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Pioneering Sustainability In Nuclear Medicine: A Comprehensive Exploration Of Environmental, Economic, And Social Dimensions In Global Healthcare Practice

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ABSTRACT
The integration of sustainable development principles into nuclear medicine marks a significant shift toward healthcare that is environmentally responsible, economically practical, and socially fair. This scoping review takes a detailed look at global strategies for sustainability in nuclear medicine, following the Joanna Briggs Institute (JBI) methodology to evaluate evidence from 36 peer-reviewed studies published between 1978 and 2024.
Findings show that nuclear medicine departments around the world are actively adopting sustainable practices across three main areas: environmental sustainability (highlighted in 83.3% of studies, focusing on reducing waste, improving energy efficiency, and optimizing radiopharmaceutical use), economic sustainability (covered in 33.3% of studies, emphasizing cost-effectiveness and resource management), and social sustainability (featured in 25% of studies, exploring healthcare equity and workforce development).
Geographically, Spain leads research efforts in this area, followed by notable contributions from Saudi Arabia and Brazil. When it comes to medical procedures, studies show equal focus on therapeutic applications (33.3%) and combined diagnostic-therapeutic approaches (33.3%), with strong attention to SPECT imaging (18.1%) and growing interest in PET/CT sustainability (9.7%). Hospital-based programs (63.9%) dominate compared to non-hospital settings (22.2%), highlighting the greater ability of hospitals to implement wide-ranging sustainability initiatives.
"Critical quality assessment reveals that 88.9% of included studies represent Level 4-5 evidence according to the Oxford Centre for Evidence-Based Medicine framework, with only one randomized controlled trial identified. This concentration of lower-level evidence limits the strength of causal inferences, particularly regarding quantitative claims of environmental impact reduction."
Environmental actions have achieved measurable impact, such as a 64% reduction in CO2 emissions per procedure through waste reduction and a 30% decrease in energy use by optimizing protocols. However, significant gaps remain in understanding the broader economic impacts and the social implications of these initiatives.
Overall, this review shows that nuclear medicine is actively advancing sustainable development goals, while also pointing out the need for more research and stronger implementation in key areas.

1.INTRODUCTION

Sustainable development in healthcare signals a fundamental shift away from traditional practice models toward more holistic approaches that balance clinical quality with environmental care, economic efficiency, and social responsibility. Within this framework, nuclear medicine stands out as both a challenge and an opportunity due to its reliance on advanced technology and the use of radioactive materials. The discipline's dependence on isotopes, energy-demanding imaging systems, and highly regulated waste management procedures makes sustainability particularly complex. At the same time, these challenges open the door to innovative solutions that can reduce environmental impact while preserving the precision and effectiveness of both diagnostic and therapeutic practices[1].

Sustainability in nuclear medicine is best understood through three interconnected dimensions that together define responsible and future-focused healthcare practice. **Environmental sustainability** centers on the ecological impact of nuclear medicine, including the generation of radioactive waste, patterns of energy use, and the carbon footprint tied to radiopharmaceutical production and imaging procedures. **Economic sustainability** emphasizes the financial stability of services over time, focusing on cost-effectiveness, resource optimization, and budget planning that safeguard continued access to vital diagnostic and therapeutic care. **Social sustainability** highlights fairness and equity in healthcare delivery, addressing workforce training, inclusive access to services, and meaningful community engagement to ensure that advances in nuclear medicine benefit a wide range of populations while reducing disparities in care[2].

The need to adopt sustainable practices in nuclear medicine is becoming increasingly urgent in light of rising environmental challenges, escalating healthcare costs, and greater recognition of health disparities. Globally, the healthcare sector is responsible for about 4.4% of greenhouse gas emissions, with medical imaging contributing significantly to this footprint. Within this context, nuclear medicine procedures—particularly PET/CT scans—stand out for their high energy demands, with each procedure producing an estimated 2.01 kg of CO_2 equivalent. These figures underscore the pressing need for targeted interventions to reduce environmental impact. At the same time, healthcare systems worldwide face growing economic pressures, making it essential to develop evidence-based strategies for resource allocation and cost management that maintain high-quality patient outcomes[3].

Recent progress in sustainable nuclear medicine highlights the field's ability to innovate and adapt to global challenges. International bodies such as the International Atomic Energy Agency (IAEA), along with professional societies across the world, have increasingly positioned sustainability as a central element of nuclear medicine practice. This shift has given rise to **green nuclear medicine initiatives,** which integrate strategies like waste reduction, energy conservation, and a focus on social responsibility. Together, these efforts demonstrate the profession's commitment to advancing environmental stewardship while preserving the highest standards of clinical care[4].

METHODOLOGY

This study applied the Joanna Briggs Institute (JBI) methodology for scoping reviews, using the Population, Concept, Context (PCC) framework to guide a thorough and systematic synthesis of evidence. This structured approach was chosen to map the current body of knowledge on sustainability strategies in nuclear medicine, while also highlighting gaps in the literature and areas where future research could drive meaningful advancements[5].

Search Strategy and Databases

A comprehensive literature search was carried out across four major electronic databases—PubMed, Embase, CINAHL, and Web of Science—with the final search completed in December 2024. The strategy combined both Medical Subject Headings (MeSH) and free-text keywords to capture the full scope of research on sustainable development in nuclear medicine. Search terms were structured using combinations of concepts such as *"sustainability," "environmental impact," "economic evaluation," "social responsibility," "nuclear medicine," "radiopharmaceuticals," "waste management,"* and *"energy efficiency*[5].

The search strategy was refined through an iterative process involving consultation with information specialists and the use of pilot searches to balance sensitivity and specificity. Boolean operators and truncation symbols were applied to account for variations in terminology across databases and regional contexts. In addition, the reference lists of included studies were manually screened, and citation tracking was performed to identify further relevant publications that might not have been captured through the database searches.

Study Selection and Inclusion Criteria

Three independent reviewers systematically screened titles, abstracts, and full-text articles according to predefined inclusion and exclusion criteria. Eligible studies were peer-reviewed articles published in English that examined sustainable strategies, practices, or initiatives related to diagnostic or therapeutic nuclear medicine, radiopharmaceutical production, or nuclear medicine waste management. To be included, studies had to address at least one pillar of sustainability—environmental, economic, or social—with a clear focus on applications within nuclear medicine[6].

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Studies were excluded if they were not published in English, were limited to conference abstracts or editorials, or focused exclusively on radiation safety without addressing sustainability. Research centered on nuclear power generation, weaponry, or other non-medical nuclear applications was also excluded. Any disagreements among reviewers were resolved through discussion and consensus, with the option of consulting a fourth reviewer when necessary.

Inter-rater reliability was assessed to ensure consistency in the screening process. During title and abstract screening, the three independent reviewers achieved substantial agreement with a Cohen's kappa (κ) coefficient of 0.82 (95% CI: 0.76–0.88). For full-text screening, the inter-rater agreement remained strong with a κ of 0.79 (95% CI: 0.71–0.87). Discrepancies occurring in 12 instances (8 during title/abstract screening and 4 at full-text review) were resolved through consensus discussions among the reviewers. Any unresolved disagreements (n=3) were adjudicated by a fourth senior reviewer. The review team documented all decisions and justifications to maintain transparency in study selection.

Data Extraction and Analysis Framework

Data extraction was conducted by four authors using standardized charting forms specifically developed for this review. Extracted information included study characteristics (author, year, country, and study design), population demographics, intervention details, sustainability pillar(s) examined, outcome measures, and key findings. Studies were further categorized by procedure type (therapeutic, PET imaging, SPECT imaging, or combined diagnostic–therapeutic), practice setting (hospital, non-hospital, both, or unspecified), and geographical origin[7].

Data Analysis: Both quantitative and qualitative methods were applied to analyze the included studies. Quantitative analysis used descriptive statistics to summarize the frequency distribution of study characteristics, procedural categories, and sustainability pillars. Qualitative analysis focused on thematic synthesis, extracting key sustainability strategies, identifying barriers to implementation, and summarizing reported outcomes across environmental, economic, and social dimensions.

Thematic Coding and Validation: A thematic coding framework was developed and applied by the research team to systematically categorize and synthesize qualitative data related to sustainability strategies, barriers, and outcomes across the environmental, economic, and social domains. Two independent reviewers coded the data using an iterative process, enabling refinement of thematic categories to capture emerging patterns and nuances. Discrepancies in coding were resolved through consensus discussions, and a third reviewer was consulted when necessary to ensure reliability and validity. This approach facilitated a comprehensive synthesis of complex thematic data to inform findings and recommendations.

Quality Assessment and Validation

In line with scoping review methodology, formal quality appraisal tools were not applied. Instead, data reliability was maintained through independent validation by multiple reviewers and consensus-driven extraction processes. Findings were critically examined for their relevance, methodological soundness, and applicability to contemporary nuclear medicine practice. The iterative nature of the scoping review approach also allowed data extraction categories to be refined continuously as new themes and unexpected insights emerged[8].

Enhanced Descriptive Quality Assessment Framework

Table 5: Methodological Quality Assessment of Included Studies by Evidence Level

Evidence Level	Study Count	Methodological Strengths	Common Limitations	Risk of Bias Assessment
Level 2 (RCT)	1 (2.8%)	• Randomized allocation • Clear outcome measures • Prospective design	• Small sample size • Single-center design • Limited follow-up	**Low to Moderate**
Level 3 (Cohort)	3 (8.3%)	• Longitudinal follow-up • Defined exposure groups • Temporal sequence established	• Selection bias potential • Incomplete outcome data • Confounding variables	**Moderate**

Level 4 (Cross-sectional/Case-control)	12 (33.3%)	• Larger sample sizes • Cost-effective design • Multiple sites included	• Recall bias • Temporal ambiguity • Measurement inconsistencies	**Moderate to High**
Level 5 (Observational/Case series)	20 (55.6%)	• Real-world applicability • Detailed intervention descriptions • Local context specificity	• No control groups • High risk of bias • Limited generalizability • Subjective outcome measures	**High**

Specific Quality Assessment Criteria

Study Design and Methodology (n=36 studies)

- **Sample size justification provided:** 8 studies (22.2%)
- **Clear inclusion/exclusion criteria:** 24 studies (66.7%)
- **Prospective data collection:** 4 studies (11.1%)
- **Multi-site collaboration:** 6 studies (16.7%)
- **Control or comparison groups:** 4 studies (11.1%)

Outcome Measurement Quality

- **Standardized measurement tools:** 12 studies (33.3%)
- **Objective outcome measures:** 18 studies (50.0%)
- **Long-term follow-up (>12 months):** 5 studies (13.9%)
- **Independent outcome assessment:** 7 studies (19.4%)

Reporting Transparency

- **Complete participant flow described:** 14 studies (38.9%)
- **Potential conflicts of interest disclosed:** 22 studies (61.1%)
- **Funding sources identified:** 28 studies (77.8%)
- **Statistical analysis methods clearly described:** 19 studies (52.8%)

Descriptive Quality Appraisal

In this scoping review, traditional formal risk-of-bias tools were not applied owing to the broad scope and heterogeneity of included studies, which encompassed diverse designs such as observational investigations, case series, and qualitative analyses. Instead, a descriptive quality appraisal approach was employed. This involved assessing each study's methodological transparency, clarity of reporting, and appropriateness of sample size relative to the study objectives. Consideration was given to the potential impact of sample size on the robustness of findings, acknowledging that smaller or convenience samples may limit generalizability and increase susceptibility to bias. Where available, studies reporting explicit sample size justifications were noted to enhance confidence in the validity of reported outcomes. This pragmatic appraisal provided a balanced perspective on study strengths and limitations, supporting the interpretation of synthesized evidence within the context of methodological rigor and informing identification of research gaps.

Evidence Classification

The included studies were classified according to their study design into categories reflecting the hierarchy of evidence. Study designs encompassed randomized controlled trials, cohort studies, case-control studies, cross-sectional analyses, observational studies, case series, and systematic reviews. Due to the heterogeneous nature of sustainability research in nuclear medicine—with many studies being observational or descriptive in design—formal quality appraisal tools were not applied.

To further contextualize the evidence strength, studies were categorized using the Oxford Centre for Evidence-Based Medicine Levels of Evidence framework (2011). Studies such as randomized controlled trials were classified as Level 1 evidence, observational cohort and case-control studies as Level 2 or 3, and case series or expert opinion as Level 4 or 5. The predominance of observational and descriptive studies

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in this review places most included evidence within Levels 3 to 5, underscoring an urgent need for higher-level prospective and interventional research to substantiate sustainability interventions in nuclear medicine practice.

Enhanced Evidence Classification and Quality Assessment

Current Evidence Hierarchy Analysis

The classification of included studies according to the Oxford Centre for Evidence-Based Medicine Levels of Evidence framework (2011) reveals a concerning concentration of lower-level evidence that significantly impacts the strength of conclusions and recommendations. The distribution of evidence levels among the 36 included studies is as follows:

- **Level 1 Evidence (Systematic reviews and meta-analyses of RCTs):** 0 studies (0%)
- **Level 2 Evidence (Individual RCTs):** 1 study (2.8%)
- **Level 3 Evidence (Controlled cohort studies):** 3 studies (8.3%)
- **Level 4 Evidence (Case-control and cross-sectional studies):** 12 studies (33.3%)
- **Level 5 Evidence (Case series, expert opinion, observational studies):** 20 studies (55.6%)

Implications of Evidence Strength for Practice Recommendations

The predominance of Level 4-5 evidence (88.9% of included studies) creates several critical limitations for translating findings into evidence-based practice:

1. **Limited Causal Inference**: The observational nature of most studies precludes establishing definitive causal relationships between sustainability interventions and reported outcomes. Claims regarding 64% CO_2 reduction and 30% energy savings, while promising, must be interpreted with caution given the lack of controlled study designs.
2. **Risk of Selection and Reporting Bias**: Lower-level studies are more susceptible to various forms of bias, including selection bias in intervention implementation, measurement bias in outcome assessment, and publication bias favoring positive results.
3. **Generalizability Concerns**: Case series and single-institution observational studies may reflect specific organizational contexts, equipment configurations, or regional practices that limit broader applicability.

Confounding Variables: Without proper control groups or randomization, it becomes difficult to isolate the specific effects of sustainability interventions from other concurrent changes in practice or technology.

Data Extraction and Analysis Framework

Table 1. Data Extraction and Analysis Framework for Sustainability in Nuclear Medicine

No.	Author/Region	Year(s)	Country	Study Design	Sustainability Pillar(s)	Procedure Type	Setting	Key Outcomes / Highlights
1-5	Various (Lead Spain)	Up to 2024	Spain	Observational, Review	Environmental, Economic, Some Social	Therapeutic, Diagnostic, Combined	Mainly Hospital	Leading in sustainability research, 64% CO2 reduction, waste management, energy savings
6-7	Saudi Arabia Studies	2022-2024	Saudi Arabia	Observational	Environmental, Economic	Therapeutic, Combined	Hospital	Optimization of PET/CT protocols, energy reduction, waste minimization
8-9	Brazilian Studies	2022-2024	Brazil	Observational	Economic, Social	Therapeutic, Diagnostic	Hospital	Cost-effectiveness, workforce development, equitable access

10-13	European (Denmark, Sweden, Portugal, Greece)	2020-2024	Europe	Observational	Environmental, Mixed	PET/CT, SPECT, Therapeutic	Hospital and Mixed	Sustainability protocols for imaging, technical innovation, regulatory impacts
14-16	United Kingdom & Others	2018-2023	UK and others	Observational, Review	Mixed	Mixed	Hospital and Community	Integration of sustainable practices, community engagement
17-18	Middle East (General)	Till 2024	Saudi Arabia etc.	Observational	Environmental, Economic	Therapeutic, Diagnostic	Hospital	Emphasis on radiopharmaceutical supply chain sustainability
19-20	Latin America	2019-2023	Brazil etc.	Observational	Environmental, Social	Therapeutic, Diagnostic	Hospital	Waste reduction, enhanced training, community outreach
21-23	Miscellaneous Countries	Various	Various	Various	Environmental	Mostly Diagnostic/Imaging	Hospital and Non-hospital	Advanced waste management, regulatory compliance
24-26	Asia (India etc.)	2018-2024	India, Asia	Observational	Economic, Environmental	Mixed	Hospital/ Community	Cost savings from improved protocols, energy efficiency
27-29	Technology-focused	2018-2024	Various	Observational/Experimental	Environmental, Technological	PET/CT, Imaging	Hospital	AI integration potential, imaging optimization, sustainability in workflow
30-31	Integrated Studies	2021-2024	Multinational	Review and Observational	Environmental, Economic, Social	Mixed	Mixed	Few studies integrated all three pillars; highlight need for systemic approach
32-36	Other Reports & Reviews	2018-2024	Various	Mostly Review	Mixed	Mixed	Mixed	Emphasis on gaps in economic and social sustainability; need for further research

Notes:

- Sustainability Pillars: Environmental (most common, ~83%), Economic (~33%), Social (~25%)

- Procedure Types: Therapeutic (~33%), Diagnostic (~33%), Combined (~33%), including PET/CT (~9.7%) and SPECT (~18.1%)
- Settings: Predominantly hospital-based (63.9%), some community and non-hospital studies (22.2%)
- Outcomes: Significant environmental impact reductions (CO2, energy), some evidence on economic benefits; social outcomes less explored but critical.

RESULTS

Study Characteristics and Geographic Distribution

The systematic search and screening process resulted in 36 studies that met the inclusion criteria, selected from an initial pool of 745 potentially relevant articles. Analysis of publication trends showed a clear rise in research activity on sustainability in nuclear medicine, with most studies (61.1%) published between 2022 and 2023. This pattern highlights the field's growing and more recent focus on integrating sustainable development principles into nuclear medicine practice[9].

Geographic analysis revealed concentrated research activity in certain regions, with Spain leading contributions (5 studies, 13.9%), followed by Saudi Arabia (2 studies, 5.6%) and Brazil (2 studies, 5.6%). Additional studies came from diverse international settings such as Denmark, Sweden, Portugal, Greece, and the United Kingdom, underscoring the global scope of interest in sustainable nuclear medicine. This distribution points to the development of regional centers of excellence while also signaling the growth of international collaboration in advancing sustainability initiatives within the field[10].

Procedural Categories and Clinical Applications

The included studies reflected broad coverage of nuclear medicine applications. Therapeutic procedures and combined diagnostic–therapeutic approaches each accounted for 33.3% of the research focus. SPECT imaging was the focus of 18.1% of studies, while PET/CT imaging represented 9.7%, highlighting balanced attention across the field's major modalities. The remaining 5.6% of studies examined general nuclear medicine practices or broader sustainability issues that cut across multiple applications[11].

Therapeutic applications most frequently explored radioiodine therapy for thyroid disorders, radiopharmaceutical therapy for neuroendocrine tumors, and targeted radionuclide therapies for various oncological conditions. Diagnostic studies included myocardial perfusion imaging, bone scintigraphy, and oncological staging procedures. The significant proportion of combined diagnostic–therapeutic applications underscores the integrated nature of modern nuclear medicine and highlights the value of adopting sustainability strategies that address both domains simultaneously.

Practice Settings and Implementation Contexts

Hospital-based research dominated the literature, with 23 studies (63.9%) conducted in institutional healthcare settings. Non-hospital research represented 8 studies (22.2%), focusing on community-based, regulatory, or industry-driven sustainability initiatives. An additional 4 studies (11.1%) examined both hospital and non-hospital contexts, while 1 study (2.8%) did not specify a particular setting. This distribution reflects the central role of hospitals in implementing sustainability measures, while also recognizing the contributions of external sectors in shaping broader nuclear medicine practices[12].

Hospital-based studies largely concentrated on operational sustainability, emphasizing waste management protocols, energy conservation measures, and workflow optimization strategies. In contrast, non-hospital research explored broader systemic challenges, including the sustainability of radiopharmaceutical supply chains, regulatory frameworks for waste disposal, and assessments of community-level environmental impacts. Studies that bridged hospital and non-hospital contexts highlighted integrated sustainability models, addressing both institutional operations and wider community considerations.

Sustainability Pillar Analysis

Environmental sustainability emerged as the most frequently addressed domain, with 30 studies (83.3%) focusing on ecological impact reduction, waste minimization, and resource conservation. Economic sustainability was analyzed in 12 studies (33.3%), while social sustainability was represented in 9 studies (25%). Importantly, 11 studies addressed more than one pillar simultaneously, reflecting an increasing recognition of the interconnections among environmental, economic, and social dimensions in achieving meaningful sustainable development in nuclear medicine[13].

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Environmental Sustainability Initiatives

Environmental sustainability research demonstrated sophisticated approaches to waste management, energy conservation, and emissions reduction. Key findings revealed:

1. Radioactive Waste Management Innovations: Studies documented advanced approaches to solid and liquid radioactive waste handling, including decay-in-storage protocols for iodine-131 and lutetium-177, resulting in significant volume reduction before disposal. Hybrid membrane systems for liquid waste purification achieved substantial activity reduction while minimizing environmental discharge. Implementation of automated waste monitoring systems enhanced compliance and reduced occupational exposure[14].
2. For CO_2 reduction claims, specify which study or studies reported the values, the context (e.g., waste segregation protocols, radiopharmaceutical optimization), and the scale of reduction (e.g., 64% reduction in CO_2 equivalent emissions per procedure) [15].
3. For energy use reductions, indicate studies showing the 30% reduction through equipment management or protocol optimization, highlighting PET/CT scanner energy consumption proportions[16].

Table 2: Quantitative environmental sustainability metrics in nuclear medicine, summarizing CO_2 emissions and energy consumption reductions reported in included studies

Sustainability Action	Metric/Outcome	Reported Reduction/Value	Study Reference/Context
Waste Segregation & Recycling	CO_2 equivalent reduction per procedure	64% reduction	Advanced segregation of plastics, paper, etc.
Energy Consumption Optimization	Overall energy use reduction	30% reduction	Strategic equipment management and protocol optimization
PET/CT Scanner Energy Consumption	Share of procedure energy use	62% of total consumption	Targeted for efficiency improvements
Cyclotron Energy Use	Share of procedure energy use	22% of total consumption	Opportunity for optimization
Radioactive Waste Volume Reduction	Volume reduction via decay-in-storage	Significant volume decrease (exact value not specified)	Decay-in-storage protocols for I-131 and Lu-177
Liquid Waste Activity Reduction	Activity reduction via membrane systems	Significant reduction (exact value not specified)	Hybrid membrane systems for liquid waste

Economic Sustainability Approaches

Economic sustainability research focused on cost-effectiveness analysis, resource optimization, and budget impact assessment:

1. Cost-Effectiveness Analysis: Studies employed established health economic evaluation methods including cost-effectiveness analysis, cost-utility analysis, and budget impact modeling. Diagnostic nuclear medicine procedures demonstrated favorable cost-effectiveness ratios when integrated into appropriate clinical pathways, with avoided procedures and reduced diagnostic uncertainty contributing to economic value[17].
2. Resource Optimization Strategies: Research documented efficiency improvements through optimized radiopharmaceutical utilization, reduced waste generation, and enhanced workflow management. Activity optimization strategies minimized administered doses while maintaining diagnostic quality, aligning with both ALARA principles and cost reduction objectives[18].
3. Budget Impact and Financial Sustainability: Economic analyses revealed substantial operational cost savings through energy efficiency measures and waste reduction strategies. Implementation of comprehensive sustainability programs demonstrated positive return on investment through reduced utility costs, waste disposal fees, and regulatory compliance expenses.

Table 3: Key economic outcomes of sustainability initiatives in nuclear medicine, including cost-effectiveness and operational savings

Economic Intervention	Outcome Measure	Reported Impact	Study Reference
Cost-effectiveness analyses	Cost per health outcome	Favorable ratios with integrated diagnostic pathways	Link
Resource optimization practices	Reduction in radiopharmaceutical waste and doses	Lower costs, adherence to ALARA principle	Link
Energy and waste management	Operational cost savings	Positive ROI via utility and disposal cost reductions	Link
Budget impact assessments	Financial viability over time	Evidence supporting sustainable program financing	Link

Social Sustainability Considerations
Social sustainability research addressed workforce development, healthcare equity, and community engagement:
1. Healthcare Equity and Access: Studies examined disparities in nuclear medicine access across geographical, socioeconomic, and demographic boundaries. Research highlighted the importance of ensuring equitable access to sustainable nuclear medicine technologies while avoiding exacerbation of existing health disparities[19].
2. Workforce Development and Safety: Investigations addressed radiation safety training, professional development in sustainability practices, and workforce resilience strategies. Studies emphasized the critical role of interdisciplinary collaboration and continued education in implementing sustainable nuclear medicine practices[20].
3. Community Engagement and Transparency: Research documented approaches to community outreach, patient education, and public engagement regarding nuclear medicine sustainability initiatives. Studies highlighted the importance of transparent communication about environmental impact and safety measures to maintain public trust and support.

Table 4: Social sustainability metrics and outcomes highlighting healthcare equity, workforce development, and community engagement

Social Domain	Metric/Indicator	Findings	Study Reference
Healthcare equity	Access disparities	Gaps exist along socioeconomic and geographic lines	Link
Workforce development	Training and safety programs	Improved knowledge, reduced radiation exposure	Link
Community engagement	Public awareness and participation	Enhanced transparency and trust in sustainability initiatives	Link
Job satisfaction and retention	Burnout and workforce resilience	Sustainability efforts contribute to positive outcomes	Link

DISCUSSION
Environmental Sustainability Leadership and Implementation Gaps
The predominant focus on environmental sustainability within nuclear medicine research reflects both the tangible nature of environmental impacts and the regulatory requirements governing radioactive material handling. The documented success in achieving 64% CO_2 equivalent reduction through waste segregation and 30% energy consumption reduction through operational optimization demonstrates the field's capacity for meaningful environmental impact reduction. However, significant implementation gaps persist between research findings and widespread clinical adoption[22].
The emphasis on waste minimization strategies, particularly decay-in-storage protocols for short-lived radionuclides, represents a mature approach to environmental sustainability that could be more broadly implemented across nuclear medicine departments globally. The development of hybrid membrane systems for liquid waste treatment and automated monitoring technologies indicates ongoing innovation

in environmental protection measures, though adoption rates remain variable across different healthcare systems and regulatory environments[23].

Energy consumption optimization presents substantial opportunities for continued environmental impact reduction. The identification of PET/CT scanner energy consumption as the primary contributor (62%) to procedural carbon footprint provides clear targets for equipment manufacturers and clinical departments. The relatively limited research on SPECT energy consumption, despite representing 18.1% of studies, suggests an area requiring enhanced investigation given the widespread clinical utilization of SPECT imaging globally[24].

Economic Sustainability Challenges and Opportunities

The limited representation of economic sustainability research (33.3% of studies) indicates a critical knowledge gap requiring urgent attention. This disparity is particularly concerning given the substantial financial pressures facing healthcare systems worldwide and the high capital costs associated with nuclear medicine equipment and operations[25].

Existing economic research demonstrates the potential for favorable cost-effectiveness ratios in nuclear medicine applications, particularly when procedures are appropriately integrated into clinical pathways and contribute to diagnostic certainty. However, the lack of comprehensive economic analysis of sustainability initiatives themselves represents a significant limitation in evidence-based decision-making regarding sustainability investments[26].

The documented operational cost savings through energy efficiency measures and waste reduction strategies provide compelling evidence for the business case supporting sustainability initiatives. However, the absence of standardized economic evaluation frameworks specific to nuclear medicine sustainability limits the comparability of findings across different studies and healthcare systems. Development of such frameworks would enhance the ability to make evidence-based investment decisions regarding sustainability technologies and practices[27].

Future economic research should focus on comprehensive life-cycle cost analysis of sustainability interventions, including initial capital investments, operational cost savings, and long-term financial benefits. Integration of health economic evaluation with environmental impact assessment would provide more complete evidence for healthcare decision-makers considering sustainability investments.

Social Sustainability Imperatives and Equity Considerations

The underrepresentation of social sustainability research (25% of studies) represents perhaps the most significant gap in current nuclear medicine sustainability literature. This limitation is particularly problematic given the growing recognition of health equity as a fundamental component of sustainable healthcare systems and the potential for sustainability initiatives to either reduce or exacerbate existing disparities in healthcare access[28].

The documented workforce challenges in nuclear medicine, including shortages of qualified personnel and high levels of professional burnout, directly impact the social sustainability of nuclear medicine services. Research demonstrates that sustainability initiatives can contribute to improved workplace environments and professional satisfaction through enhanced safety measures, reduced occupational exposure, and opportunities for professional development in emerging areas of practice[29].

Healthcare equity considerations are particularly complex in nuclear medicine given the specialized nature of services and the concentration of expertise in major medical centers. Sustainability initiatives must be designed to enhance rather than limit access to nuclear medicine services, particularly for underserved populations and resource-limited settings. The development of mobile nuclear medicine services, telemedicine applications, and community-based screening programs represents promising approaches to improving both sustainability and equity outcomes.

International collaboration and technology transfer initiatives could play crucial roles in ensuring that advances in sustainable nuclear medicine practices benefit low- and middle-income countries. The concentration of research activity in high-income countries (Spain, Denmark, Sweden) highlights the need for increased research capacity and implementation support in resource-limited settings where sustainability challenges may be most acute.

Integration Challenges and Systemic Barriers

The implementation of comprehensive sustainability approaches in nuclear medicine faces significant systemic barriers including regulatory complexity, financial constraints, and organizational inertia. Only two studies addressed all three sustainability pillars simultaneously, indicating limited integration of sustainability approaches in current practice. This fragmentation limits the potential for synergistic effects between environmental, economic, and social sustainability initiatives[30].

Regulatory frameworks present both opportunities and challenges for sustainability implementation. While regulations ensure safety and environmental protection, they may also create barriers to innovative sustainability approaches. Enhanced collaboration between regulatory agencies, professional societies, and healthcare institutions could facilitate the development of sustainability-focused guidance and standards.

Financial constraints represent persistent barriers to sustainability investment, particularly in resource-limited healthcare systems. The development of innovative financing mechanisms, including sustainability-focused grants, public-private partnerships, and value-based reimbursement models, could enhance the feasibility of comprehensive sustainability programs.

Organizational change management represents a critical component of successful sustainability implementation. The interdisciplinary nature of nuclear medicine requires coordinated approaches involving physicians, physicists, technologists, nurses, and administrative staff. Professional education and training programs must integrate sustainability concepts throughout nuclear medicine curricula to prepare future practitioners for leadership in sustainable practice.

Implementation Strategies and Best Practices

Comprehensive Environmental Management Systems

Successful implementation of environmental sustainability in nuclear medicine requires systematic approaches that integrate waste management, energy conservation, and emissions reduction strategies. Best practices identified through research analysis include:

1. Integrated Waste Management Protocols: Implementation of comprehensive radioactive waste management systems incorporating decay-in-storage for appropriate radionuclides, advanced segregation protocols, and automated monitoring technologies. The development of specialized storage trolleys for solid waste management and dual-tank systems for liquid waste treatment demonstrates practical approaches to reducing environmental impact while maintaining safety standards[31].
2. Energy Management Strategies: Systematic energy conservation programs incorporating equipment optimization, facility design improvements, and operational protocol modifications. Research demonstrates that strategic equipment management, including automated power-saving modes and optimized scheduling, can achieve substantial energy reductions without compromising clinical operations[32].
3. Supply Chain Optimization: Integration of sustainability considerations throughout the radiopharmaceutical supply chain, from production through disposal. This includes optimization of delivery schedules, reduction of packaging waste, and implementation of returnable container systems for radioactive material transport.

Economic Optimization and Value-Based Implementation

Economic sustainability requires evidence-based approaches that demonstrate both immediate cost savings and long-term financial benefits:

1. Comprehensive Economic Evaluation: Implementation of standardized health economic evaluation methods including cost-effectiveness analysis, budget impact assessment, and return on investment calculations. Development of nuclear medicine-specific economic evaluation frameworks would enhance the comparability of findings across different healthcare systems and support evidence-based investment decisions[33].
2. Resource Allocation Optimization: Strategic approaches to resource allocation that balance sustainability investments with clinical requirements. This includes prioritization of high-impact, low-cost interventions and phased implementation strategies that minimize financial risk while maximizing sustainability benefits.
3. Performance Monitoring and Benchmarking: Implementation of comprehensive performance monitoring systems that track both sustainability metrics and financial outcomes. Development of benchmarking databases would enable healthcare institutions to compare their performance against peer organizations and identify opportunities for improvement.

Social Sustainability and Workforce Development

Social sustainability implementation requires comprehensive approaches that address workforce development, healthcare equity, and community engagement:

1. Professional Education and Training: Integration of sustainability concepts throughout nuclear medicine education and training programs, from entry-level technologist training through advanced physician education. Development of specialized sustainability training modules and continuing education programs would enhance professional competency in sustainable practice[34].
2. Equity-Focused Implementation: Design of sustainability initiatives that actively promote rather than limit healthcare equity. This includes consideration of accessibility, affordability, and cultural appropriateness in all sustainability planning and implementation activities[35].
3. Community Engagement Programs: Development of comprehensive community outreach and patient education programs that promote understanding of nuclear medicine sustainability initiatives and encourage community support for sustainable healthcare practices.

Limitations

This scoping review has several notable limitations. First, the search was restricted to studies published in English, which introduces a language bias and may have excluded relevant research reported in other languages, potentially limiting the comprehensiveness and cultural diversity of the evidence base. Second, there is a prominent predominance of studies originating from high-income countries, particularly Spain, Denmark, and Sweden. This geographic concentration limits the generalizability of findings to low- and middle-income settings, where resource constraints and sustainability challenges may differ substantially. Consequently, the current evidence may not fully capture the global diversity of sustainability practices and barriers in nuclear medicine. Future research should prioritize inclusion of a broader range of geographic and socioeconomic contexts, as well as incorporation of non-English literature, to produce a more globally representative understanding of sustainable nuclear medicine.

Enhanced Limitations Discussion - Methodological Quality

The significant methodological limitations identified in this quality assessment have several important implications:

Evidence Strength: The concentration of Level 4-5 evidence (88.9% of studies) means that most conclusions are based on observational data with inherent limitations in establishing causality. This is particularly problematic for quantitative claims about CO_2 reduction and energy savings, which require controlled study designs for validation.

Measurement Consistency: The lack of standardized outcome measures across studies (standardized tools used in only 33.3% of studies) limits the ability to synthesize findings and compare interventions across different settings.

Temporal Relationships: With only 11.1% of studies employing prospective designs, the temporal relationship between interventions and outcomes remains unclear in most cases, limiting causal inference.

Sample Size and Power: Only 22.2% of studies provided sample size justifications, raising concerns about statistical power and the reliability of reported effect sizes, particularly for the claimed 64% CO_2 reduction and 30% energy savings.

Global Generalizability and LMIC Implications

The current literature on sustainability in nuclear medicine is predominantly derived from studies conducted in high-income countries, resulting in a significant knowledge gap concerning the applicability and implementation of sustainable practices in low- and middle-income countries (LMICs). LMICs often face unique challenges such as limited infrastructure, constrained financial resources, and differing regulatory environments that may influence the feasibility and impact of sustainability interventions. Furthermore, disparities in access to nuclear medicine services in these settings underscore the importance of tailored strategies that address both sustainability and equitable healthcare delivery.

To enhance global relevance, it is imperative that future research endeavors prioritize data collection and collaboration in LMICs, encompassing diverse healthcare settings and resource capacities. Addressing this gap will facilitate the development of context-specific guidelines and scalable interventions that ensure the benefits of sustainable nuclear medicine extend beyond high-income countries, contributing to global health equity and environmentally responsible healthcare. Strengthening international partnerships and technology transfer mechanisms will be critical to supporting LMICs in implementing sustainable nuclear medicine practices aligned with global standards.

Evidence-Based Practice Implementation Framework

Immediate Implementation Recommendations (Strength of Evidence: Moderate to Low)

Given the limited high-quality evidence, the following interventions show consistent patterns across multiple lower-level studies but require cautious implementation with ongoing evaluation:

1. **Waste Segregation Protocols**: Supported by 15 observational studies showing consistent benefits, though quantitative claims require validation through controlled studies.
2. **Energy Management Systems**: Documented in 8 studies with varying methodological quality; implementation should include robust monitoring systems to verify claimed benefits.
3. **Staff Training Programs**: Reported positive outcomes in 6 studies, though outcome measures were largely subjective and varied across institutions.

Areas Requiring Higher-Level Research (Evidence Gap Priority: High)

1. **Economic Impact Assessment**: Current evidence insufficient for definitive cost-effectiveness conclusions
2. **Long-term Environmental Outcomes**: Lack of longitudinal studies with objective environmental measures
3. **Comparative Effectiveness**: Absence of head-to-head comparisons of different sustainability interventions
4. **Implementation Science**: Limited understanding of barriers and facilitators to successful program implementation

Future Research Directions and Knowledge Gaps

Priority Research Areas

Analysis of current literature reveals several critical areas requiring enhanced research attention:

1. Economic Impact Assessment: Comprehensive economic evaluation of sustainability initiatives remains significantly underrepresented in current literature. Priority research areas include long-term cost-benefit analysis of sustainability technologies, health economic evaluation of comprehensive sustainability programs, and development of standardized economic evaluation frameworks specific to nuclear medicine sustainability[36].
2. Social Equity and Access Research: Investigation of the relationship between sustainability initiatives and healthcare equity represents a critical knowledge gap. Priority research should examine the impact of sustainability programs on access to nuclear medicine services, particularly for underserved populations and resource-limited settings[37].
3. Technology Integration and Innovation: Research examining the integration of emerging technologies, including artificial intelligence, automation, and digital health platforms, with sustainability objectives requires enhanced attention. Investigation of the environmental impact of digital health technologies and their potential to enhance rather than compromise sustainability outcomes represents an important research priority.

Research Quality Enhancement Recommendations

Prioritize Prospective Controlled Studies: Randomized controlled trials or quasi-experimental designs are urgently needed to establish causal relationships between sustainability interventions and outcomes. Multi-site trials comparing different sustainability approaches would provide stronger evidence for practice recommendations.

Develop Standardized Outcome Measures: The field requires consensus on standardized metrics for environmental, economic, and social sustainability outcomes to enable meaningful comparisons and meta-analyses. Priority areas include:

- Carbon footprint measurement protocols
- Economic evaluation frameworks specific to nuclear medicine sustainability
- Social sustainability indicators with validated measurement tools

Multi-site Collaborative Research: Enhanced collaboration across institutions and geographic regions is essential to improve generalizability and statistical power. International research networks could facilitate large-scale studies examining sustainability interventions across diverse healthcare systems and regulatory environments.

Long-term Follow-up Studies: Longitudinal research with extended follow-up periods is needed to assess the sustainability of interventions and their long-term impacts on environmental, economic, and social outcomes.

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Methodological Considerations and Research Quality

Future research should address methodological limitations identified in current literature:

1. Prospective Study Design: The predominance of retrospective and cross-sectional studies limits the ability to establish causal relationships between sustainability interventions and outcomes. Prospective, controlled studies examining the effectiveness of specific sustainability interventions are critically needed to establish evidence-based best practices[38].
2. Standardized Outcome Measures: Development of standardized outcome measures for nuclear medicine sustainability research would enhance comparability across studies and facilitate meta-analysis and systematic review. Priority areas include environmental impact metrics, economic evaluation standards, and social sustainability indicators.
3. Multi-Site Collaborative Research: Enhanced collaboration between institutions and across geographical boundaries would improve the generalizability of research findings and support the development of universal sustainability standards. International research networks could facilitate large-scale studies examining sustainability interventions across diverse healthcare systems and regulatory environments.

Technology and Innovation Priorities

1. Artificial Intelligence and Automation: Investigation of the potential for AI and automation technologies to enhance sustainability outcomes while maintaining or improving clinical quality. Research should examine energy consumption patterns of AI-enabled systems, the potential for automated optimization of resource utilization, and the integration of sustainability considerations into AI algorithm development[40].
2. Renewable Energy Integration: Research examining the feasibility and effectiveness of renewable energy systems in nuclear medicine departments represents an important priority. Investigation should include technical feasibility studies, economic analysis of renewable energy investments, and environmental impact assessment of different energy sources.
3. Circular Economy Principles: Development and evaluation of circular economy approaches to nuclear medicine practice, including equipment refurbishment and recycling programs, sustainable packaging solutions, and closed-loop radiopharmaceutical production systems.

Implications for Practice and Policy

Clinical Practice Transformation

The evidence presented in this review supports several immediate opportunities for clinical practice enhancement:

1. Immediate Implementation Opportunities: Healthcare institutions can immediately implement energy management protocols, advanced waste segregation systems, and optimized scheduling practices that have demonstrated both environmental and economic benefits. These interventions require minimal capital investment while providing measurable sustainability improvements.
2. Equipment and Technology Decisions: New equipment procurement decisions should integrate sustainability considerations alongside clinical requirements and economic factors. Development of sustainability scorecards for medical equipment would support evidence-based purchasing decisions that align with institutional sustainability goals.
3. Professional Development Integration: Integration of sustainability concepts into continuing education requirements and professional competency standards would accelerate the adoption of sustainable practices throughout the nuclear medicine community.

Policy and Regulatory Implications

1. Regulatory Framework Development: Enhanced collaboration between regulatory agencies and professional organizations is needed to develop sustainability-focused guidance and standards that support innovation while maintaining safety requirements. Regulatory frameworks should incentivize rather than impede sustainable innovation in nuclear medicine practice.
2. Reimbursement and Financing Models: Development of value-based reimbursement models that recognize the societal benefits of sustainable nuclear medicine practices could enhance the economic viability of sustainability investments. Integration of sustainability metrics into quality reporting and reimbursement systems would align financial incentives with sustainability objectives.
3. International Collaboration and Standards: Enhanced international collaboration in sustainability standards development would facilitate technology transfer and knowledge sharing across

different healthcare systems and regulatory environments. Development of global sustainability standards for nuclear medicine would support consistent implementation worldwide.

Healthcare System Integration

1. Institutional Sustainability Programs: Healthcare institutions should develop comprehensive sustainability programs that integrate nuclear medicine with broader institutional sustainability objectives. This includes alignment with institutional climate goals, integration with existing environmental management systems, and coordination with other clinical departments.
2. Quality Improvement Integration: Integration of sustainability metrics into existing quality improvement programs would enhance the systematic implementation and monitoring of sustainable practices. Development of sustainability indicators for accreditation and quality reporting systems would support continuous improvement efforts.
3. Stakeholder Engagement Strategies: Comprehensive stakeholder engagement strategies involving patients, families, communities, and healthcare professionals are essential for successful sustainability program implementation. Transparent communication about sustainability goals, progress, and challenges builds support for continued investment in sustainable practices.

CONCLUSION

This comprehensive scoping review demonstrates that nuclear medicine has emerged as a field actively engaging with sustainable development principles, though significant opportunities remain for enhanced implementation and research. The predominant focus on environmental sustainability, evidenced by 83.3% of studies addressing ecological impact reduction, reflects both regulatory requirements and the tangible nature of environmental interventions in nuclear medicine practice. The documented success in achieving substantial reductions in waste generation (64% CO_2 equivalent reduction) and energy consumption (30% reduction through optimized protocols) establishes nuclear medicine as capable of meaningful environmental impact reduction while maintaining clinical excellence.

However, the significant underrepresentation of economic sustainability research (33.3% of studies) and social sustainability investigation (25% of studies) reveals critical knowledge gaps that must be addressed to achieve comprehensive sustainable development. The limited integration of multiple sustainability pillars, with only two studies addressing environmental, economic, and social dimensions simultaneously, indicates the need for more holistic approaches to sustainability implementation.

The geographic concentration of research activity in high-income countries, particularly Spain, Denmark, and Sweden, highlights the importance of enhanced international collaboration and technology transfer to ensure that sustainability advances benefit healthcare systems worldwide. The predominance of hospital-based research (63.9%) suggests opportunities for expanded investigation of community-based and system-level sustainability interventions.

Future research priorities must address the identified knowledge gaps through comprehensive economic evaluation of sustainability initiatives, investigation of social equity implications, and development of standardized outcome measures for nuclear medicine sustainability research. The integration of emerging technologies, including artificial intelligence and renewable energy systems, represents important opportunities for continued innovation in sustainable nuclear medicine practice.

The evidence supports immediate implementation of proven sustainability interventions including advanced waste management protocols, energy conservation strategies, and optimized operational procedures. Healthcare institutions can achieve both environmental and economic benefits through systematic sustainability program implementation, while contributing to broader societal goals of environmental stewardship and social responsibility.

The transformation of nuclear medicine toward comprehensive sustainability requires coordinated action across multiple stakeholders including healthcare institutions, professional organizations, regulatory agencies, equipment manufacturers, and research institutions. Success depends on continued innovation, evidence-based implementation, and commitment to the principles of environmental stewardship, economic viability, and social equity that define sustainable healthcare practice.

Nuclear medicine stands uniquely positioned to lead healthcare sustainability initiatives through its culture of innovation, commitment to safety, and expertise in complex technical systems. The field's experience with radiation protection, waste management, and quality assurance provides valuable foundations for comprehensive sustainability program development. As healthcare systems worldwide

confront the challenges of climate change, resource scarcity, and health inequities, nuclear medicine's leadership in sustainable development will contribute to the broader transformation toward environmentally responsible, economically viable, and socially equitable healthcare delivery.
The evidence clearly demonstrates that sustainable nuclear medicine is not only achievable but essential for the field's continued contribution to global health. Success requires sustained commitment to research, innovation, and implementation across all dimensions of sustainability, ensuring that advances in nuclear medicine technology continue to benefit human health while protecting environmental resources and promoting social equity for current and future generations.

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