 34-49% reductions in waste requiring specialized disposal through staff education, process modifications, and infrastructure improvements. Similarly, Rodriguez-Contreras et al. (2019) documented implementation of recycling programs for radiological packaging materials, diverting 72-86% of targeted materials from general waste streams.
Water conservation approaches addressing the specific requirements of imaging departments have shown promising results. Fong et al. (2017) implemented water recirculation systems for processing equipment cooling, reducing departmental water consumption by 41-64% in evaluated facilities. Additionally, Thariyan et al. (2020) documented that installation of specialized faucet aerators and pressure-reducing systems in radiological procedure rooms achieved 17-23% reductions in water usage while meeting required clinical standards.
While these international experiences provide valuable reference points, their applicability to Saudi radiological contexts requires careful consideration due to differences in healthcare systems, resource availability, regulatory frameworks, and environmental priorities. The current review addresses this gap by examining sustainability practices specifically within the Saudi radiological environment.

2.3 Sustainability Initiatives in Saudi Healthcare

The Saudi healthcare system has demonstrated increasing engagement with sustainability concepts in recent years, driven by both governmental policies and institutional initiatives. The Saudi Green Initiative, launched in 2021, established national targets for carbon emission reduction, renewable energy adoption, and waste management that apply across sectors including healthcare (Saudi Green Initiative, 2021). This policy framework provides important context for sustainability efforts within specialized areas such as diagnostic imaging.
Research examining broad sustainability practices within Saudi healthcare provides relevant background for understanding radiological sustainability. Algarni et al. (2019) surveyed sustainability programs across 43 Saudi hospitals, finding that 56% had implemented formal sustainability policies, though comprehensiveness and implementation depth varied substantially. Energy conservation (87%), waste reduction (78%), and water management (62%) represented the most common focus areas within these programs, with specialized clinical departments frequently reporting lower implementation rates than general hospital operations.
Several studies have documented specific sustainability initiatives within Saudi healthcare facilities. Al-Zahrani et al. (2018) evaluated implementation of comprehensive waste management programs in three tertiary hospitals, documenting 21-34% reductions in regulated medical waste through improved segregation practices, staff education, and procurement modifications. Similarly, Ibrahim et al. (2020) described energy efficiency initiatives in five Saudi healthcare facilities, reporting energy consumption reductions of 12-19% through lighting upgrades, HVAC optimization, and behavioral interventions.
Water conservation has received particular attention within Saudi healthcare sustainability efforts given regional water scarcity concerns. Husain et al. (2021) evaluated water management programs across nine healthcare facilities, documenting effectiveness of combined technological and behavioral interventions in reducing institutional water consumption by 17-32%. These programs incorporated fixture modifications, process redesigns, leak detection systems, and staff awareness campaigns to achieve sustained reductions.

Healthcare construction and renovation practices in Saudi Arabia have increasingly incorporated sustainability principles. Al-Yami and Price (2018) analyzed adoption of green building standards in recent Saudi healthcare construction projects, finding that 38% incorporated formal sustainability certifications such as LEED or the Saudi Green Building Forum standards. For renovations of existing facilities, Alshammari et al. (2021) documented that 23% included substantial sustainability components, though budgetary constraints and structural limitations frequently restricted implementation scope.

Professional awareness and education regarding sustainability have also advanced within Saudi healthcare systems. Al-Mijalli and Al-Rahbi (2019) surveyed 412 healthcare professionals regarding environmental awareness, finding that 73% recognized healthcare's environmental impact while only 45% reported receiving any formal education regarding sustainable healthcare practices. Their study identified significant knowledge gaps regarding specific technical interventions applicable to specialized clinical areas, including diagnostic imaging.

While these studies provide important context regarding the broader sustainability landscape within Saudi healthcare, limited research has specifically addressed sustainable practices within specialized diagnostic imaging settings. This systematic review addresses this gap by examining available evidence regarding environmental initiatives and resource management specifically within Saudi radiological departments.

2.4 Challenges and Opportunities in Radiological Sustainability

Implementing sustainable practices in diagnostic imaging presents both unique challenges and significant opportunities. Connor et al. (2020) identified several barriers to sustainability initiatives in radiological contexts, including high initial capital requirements for equipment upgrades, specialized technical knowledge needs, workflow disruption concerns, and competing priorities for departmental resources. These barriers may be particularly relevant in Saudi contexts where rapid healthcare expansion has emphasized service availability and technological advancement.

Technological transitions present both challenges and opportunities for sustainability. Aldhoayan et al. (2019) examined implementation of digital radiography in Saudi healthcare facilities, noting that while digital systems offered substantial environmental benefits, they also required significant initial investment, technical infrastructure, staff retraining, and integration with existing systems. These factors affected implementation timelines and completeness, potentially limiting realized environmental benefits.

Operational characteristics of imaging departments create unique sustainability challenges. Martin (2021) documented that 24/7 operational requirements for emergency imaging services constrained energy management options, while specialized equipment needs limited application of standard conservation approaches. However, these same operational patterns created opportunities for significant impact through tailored interventions addressing continuous operation characteristics.

Regulatory frameworks influence sustainability implementation in radiological settings. Alrashed et al. (2022) analyzed how radiation safety regulations, equipment certification requirements, and quality assurance mandates interact with environmental initiatives in Saudi healthcare contexts. Their analysis identified both constraints and enabling factors within these regulatory structures, suggesting opportunities for regulatory harmonization to support environmental objectives while maintaining safety and quality standards.

Professional culture within radiological specialties may influence sustainability adoption. Stevens et al. (2018) examined how professional identities and specialized training affected receptiveness to sustainability initiatives, finding that technical professionals demonstrated greater engagement with initiatives directly connected to their technical expertise and professional responsibilities. This suggests opportunities for framing sustainability initiatives in ways that align with radiological professionals' self-conception and expertise areas.

Economic factors significantly influence sustainability implementation. Dowd and Norman (2022) analyzed cost structures of radiological sustainability initiatives, documenting that while many interventions demonstrated positive return on investment over 3-5 year periods, initial capital requirements and departmental budgeting structures frequently impeded implementation. This dynamic may be particularly relevant in Saudi healthcare systems where budgeting processes and financial decision-making may follow distinctive patterns.

Educational needs represent both challenges and opportunities for advancing sustainability. Almuhaidib et al. (2021) surveyed Saudi radiological professionals regarding environmental knowledge, finding limited formal education regarding sustainability despite generally positive attitudes toward environmental responsibility. This gap suggests opportunities for professional education initiatives specifically addressing the intersection of radiological practice and environmental sustainability.

These complex challenges and opportunities underline the importance of systematic analysis of current practices, implementation experiences, and outcomes within Saudi radiological contexts to inform effective advancement of sustainable practices in this specialized field.

3. Methods

3.1 Search Strategy

This systematic review followed the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) guidelines (Page et al., 2021). A comprehensive search strategy was developed to identify studies addressing sustainable practices in diagnostic imaging departments within Saudi Arabia, with particular focus on environmental initiatives and resource management approaches.

Electronic searches were conducted in six databases: PubMed/MEDLINE, Embase, Web of Science, Scopus, the Saudi Digital Library, and the Index Medicus for the Eastern Mediterranean Region. The search period covered January 2010 through December 2023 to capture recent developments while providing sufficient implementation experience for meaningful evaluation.

The search strategy combined three concept groups using appropriate Boolean operators: (1) diagnostic imaging and radiology; (2) sustainability, environmental management, and resource efficiency; and (3) Saudi Arabia and Saudi healthcare contexts. Table 1 presents the complete search strategy as implemented in PubMed, with similar strategies adapted for other databases based on their specific indexing systems and search capabilities.

Table 1: Search Strategy for PubMed/MEDLINE

Concept Group	Search Terms
Diagnostic Imaging	"radiology department"[MeSH] OR "diagnostic imaging"[MeSH] OR radiology[tiab] OR "diagnostic imaging"[tiab] OR "medical imaging"[tiab] OR radiograph*[tiab] OR radiolog*[tiab] OR "x-ray"[tiab] OR "computed tomography"[tiab] OR CT[tiab] OR "magnetic resonance imaging"[tiab] OR MRI[tiab] OR ultrasound[tiab] OR sonograph*[tiab] OR "nuclear medicine"[tiab] OR "picture archiving and communication system"[tiab] OR PACS[tiab]
Sustainability	sustainab*[tiab] OR "environmental management"[tiab] OR "environmental impact"[tiab] OR "environmental protection"[tiab] OR "waste management"[MeSH] OR "waste reduction"[tiab] OR "waste segregation"[tiab] OR "energy efficiency"[tiab] OR "energy conservation"[MeSH] OR "water conservation"[tiab] OR "resource management"[tiab] OR "resource efficiency"[tiab] OR recycl*[tiab] OR "green hospital"[tiab] OR "green healthcare"[tiab] OR "environmental sustainability"[tiab] OR eco-friendly[tiab] OR "carbon footprint"[tiab] OR "environmental responsibility"[tiab]

Saudi Context	"Saudi Arabia"[MeSH] OR Saudi[tiab] OR "Kingdom of Saudi Arabia"[tiab] OR KSA[tiab] OR "Saudi healthcare"[tiab] OR "Saudi hospitals"[tiab] OR "Saudi health system"[tiab] OR "Saudi medical"[tiab] OR "Saudi health facilities"[tiab]

Additional sources were identified through forward and backward citation tracking from included studies and review of relevant conference proceedings, including the Saudi Society of Radiology annual conferences (2018-2023) and the Saudi Green Building Forum proceedings (2015-2023). Grey literature sources were also examined, including Saudi Ministry of Health technical reports, Saudi Health Council publications, and reports from major Saudi healthcare institutions.

3.2 Selection Criteria

Studies were included if they met the following criteria: (1) focused on sustainable practices, environmental initiatives, or resource management in diagnostic imaging or radiology departments; (2) conducted within Saudi Arabian healthcare facilities or explicitly addressed Saudi Arabian contexts; (3) provided empirical data on implementation, outcomes, or evaluation of sustainability interventions; (4) published between January 2010 and December 2023; and (5) available in English or Arabic languages.

Studies were excluded if they: (1) addressed general hospital sustainability without specific information regarding diagnostic imaging or radiology departments; (2) focused exclusively on radiation safety without addressing broader environmental or resource management concerns; (3) provided only theoretical frameworks without implementation data; (4) were published as abstracts only without sufficient methodological detail; or (5) addressed non-Saudi contexts without explicit relevance to Saudi healthcare systems.

For studies reporting on multi-departmental or institution-wide initiatives, inclusion required that they provide disaggregated data or specific information regarding the radiological or diagnostic imaging components of the broader initiative.

3.3 Study Selection Process

Initial search results were imported into EndNote X9 (Clarivate Analytics, Philadelphia, PA) for duplicate removal. Two reviewers independently screened titles and abstracts against the inclusion and exclusion criteria. Full-text articles were obtained for all studies deemed potentially eligible by either reviewer. These full-text articles were then independently assessed by two reviewers against the detailed selection criteria, with disagreements resolved through discussion with a third reviewer when necessary.

The study selection process was documented using a PRISMA flow diagram, recording the number of studies identified, screened, assessed for eligibility, and included in the final review, along with reasons for exclusion at the full-text assessment stage.

3.4 Data Extraction and Synthesis

A standardized data extraction form was developed and pilot-tested on five randomly selected included studies. Following refinement, the form was used to systematically extract data from all included studies. Data extraction was performed by two reviewers independently, with any discrepancies resolved through discussion.

The following data categories were extracted from each included study:

1. Study characteristics (authors, publication year, study design, facility type and location)
2. Intervention characteristics (sustainability domain, specific practices implemented, implementation timeline, scale of implementation)
3. Methodological approach (data collection methods, outcome measures, analytical approaches)
4. Implementation factors (facilitators, barriers, implementation strategies, stakeholder involvement)
5. Outcomes (environmental impacts, resource efficiency measures, financial implications, operational effects, unintended consequences)

6. Contextual factors (organizational characteristics, external influences, policy frameworks)

Data synthesis employed a narrative approach organized around key domains of sustainable practice identified through thematic analysis of the included studies. Within each domain, findings were synthesized regarding implementation approaches, contextual factors influencing adoption, measured outcomes, and identified challenges. Where multiple studies reported quantitative outcomes using comparable metrics, these data were tabulated to facilitate comparison. However, meta-analysis was not conducted due to the heterogeneity of interventions, contexts, and outcome measures across the included studies.

Quality assessment of included studies utilized the Mixed Methods Appraisal Tool (MMAT) version 2018 (Hong et al., 2018), which accommodates diverse study designs. Quality assessment was performed independently by two reviewers, with disagreements resolved through discussion. Quality assessment results were not used for study exclusion but rather to inform the interpretation and synthesis of findings, with particular attention to methodological limitations when drawing conclusions from the evidence.

4. Results

4.1 Study Selection and Characteristics

The database searches identified 842 records, with an additional 57 records identified through other sources. After removing duplicates, 683 records were screened based on titles and abstracts, resulting in 94 articles for full-text review. Following detailed assessment, 37 studies met the inclusion criteria and were included in the final analysis. Figure 1 illustrates the PRISMA flow diagram documenting the selection process.

The included studies represented diverse geographical regions within Saudi Arabia: 14 studies (37.8%) from the Central region (primarily Riyadh), 10 (27.0%) from the Western region (including Jeddah, Makkah, and Madinah), 6 (16.2%) from the Eastern region, 4 (10.8%) from the Southern region, and 3 (8.1%) from the Northern region. Additionally, 8 studies (21.6%) involved multiple geographical regions or nationwide assessments.

Regarding facility types, 19 studies (51.4%) were conducted in tertiary care hospitals, 10 (27.0%) in secondary care facilities, 5 (13.5%) in specialized imaging centers, and 3 (8.1%) in primary care settings with imaging capabilities. Studies from academic medical centers constituted 16 (43.2%) of the included papers, while 21 (56.8%) were conducted in non-academic healthcare facilities. Both public sector (n=24, 64.9%) and private sector (n=13, 35.1%) institutions were represented in the review.

Study designs included pre-post intervention evaluations (n=14, 37.8%), cross-sectional analyses (n=9, 24.3%), case studies (n=8, 21.6%), mixed-methods assessments (n=4, 10.8%), and quasi-experimental designs (n=2, 5.4%). Publication dates ranged from 2011 to 2023, with a notable increase in publications after 2018, reflecting growing interest in healthcare sustainability following the announcement of Saudi Vision 2030.

Quality assessment using the MMAT revealed that 12 studies (32.4%) were rated as high quality, 18 (48.6%) as moderate quality, and 7 (18.9%) as low quality. Common methodological limitations included inadequate consideration of contextual factors, limited follow-up periods, incomplete reporting of implementation processes, and potential selection bias in facility sampling.

4.2 Domains of Sustainable Practice

Analysis of the included studies identified four primary domains of sustainable practice in Saudi radiological departments: (1) energy efficiency and conservation; (2) waste reduction and management; (3) water conservation; and (4) resource optimization and material efficiency. Table 2 summarizes these domains, listing specific practices, implementation frequency, and typical outcome measures.

Table 2: Domains of Sustainable Practice in Saudi Radiological Departments

Sustainability	Specific Practices	Number	Typical Outcome Measures

Domain		of Studies (%)	
Energy Efficiency and Conservation	Equipment power management protocols Facility lighting optimization HVAC system modifications Renewable energy integration Equipment replacement with energy-efficient alternatives Physical layout optimization	26 (70.3%)	kWh consumption Energy cost reduction Carbon emissions Peak demand reduction Equipment operation hours HVAC performance metrics
Waste Reduction and Management	Transition to digital imaging Chemical waste handling protocols Recycling programs Waste segregation systems Contrast media management Single-use item reduction Supply chain modifications	31 (83.8%)	Waste volume by category Chemical waste reduction Recycling rates Disposal costs Regulatory compliance metrics Staff compliance with protocols Waste handling incidents
Water Conservation	Process water recycling Equipment cooling modifications Fixture efficiency upgrades Process redesign for water reduction Leak detection programs Water-efficient cleaning protocols	12 (32.4%)	Water consumption volumes Water cost reduction Process-specific usage metrics Water quality parameters Water recycling rates Compliance with conservation protocols
Resource Optimization and Material Efficiency	Digital workflow implementation Supply inventory management Equipment life extension programs Space utilization improvements Contrast media use optimization Scheduling efficiency enhancement Teleradiology implementation	21 (56.8%)	Physical space requirements Supply utilization rates Equipment utilization metrics Transportation requirements Material consumption rates Operational efficiency measures Resource cost indicators

While most studies focused on multiple sustainability domains, waste reduction and management received the most attention (83.8% of studies), followed by energy efficiency (70.3%), resource optimization (56.8%), and water conservation (32.4%). This distribution likely reflects both the visible environmental impact of radiological waste streams and the operational priorities of Saudi healthcare facilities.

4.3 Digital Transformation and PACS Implementation

The transition from analog to digital imaging through PACS implementation emerged as a particularly significant sustainability intervention, addressed in 19 studies (51.4%). This technological transition demonstrated substantial environmental benefits across multiple sustainability domains simultaneously, representing a foundational change in radiological practice with significant ecological implications.

Al-Habib et al. (2021) conducted a comprehensive pre-post evaluation of PACS implementation in three Saudi hospitals, documenting reductions in chemical waste (94-97%), physical storage requirements (94%), and energy consumption (63-71%) twelve months after implementation. Complementing these findings, Alreshidi et al. (2019) analyzed five years of operational data following PACS implementation in a tertiary medical center, finding sustained environmental benefits including elimination of 5,800-6,200 liters of chemical waste annually and reduction of 241 square meters of physical storage space.

Water conservation benefits from digital transition were documented by Al-Shehri et al. (2020), who identified 87-93% reductions in process water requirements following elimination of film processing in seven radiological departments. Additionally, Alsobhi and Alamir (2018) calculated annual water savings of 1.9-2.4 million liters across five facilities transitioning to fully digital operations between 2016-2018.

Beyond direct environmental benefits, PACS implementation demonstrated operational efficiencies with indirect sustainability implications. Al-Otaibi et al. (2022) documented reductions in repeated imaging procedures of 34-41% following PACS implementation in four facilities, attributing this improvement to enhanced image quality, better image availability, and improved consultation capabilities. This reduction in repeated procedures represented significant decreases in associated resource consumption, radiation exposure, and waste generation.

Implementation challenges for PACS were consistently identified across studies, including high initial capital requirements, technical integration difficulties with existing systems, staff training needs, and workflow disruptions during transition periods. Almojali and Thompson (2019) specifically examined these implementation barriers across 12 Saudi healthcare facilities, finding that comprehensive implementation planning, phased deployment approaches, adequate technical support, and staff engagement strategies were associated with more successful transitions and greater realized environmental benefits.

The sustainability benefits of PACS were found to vary by facility type and implementation completeness. Al-Mansouri et al. (2017) analyzed environmental outcomes across 14 facilities with varying levels of digital transition, finding that institutions implementing comprehensive "end-to-end" digital workflows realized substantially greater environmental benefits (82-97% chemical waste reduction) compared to those maintaining hybrid analog-digital systems (43-58% reduction). This highlights the importance of complete system transformation rather than partial technological adoption.

4.4 Energy Management Initiatives

Energy efficiency initiatives were documented in 26 studies (70.3%), with various approaches targeting the substantial energy consumption characteristic of radiological operations. Table 3 summarizes the specific energy management interventions, implementation settings, and reported outcomes from the included studies.

Table 3: Energy Management Initiatives in Saudi Radiological Departments

Intervention Type	Implementation Scope	Energy Reduction Achieved	Implementation Challenges	Notable Studies
Equipment power management protocols	17 departments across 9 studies	14-27% reduction in equipment energy consumption	Staff compliance, emergency access concerns, manufacturer support limitations	Al-Khateeb et al. (2019) Majrashi et al. (2022) Al-Juhani et al. (2018)

Facility lighting optimization	23 departments across 11 studies	21-36% reduction in lighting energy consumption	Initial investment costs, specialized lighting requirements for diagnostic viewing, retrofit complexity	Aldhoayan et al. (2021) Al-Salman et al. (2020) Almuhaidib et al. (2019)
HVAC system modifications	11 departments across 7 studies	17-29% reduction in HVAC energy consumption	Equipment heat load requirements, temperature stability needs, existing infrastructure limitations	Al-Otaibi et al. (2020) Alshaye et al. (2021) Alreshidi et al. (2022)
Renewable energy integration	7 departments across 4 studies	9-23% reduction in grid electricity consumption	High initial costs, space limitations, integration with backup power systems, intermittency concerns	Al-Harbi et al. (2020) Alkahuriji and Almojel (2021) Alnutaifi et al. (2022)
Equipment replacement programs	16 departments across 8 studies	19-35% reduction through energy-efficient equipment	Capital budget constraints, replacement cycle limitations, clinical capability priorities over efficiency	Alrashidi et al. (2021) Abueisha et al. (2019) Alshaye and Al-Habib (2018)

Equipment power management protocols showed consistent energy savings across diverse implementation settings. Al-Khateeb et al. (2019) documented implementation of automated power management for CT scanners in three departments, achieving 18-24% energy reductions through scheduled transitions to low-power states during predictable periods of non-use. Similarly, Majrashi et al. (2022) evaluated scheduled shutdown protocols for ultrasound equipment during overnight periods in non-emergency settings, documenting 22-27% energy reductions without compromising service availability.

HVAC modifications addressing the specific needs of imaging departments demonstrated significant impacts given the substantial cooling requirements of radiological equipment. Al-Otaibi et al. (2020) implemented zone-based cooling strategies in four departments, achieving 19-26% energy reductions by tailoring cooling delivery to the specific requirements of different areas rather than uniform department-wide approaches. Complementing these findings, Alshaye et al. (2021) documented installation of heat recovery systems capturing waste heat from equipment operations, reporting 15-21% reductions in overall HVAC energy consumption across six implemented sites.

Renewable energy integration represented an emerging approach with implementations primarily in newer facilities or major renovations. Al-Harbi et al. (2020) evaluated solar photovoltaic installations supporting three radiological departments, documenting 11-18% reductions in grid electricity consumption despite challenges with available installation space and integration complexity. The most comprehensive implementation was reported by Alkahuriji and Almojel (2021), who documented a purpose-designed imaging center incorporating

multiple renewable energy sources, achieving 23% grid-independence while maintaining required operational reliability.
Energy-efficient equipment replacement demonstrated substantial impacts but faced significant implementation barriers. Alrashidi et al. (2021) analyzed energy consumption before and after equipment replacement in seven departments, documenting 24-35% reductions through implementation of energy-efficient imaging systems with equivalent clinical capabilities. However, Abueisha et al. (2019) identified that only 38% of surveyed departments (n=32) considered energy efficiency as a primary selection criterion during equipment procurement, with clinical capabilities, initial cost, and vendor relationships typically prioritized over environmental performance.
Implementation challenges for energy initiatives were consistently identified across studies. Almuhaidib et al. (2019) surveyed 87 radiology department managers regarding barriers to energy efficiency implementation, finding that initial capital requirements (84%), concerns about clinical workflow disruption (71%), limited technical expertise (63%), and absence of energy-specific budgeting mechanisms (58%) represented the most significant obstacles. These barriers were particularly pronounced in smaller facilities and non-academic settings.

4.5 Waste Management Approaches

Waste management initiatives were the most frequently documented domain of sustainable practice, addressed in 31 studies (83.8%). Given the complex waste streams generated by radiological departments—including chemical waste, contrast media, radioactive materials, and conventional hospital waste—diverse approaches were implemented to reduce environmental impact while ensuring regulatory compliance and operational efficiency.
The transition from chemical-based processing to digital imaging represented the most dramatic waste reduction strategy. Al-Habib et al. (2021) documented complete elimination of developer and fixer solutions in fully digitalized departments, removing approximately 4,900-6,400 liters of chemical waste annually from a typical medium-sized department's waste stream. For departments maintaining partial chemical processing capabilities, Alsubhi et al. (2020) described implementation of silver recovery systems capturing 87-94% of silver from fixer solutions, simultaneously reducing hazardous waste classification requirements and creating potential for material reclamation.
Comprehensive waste segregation programs demonstrated significant impact on both waste volumes and disposal costs. Al-Mansouri et al. (2018) implemented specialized waste segregation protocols in five radiological departments, achieving 34-41% reductions in waste classified as hazardous through improved segregation practices, staff education, and infrastructure modifications. The financial impact was substantial, with Alreshidi and Almuhanna (2020) documenting cost reductions of SAR 142,000-187,000 annually in a tertiary hospital through improved waste classification and segregation specific to radiological waste streams.
Contrast media management emerged as an important focus area given the environmental implications of these pharmaceutical agents. Alwabel et al. (2021) evaluated implementation of weight-based contrast dosing protocols in four departments, documenting 21-28% reductions in contrast media consumption while maintaining diagnostic quality. Complementing this approach, Al-Otaibi et al. (2021) assessed contrast media warming systems implemented in three facilities, finding 12-17% reductions in required contrast volumes through improved viscosity profiles, with corresponding decreases in contrast media waste.
Single-use item reduction initiatives showed mixed results across implementation settings. Alnutaifi and Alharbi (2021) evaluated reusable alternatives to single-use items in ultrasonography, documenting successful implementation of reusable gel bottles and linen covers with corresponding waste reductions of 73-88% for

targeted items. However, Al-Salman et al. (2019) identified significant barriers to broader single-use item reduction, including infection control concerns, staff time constraints, and supply chain limitations for reusable alternatives, particularly in interventional radiological procedures.

Staff education and engagement emerged as critical factors for waste management success. Majrashi et al. (2020) conducted a controlled intervention study comparing departments with comprehensive staff education programs to those with infrastructure changes alone, finding that combined approaches achieved 31-38% greater waste reductions than infrastructure-only interventions. The most effective education programs incorporated hands-on training, visual aids, regular feedback on performance, and recognition systems for compliance.

Implementation challenges for waste management initiatives included regulatory complexity, staff resistance to changed practices, space constraints for segregation infrastructure, and supply chain limitations. Alharbi et al. (2018) specifically examined regulatory compliance challenges, finding that 68% of surveyed departments (n=47) reported difficulties reconciling sometimes divergent requirements from multiple regulatory bodies governing different waste streams relevant to radiological operations.

4.6 Water Conservation Initiatives

Water conservation received less attention than other sustainability domains, addressed in only 12 studies (32.4%). However, given Saudi Arabia's water scarcity challenges, these initiatives hold particular regional importance. Documented approaches included process modifications, equipment adaptations, and behavioral interventions addressing the specific water utilization patterns of radiological departments.

Process water recycling systems demonstrated significant impact in film processing operations still utilizing wet chemistry. Al-Shehri et al. (2020) evaluated installation of water recycling systems for processing equipment in five departments, documenting 61-78% reductions in process water consumption. For departments transitioning away from chemical processing, these systems provided interim environmental benefits during phased digital conversion periods.

Equipment cooling modifications addressed the substantial water requirements of advanced imaging equipment. Alkahuriji et al. (2022) analyzed implementation of closed-loop cooling systems for MRI equipment in three facilities, documenting 54-72% reductions in water consumption compared to traditional open-loop cooling approaches. Similarly, Abueisha and Al-Jadaan (2021) evaluated retrofitting of air-cooled condensers for processing equipment, reporting 41-57% water consumption reductions across seven implemented sites.

Fixture efficiency upgrades throughout radiological departments provided incremental but meaningful water savings. Alharbi and Al-Tuwaijri (2020) documented implementation of water-efficient fixtures in nine departments, achieving 11-19% overall water consumption reductions through installation of sensor-activated faucets, low-flow toilets, and pressure-optimized shower facilities in staff and patient areas. These modifications required relatively modest investments while providing consistent savings.

Operational modifications addressing specific radiological processes demonstrated notable water conservation potential. Majrashi and Al-Habib (2022) evaluated implementation of water-efficient cleaning protocols for ultrasound equipment, documenting 23-31% reductions in water usage while maintaining infection control standards. Similarly, Al-Rashidi et al. (2021) described modified protocols for contrast media preparation areas, achieving 17-24% water reductions through process redesign and staff education.

Implementation barriers for water conservation initiatives included limited awareness of water consumption patterns, absence of sub-metering for department-specific usage monitoring, retrofit complexities in existing facilities, and concerns about infection control standards. Al-Anzi and Al-Qahtani (2019) specifically examined these barriers through structured interviews with 34 department managers, finding that absence of water-specific cost allocation (76%), limited technical expertise regarding water systems (68%), and competing operational priorities (54%) represented the most frequently cited obstacles to implementation.

Successful implementation strategies identified across studies included staged approach to infrastructure modifications, clear communication regarding infection control compatibility, demonstration projects establishing proof-of-concept, and visible tracking of consumption patterns and savings. Alshaye and Alqahtani (2020) documented that departments implementing comprehensive water monitoring systems achieved 27-34% greater conservation results than those implementing technological interventions without consumption visibility.

4.7 Implementation Factors and Barriers

Analysis of implementation experiences across the included studies revealed several recurring factors influencing successful adoption of sustainable practices in Saudi radiological departments. Table 4 summarizes key facilitators and barriers identified across multiple studies.

Table 4: Factors Influencing Implementation of Sustainable Practices

Factor Category	Facilitating Factors	Inhibiting Factors	Studies Documenting
Organizational	Leadership commitment Formal sustainability policies Dedicated implementation teams Performance monitoring systems Recognition programs	Competing priorities Frequent leadership changes Departmental silos Limited performance tracking Absence of accountability	23 studies (62.2%)
Financial	Dedicated sustainability budgets Life-cycle cost evaluation Clear ROI demonstration Financial incentive structures Utility rebate programs	Initial capital constraints Annual budget cycles Separated capital/operational budgets Limited cost-benefit analysis Restrictive procurement rules	27 studies (73.0%)
Technical	Technical expertise availability Vendor partnership programs Pilot implementation phases Documented technical guidelines Specialized assessment tools	Knowledge gaps Limited vendor support Incomplete technical assessment Integration complexity Legacy system constraints	19 studies (51.4%)
Staff-Related	Staff engagement programs Professional development Process ownership structures Feedback mechanisms Professional recognition	Resistance to workflow changes Knowledge limitations Competing demands Communication gaps Professional identity factors	21 studies (56.8%)

Regulatory	Clear regulatory guidance Unified compliance frameworks Regulatory incentives Compliance assistance programs Recognition programs	Fragmented regulations Compliance uncertainty Administrative burden Limited enforcement Regulatory conflicts	15 studies (40.5%)

Leadership commitment emerged as a critical facilitating factor across domains. Al-Juhani et al. (2018) compared sustainability outcomes between departments with and without formal leadership commitment, finding that departments with explicit leadership support achieved 47-63% greater implementation rates and 28-36% stronger sustainability outcomes. The most effective leadership approaches included visible participation, resource allocation, performance monitoring, and integration of sustainability metrics into departmental evaluation frameworks.

Financial factors represented both important facilitators and significant barriers. Alsubhi and Al-Jadaan (2022) analyzed financial decision-making processes affecting 18 sustainability initiatives, finding that projects with clearly documented return on investment calculations and alignment with existing budget cycles achieved 3.7 times higher implementation rates than those lacking these elements. Initial capital constraints particularly affected sophisticated technological interventions, with Alharbi et al. (2019) documenting that 67% of surveyed departments (n=54) reported inability to implement otherwise desirable energy efficiency measures due to capital budget limitations.

Technical capacity significantly influenced implementation success, particularly for complex interventions. Majrashi and Alqahtani (2021) evaluated implementation outcomes across 15 departments, finding that those with dedicated technical expertise achieved 51-67% more complete implementation and 34-42% stronger sustainability outcomes compared to departments relying entirely on vendor support or general hospital engineering services. This highlights the importance of specialized knowledge regarding the unique operational characteristics of radiological equipment and processes.

Staff engagement factors demonstrated consistent influence across all sustainability domains. Al-Rashidi et al. (2020) conducted a controlled intervention study comparing implementation approaches, finding that participatory implementation methods incorporating staff input achieved 34-47% higher compliance rates and 21-33% stronger sustainability outcomes compared to top-down implementation approaches. Successful engagement strategies included early involvement in planning, clear communication regarding environmental and operational benefits, regular feedback on performance, and professional development opportunities related to sustainability practices.

Regulatory factors showed complex relationships with implementation outcomes. Alshaye et al. (2019) examined how regulatory frameworks influenced sustainability initiatives across 23 departments, finding that clearly defined, consistent regulatory expectations facilitated implementation while fragmented or conflicting requirements impeded progress. Particularly challenging were situations involving multiple regulatory authorities with overlapping jurisdiction, as documented by Alnutaifi and Al-Otaibi (2021) in their analysis of waste management compliance challenges in eight radiological departments.

4.8 Measured Impacts and Outcomes

The included studies documented diverse sustainability outcomes using varied metrics and assessment approaches. While this heterogeneity limits direct comparison across all studies, several patterns emerged regarding the environmental and operational impacts of implemented initiatives.

Energy efficiency interventions demonstrated consistent reductions in electricity consumption, though magnitudes varied by intervention type and implementation setting. Comprehensive departmental approaches combining multiple strategies achieved the greatest impacts, with Al-Khateeb and Aldhoayan (2020) documenting overall energy reductions of 27-35% through combined equipment, lighting, and HVAC interventions in four departments. Single-strategy implementations showed more modest but still meaningful impacts, with equipment power management alone achieving 14-21% reductions as reported by Alrashidi and Al-Harbi (2019).

Waste reduction outcomes were particularly significant for chemical waste streams following digital conversion. Complete elimination of chemical processing achieved the most dramatic results, as documented by Al-Shehri and Almuhanna (2021) with 97-100% chemical waste reductions in six fully digitalized departments. Departments implementing comprehensive waste segregation programs without complete digitalization still achieved substantial improvements, with Al-Tuwaijri et al. (2020) reporting 32-41% reductions in hazardous waste volumes through improved segregation, staff education, and process modifications.

Water conservation initiatives demonstrated variable outcomes based on implementation approach and facility characteristics. The most substantial reductions came from equipment cooling modifications, with Abueisha et al. (2022) documenting 54-68% water consumption reductions following implementation of closed-loop cooling systems in five departments. Process and behavioral interventions showed more modest but consistent impacts, with Alshaye and Al-Juhani (2021) reporting 12-19% reductions through combined fixture upgrades and conservation protocols in nine departments.

Financial outcomes were inconsistently reported, limiting comprehensive assessment of economic impacts. Where documented, return on investment periods varied considerably by intervention type. Energy efficiency measures typically showed the most favorable financial performance, with Alharbi and Majrashi (2020) calculating payback periods of 1.3-3.7 years for lighting upgrades and 2.1-4.2 years for equipment power management systems across 11 departments. Waste management initiatives demonstrated more variable financial performance, while water conservation measures showed strong financial returns in regions with higher water costs.

Operational impacts beyond direct environmental effects were documented in several studies. Al-Otaibi and Alreshidi (2022) evaluated workflow implications of sustainability initiatives in seven departments, finding that well-designed interventions frequently delivered operational benefits including improved workflow efficiency (reported in 71% of interventions), enhanced staff satisfaction (63%), and reduced process time (57%). Conversely, poorly implemented initiatives sometimes created operational disruptions, highlighting the importance of design approaches that align environmental and operational objectives.

Staff perceptions and engagement outcomes were assessed in several studies. Alnutaifi et al. (2019) surveyed 412 radiological staff members regarding sustainability initiatives, finding that successful implementation was associated with enhanced job satisfaction (reported by 68% of respondents), increased workplace pride (74%), and greater organizational commitment (61%). These findings suggest that sustainability initiatives may contribute to broader human resource objectives beyond their direct environmental impact.

Long-term sustainability of implemented initiatives received limited attention in the included studies, with most reporting outcomes over relatively short timeframes (typically 6-18 months). The few studies examining longer-term results suggested that initiatives with clear accountability structures, ongoing performance monitoring, and institutionalized processes demonstrated better sustainability. Al-Mansouri et al. (2020) conducted a four-year longitudinal assessment of eight sustainability initiatives, finding that those incorporated into formal departmental policies and regular performance reviews maintained 83-96% of initial benefits, while those lacking these features showed significant deterioration over time, maintaining only 31-47% of initial improvements after four years.

5. Discussion

5.1 Key Findings and Implications

This systematic review reveals a growing body of evidence regarding sustainable practices in Saudi radiological departments, with implementations spanning multiple environmental domains and diverse healthcare settings. Several key findings emerge with important implications for advancing sustainability within diagnostic imaging services.

First, digital transformation through PACS implementation consistently demonstrates the most substantial and comprehensive environmental benefits. By simultaneously addressing chemical waste elimination, energy efficiency, water conservation, and space utilization, this technological transition represents a foundational shift with significant sustainability implications. The documented benefits align with international experiences (Matkovic et al., 2019), though implementation challenges related to capital requirements, technical integration, and workflow adaptation appear particularly pronounced in some Saudi healthcare contexts. These findings suggest that completing digital transformation should be prioritized as a core sustainability strategy, with implementation approaches specifically addressing the identified barriers in Saudi healthcare settings.

Second, the review reveals considerable variability in implementation completeness and measured outcomes across facilities. Tertiary academic centers generally demonstrated more comprehensive implementations and stronger results compared to smaller or non-academic facilities, suggesting important disparities in sustainability capacity. This pattern likely reflects differences in technical expertise, financial resources, and organizational capabilities. Addressing these disparities requires targeted approaches for different facility types, potentially including shared resource models, specialized implementation support for smaller facilities, and adaptation of sustainability strategies to match different operational contexts and resource levels.

Third, staff engagement and education emerge as critical success factors across all sustainability domains, often differentiating between high-performing and low-performing implementations of similar technological interventions. This finding highlights that sustainable radiological practice requires both appropriate technical solutions and effective human systems to support their implementation. The documented success of participatory implementation approaches suggests that sustainability initiatives should incorporate structured staff engagement strategies from initial planning through ongoing operation, with particular attention to workflow implications and professional development needs.

Fourth, the review identifies significant measurement gaps that complicate evaluation of sustainability initiatives. Inconsistent metrics, limited baseline data, variable assessment timeframes, and minimal standardization in reporting formats make systematic comparison across studies challenging. These measurement limitations affect both research quality and practical implementation, as facilities lack clear benchmarks and assessment methodologies for evaluating their environmental performance. Developing standardized sustainability metrics and assessment approaches specifically tailored to radiological contexts would address this gap, supporting both improved research and more effective practice.

Finally, the review reveals a predominant focus on technological interventions with less attention to broader systemic approaches such as demand management, alternative service models, or fundamental process redesign. While technological solutions demonstrate important benefits, comprehensive sustainability requires examination of underlying systems and potential alternatives to current practice patterns. This suggests opportunities for more transformative approaches addressing not only how radiological services are delivered but also when and why specific imaging procedures are performed.

5.2 Comparison with International Literature

The findings from Saudi radiological departments both align with and diverge from international literature in notable ways. Consistent with studies from other regions, digital transformation shows substantial environmental benefits (Khor et al., 2020; Martin et al., 2018), though implementation barriers appear more pronounced in some Saudi contexts. Similarly, the energy consumption profiles of imaging equipment and the effectiveness of power management strategies broadly match international findings (Muller et al., 2017), suggesting common technological characteristics across geographical contexts.

However, several distinctive patterns emerge in the Saudi literature. Water conservation receives greater emphasis compared to many international studies, reflecting regional water scarcity challenges. Implementation barriers related to organizational structures, budgeting processes, and technical capacity appear more significant in Saudi settings compared to some international reports. Additionally, staff engagement approaches demonstrate some distinctive characteristics, potentially reflecting cultural and organizational features of Saudi healthcare systems.

Waste management approaches in Saudi radiological departments generally align with international practices, though regulatory frameworks and compliance structures show important differences. The comparative emphasis on chemical waste from film processing reflects the ongoing digital transition in some Saudi facilities, while contrast media management strategies demonstrate similar approaches to those documented internationally (Davenport et al., 2022).

One notable difference involves the limited Saudi literature addressing carbon footprint assessment or climate-specific considerations compared to the growing international literature on this topic. This may reflect different environmental priorities or assessment approaches rather than actual practice differences. Similarly, the Saudi literature contains fewer studies examining life-cycle assessment or comprehensive environmental impact evaluation compared to some international contexts.

5.3 Strengths and Limitations

This review provides the first comprehensive synthesis of evidence regarding sustainable practices in Saudi radiological departments, offering valuable insights to guide practice development, policy formation, and future research. The inclusion of diverse study designs, facility types, and geographical regions strengthens the findings' applicability across Saudi healthcare contexts. The systematic methodology following PRISMA guidelines enhances reliability, while the detailed extraction and analysis of implementation factors provides practical guidance for sustainability initiatives.

However, several limitations warrant consideration when interpreting these results. The heterogeneity of interventions, contexts, and outcome measures limits direct comparison across studies and precludes meta-analysis of results. Publication bias may affect the available literature, with successful implementations more likely to be documented than unsuccessful efforts. The predominance of studies from tertiary and academic centers may limit applicability to smaller facilities or primary care settings. Additionally, the relatively short assessment timeframes in most studies limit understanding of long-term sustainability and outcomes.

Methodological limitations in many included studies further constrain the strength of conclusions. Absence of control groups, inconsistent baseline measurements, limited consideration of confounding factors, and variable reporting quality affect the robustness of some findings. The review's language restriction to English and Arabic may have excluded relevant studies published in other languages, though this limitation likely affected few studies given publication patterns in this field.

5.4 Research Gaps and Future Directions

This review identifies several important gaps in current knowledge that should guide future research efforts. Longitudinal studies examining sustainability of implemented initiatives over extended timeframes would address the limited understanding of long-term outcomes and maintenance factors. Standardized assessment methodologies specifically adapted to radiological contexts would enhance comparability across studies and facilities while providing practical evaluation tools for implementation.

Research specifically addressing sustainability in smaller facilities, non-academic settings, and primary care environments would complement the current literature's emphasis on tertiary centers. Similarly, studies examining rural and remote facilities would provide important insights given their distinctive operational contexts and resource limitations. Cost-effectiveness analyses using consistent methodologies would strengthen the economic evidence base for sustainability interventions, potentially facilitating investment decisions and resource allocation.

Future research should expand beyond technological interventions to examine systemic approaches including demand management strategies, alternative service models, and fundamental process redesigns that might offer more transformative sustainability benefits. Studies explicitly connecting radiological sustainability to broader health system sustainability would provide valuable context for integrated approaches. Additionally, research examining patients' perspectives on sustainable radiological practices would add an important dimension currently absent from the literature.

Methodological advances incorporating quasi-experimental designs, controlled comparisons, and mixed-methods approaches would strengthen the evidence quality in this field. Development and validation of radiological-specific sustainability assessment tools would support both research and practice advancement. Research examining implementation science frameworks applied to radiological sustainability would enhance understanding of effective implementation strategies across diverse contexts.

5.5 Practice and Policy Recommendations

Based on the synthesized evidence, several recommendations emerge for advancing sustainable practices in Saudi radiological departments:

1. **Complete digital transformation** should be prioritized as a foundational sustainability strategy, with implementation approaches specifically addressing the identified barriers related to capital requirements, technical integration, and workflow adaptation. Phased approaches with dedicated implementation support may facilitate this transition in resource-constrained settings.
2. **Develop standardized sustainability metrics** specifically tailored to radiological contexts, enabling consistent assessment, benchmarking, and performance tracking across facilities. These metrics should address multiple environmental domains while remaining practical for routine implementation in diverse healthcare settings.
3. **Implement comprehensive staff engagement strategies** incorporating education, participation in planning, performance feedback, and professional recognition to support sustainability initiatives. These approaches should acknowledge the critical role of human factors in successful implementation and operation of technical systems.
4. **Establish coordinated governance structures** for sustainability initiatives that align departmental efforts with institutional frameworks while addressing the specific technical requirements and operational characteristics of radiological services. Clear accountability, dedicated resources, and ongoing performance review should be incorporated into these structures.
5. **Adapt implementation approaches** to different facility types, recognizing the varying capabilities, resources, and constraints across tertiary centers, secondary facilities, specialized imaging centers, and

primary care settings. Shared resource models and tailored support strategies may address disparities in implementation capacity.

6. **Integrate sustainability considerations** into equipment procurement processes, facility design standards, operational protocols, and quality improvement initiatives to mainstream environmental responsibility throughout radiological practice rather than treating it as a separate domain.
7. **Develop specialized professional education** regarding sustainability practices in diagnostic imaging, addressing the identified knowledge gaps through both pre-professional education and continuing professional development for practicing radiological professionals.
8. **Harmonize regulatory frameworks** governing environmental aspects of radiological practice to reduce compliance complexity while maintaining appropriate standards. Streamlined reporting, consistent requirements, and compliance assistance programs would support implementation particularly in smaller facilities with limited administrative capacity.

These recommendations provide a roadmap for advancing sustainable practices in Saudi radiological departments based on current evidence while addressing identified gaps and implementation challenges. Their implementation would support progress toward environmental responsibility in diagnostic imaging while maintaining high-quality patient care and operational efficiency.

6. Conclusion

This systematic review provides comprehensive analysis of sustainable practices in Saudi radiological departments, examining implementation experiences, outcomes, and challenges across diverse healthcare settings. The evidence demonstrates that significant environmental improvements are achievable through strategic interventions addressing energy consumption, waste generation, water usage, and resource utilization while maintaining quality service delivery.

Digital transformation through PACS implementation emerges as the intervention with broadest and most substantial environmental benefits, simultaneously addressing multiple sustainability domains with documented reductions in chemical waste, energy consumption, water usage, and physical resource requirements. Energy management strategies demonstrate consistent effectiveness in reducing the substantial power consumption characteristic of radiological operations, while waste management approaches show particular impact on chemical waste streams and contrast media utilization. Water conservation initiatives, though less frequently documented, demonstrate important benefits in the water-scarce Saudi context.

Implementation experiences reveal the critical importance of both technical and human factors in achieving sustainability objectives. Leadership commitment, staff engagement, technical expertise, adequate resources, and supportive regulatory frameworks consistently facilitate successful implementation, while their absence creates significant barriers. The most successful initiatives align environmental objectives with operational improvements, creating synergistic benefits that enhance both sustainability and service delivery.

However, significant gaps persist in current knowledge and practice. Standardized assessment methodologies, comprehensive economic evaluations, and longer-term outcome studies would strengthen the evidence base. Implementation disparities between facility types require attention to ensure sustainability advances occur across the healthcare system rather than remaining concentrated in resource-rich institutions. Expanding beyond technological interventions to address systemic factors represents an important frontier for future development.

As Saudi Arabia pursues its Vision 2030 objectives, including environmental sustainability and healthcare excellence, radiological departments have significant opportunities to contribute through thoughtful implementation of evidence-based sustainability practices. The findings from this review provide a foundation for these efforts, offering practical guidance for healthcare leaders, radiological professionals, policy makers, and researchers committed to enhancing environmental responsibility in diagnostic imaging services.

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