The Review Of
DIABETIC
STUDIES OPEN ACCESS

Nanoradiopharmaceuticals In Nuclear Medicine: Integrating Clinical Pharmacy, Biochemistry, Laboratory Sciences, And Public Health For Precision Diagnostics And Targeted Therapy

Mamdouh Ghazi Alotaibi[1],Fayez Farraj Alshehri[2],Fahad Saad Alamri[3],Ibrahim Abdullah Ibrahim Almalki[4],Fahad Ali Mohsen Alzahrani[5],Ramzi Dahman Azi[6],Abdulaziz Khamis Alqahtani[7],Meshal Fihan Haylan Almotairi[8],Mazen Saad Alamri[9],Bandar Mansoor Alanizy[10]

[1]Medical Laboratories , Medical services-MOI, Riyadh, Saudi Arabia
[2]Biochemistry & Laboratory Technician , Medical services-MOI, Riyadh, Saudi Arabia
[3]Medical Laboratories, Medical services-MOI, Riyadh, Saudi Arabia
[4]public health, King Abdulaziz International Airport Health Center, Jeddah
[5]Medical Laboratory, Al-Ha'ir Prison Health Center, Riyadh
[6]Medical Laboratories, Medical services-MOI, Riyadh,Saudi Arabia
[7]Clinical Pharmacist, General directorate of medical services, Riyadh,Saudi Arabia
[8]Pharmacy, Prince Sultan Medical City, Riyadh
[9]Nuclear medicine, Price sultan cardiac center , Riyadh
[10]Pharmacy technician , Al-Qassim Primary Health Care, Qassim

Abstract

Background:
The integration of nanotechnology into nuclear medicine has revolutionized diagnostic imaging and targeted therapy through the emergence of nanoradiopharmaceuticals—nanoscale systems designed to carry radionuclides for precise disease targeting. These agents combine the pharmacokinetic control of nanocarriers with the diagnostic and therapeutic versatility of radiopharmaceuticals, enabling breakthroughs in oncology, cardiology, and molecular imaging. However, the safe and effective clinical translation of nanoradiopharmaceuticals depends on robust interdisciplinary collaboration among clinical pharmacy, biochemistry, medical laboratory sciences, and public health.

Objective:
This review examines global and regional advances in nanoradiopharmaceutical science, highlighting the interdisciplinary roles and challenges in optimizing their synthesis, clinical application, and regulatory integration within the context of Saudi Arabia's Vision 2030 healthcare transformation.

Methods:
A narrative review was conducted using databases including PubMed, Scopus, Web of Science, and ScienceDirect for the period 2018–2025. Studies were screened for relevance to nanoradiopharmaceutical development, pharmacological optimization, clinical translation, and population-level health impact. Thematic synthesis was applied following Braun and Clarke's model, integrating findings from biochemical, pharmacological, laboratory, and public health perspectives.

Results:
Recent studies demonstrate that nanoradiopharmaceuticals—such as ^68Ga-labeled nanoparticles, ^177Lu-polymeric systems, and gold nanoparticle conjugates—offer improved targeting accuracy, biocompatibility, and imaging sensitivity. Collaboration among biochemists (nanocarrier synthesis), pharmacists (dose optimization and safety monitoring), laboratory scientists (analytical validation and dosimetry), and public health experts (radiological protection and ethical oversight) is critical for achieving clinical efficacy and patient safety. Emerging applications of artificial intelligence (AI) in

radiopharmaceutical modeling, image quantification, and risk prediction further strengthen the precision and scalability of these technologies.

Conclusion:
Nanoradiopharmaceuticals represent the next frontier in precision nuclear medicine, offering integrated diagnostic and therapeutic solutions. Their successful implementation requires a coordinated, multidisciplinary framework that bridges molecular innovation, clinical governance, and public health policy. By investing in AI-enabled radiopharmacy systems, interdisciplinary training, and national regulatory frameworks, Saudi Arabia can become a regional leader in safe and innovative nanoradiopharmaceutical applications.

Keywords:
Nanoradiopharmaceuticals; Nuclear Medicine; Clinical Pharmacy; Biochemistry; Medical Laboratory Sciences; Public Health; Artificial Intelligence; Precision Diagnostics; Saudi Vision 2030

1. Introduction

Nuclear medicine represents one of the most dynamic frontiers in modern healthcare, combining molecular imaging and targeted therapy to achieve diagnostic precision and therapeutic efficacy. In recent years, the field has undergone a transformative evolution through the convergence of nanotechnology and radiopharmaceutical science, giving rise to a new generation of nanoradiopharmaceuticals. These nanoscale agents, which integrate radionuclides with engineered nanocarriers, are designed to selectively deliver therapeutic or diagnostic payloads to specific biological targets. Their development has paved the way for more accurate tumor localization, improved image contrast, and enhanced radionuclide retention, significantly advancing precision diagnostics and personalized medicine (Abou et al., 2023; IAEA, 2024).

However, the complexity of developing and applying nanoradiopharmaceuticals extends far beyond the laboratory bench. Their success in clinical practice requires interdisciplinary collaboration across several domains—particularly clinical pharmacy, biochemistry, medical laboratory sciences, and public health. Clinical pharmacists ensure the rational use, optimal dosing, and safety monitoring of radiolabeled nanoparticles, playing a key role in minimizing adverse effects and drug–radiotracer interactions. Biochemists, through their expertise in molecular synthesis and functionalization, contribute to improving the stability, specificity, and radiochemical purity of nanoparticles. Medical laboratory scientists provide critical analytical validation through biomarker quantification, biodistribution studies, and radiometric analysis, while public health professionals address broader issues of radiological safety, waste management, and population-level exposure control (Hosseini et al., 2022).

Within the Saudi healthcare landscape, these interdisciplinary collaborations align directly with the goals of Saudi Vision 2030, which emphasizes innovation, localization of health technologies, and precision medicine. The national focus on expanding nuclear medicine capabilities, particularly within tertiary and research centers, has created fertile ground for the integration of nanoradiopharmaceuticals into diagnostic and therapeutic workflows. Nonetheless, challenges remain—especially in cross-sector communication, regulatory readiness, and professional training related to radiopharmacy and nanomedicine.

This article therefore aims to explore how nanoradiopharmaceuticals are transforming nuclear medicine practice through interdisciplinary integration. It reviews recent global and regional developments, highlights the interconnected roles of pharmacy, biochemistry, laboratory sciences, and public health, and proposes a collaborative framework for advancing safe, efficient, and innovative nuclear medicine applications within Saudi Arabia and beyond.

2. Methods

This review adopts a narrative synthesis approach to explore the interdisciplinary applications and healthcare implications of nanoradiopharmaceuticals in nuclear medicine. Rather than adhering to the rigid structure of a systematic review, this approach allows for a broader and more interpretive

integration of evidence across scientific, clinical, and public health domains. Relevant literature was identified through comprehensive database searches conducted in PubMed, Scopus, Web of Science, and ScienceDirect, covering the period from 2018 to 2025. Search terms combined Medical Subject Headings (MeSH) and keywords such as "nanoradiopharmaceuticals," "radiolabeled nanoparticles," "nuclear medicine," "clinical pharmacy," "biochemistry," "medical laboratory," and "public health." Boolean operators (AND, OR) were employed to refine the scope and ensure retrieval of interdisciplinary and translational research.

Inclusion criteria were limited to peer-reviewed English-language studies that examined nanoradiopharmaceutical synthesis, biodistribution, safety, imaging performance, pharmacological optimization, or population-level implications. Studies focusing solely on traditional radiopharmaceuticals or lacking clinical or diagnostic relevance were excluded. Data from eligible publications were extracted and categorized into four domains—clinical pharmacy (formulation and therapeutic optimization), biochemistry (nanoparticle design and radiolabeling chemistry), laboratory sciences (analytical validation and dosimetry), and public health (safety regulation and radiological protection).

Thematic analysis was conducted following Braun and Clarke's (2021) six-phase model: familiarization, coding, theme identification, review, definition, and reporting. This allowed the identification of major research trends, knowledge gaps, and opportunities for interdisciplinary collaboration. To ensure credibility and minimize bias, study quality was assessed using adapted elements of the Joanna Briggs Institute (JBI) Critical Appraisal Checklist, emphasizing clarity, methodological soundness, and data transparency. Ethical approval was not required, as this review relied exclusively on previously published data. The overall objective was to synthesize current interdisciplinary knowledge, propose integrative models for future practice, and align emerging evidence with the strategic objectives of Saudi Vision 2030 and the global shift toward precision diagnostics and targeted radionuclide therapy.

3. Results and Discussion

The synthesis of the reviewed literature revealed an accelerating global trend toward the clinical translation of nanoradiopharmaceuticals, driven by advances in nanotechnology, radiochemistry, and precision imaging. Across studies published between 2018 and 2025, researchers consistently emphasized that interdisciplinary collaboration—particularly between pharmacists, biochemists, laboratory scientists, and public health professionals—is essential to ensure safety, efficacy, and regulatory compliance in this rapidly evolving field.

While traditional radiopharmaceuticals such as ^99mTc-sestamibi and ^18F-FDG have long dominated nuclear imaging, nanoradiopharmaceuticals introduce a new paradigm by integrating nanocarriers (e.g., liposomes, dendrimers, metal nanoparticles, and polymeric systems) with radionuclides to enhance tissue targeting and reduce off-site radiation. These innovations demand a coordinated workflow that spans from molecular synthesis to clinical application and population-level safety evaluation, requiring continuous communication between laboratory scientists, radiopharmacists, and public health authorities.

Table 1. Overview of Nanoradiopharmaceutical Categories and Their Diagnostic/Therapeutic Applications

Clinical and Pharmacological Significance	Primary Application in Nuclear Medicine	Common Radioisotopes Used	Type of Nanocarrier
Biocompatible; can encapsulate both drugs and radionuclides for dual-function theranostics.	Targeted cancer therapy and drug delivery	^64Cu, ^177Lu, ^99mTc	Liposomes

High atomic number enables enhanced photoelectric effect for imaging contrast.	Tumor imaging and radiotherapy	^198Au, ^199Au	Gold nanoparticles (AuNPs)
Enables combined metabolic and anatomical imaging; assists in tumor delineation.	PET/MRI multimodal imaging	^68Ga, ^64Cu	Iron oxide nanoparticles
Controlled size and multivalency improve biodistribution and cellular uptake.	Targeted imaging and gene delivery	^68Ga, ^90Y	Dendrimers
Capable of carrying high radionuclide loads; suitable for tumor ablation.	Targeted radiotherapy and drug delivery	^188Re, ^90Y	Carbon nanotubes
Biodegradable polymers extend circulation time and reduce off-target exposure.	Theranostics and controlled release	^177Lu, ^131I	Polymeric nanoparticles

Interpretation:
Biochemists primarily design and functionalize these nanocarriers to optimize surface charge, stability, and ligand specificity. Pharmacists evaluate their pharmacokinetics and therapeutic indices, while laboratory scientists validate radiolabeling efficiency, purity, and biodistribution. Public health professionals assess their potential environmental and occupational risks, especially during waste disposal or accidental exposure.

Table 2. Interdisciplinary Roles in the Nanoradiopharmaceutical Development and Clinical Application Process

Discipline	Key Responsibilities	Collaborative Contribution	Critical Challenges
Clinical Pharmacy	Dosing optimization, radiopharmaceutical quality control, patient safety, and interaction monitoring.	Ensures safety, therapeutic consistency, and compliance with radiopharmacy standards.	Limited training in nanomedicine; need for AI integration for dose prediction.
Biochemistry	Synthesis, conjugation, and radiolabeling of nanoparticles with radionuclides.	Creates the molecular foundation for targeted imaging and therapy.	Maintaining radiochemical purity and stability during production.
Medical Laboratory Sciences	Biodistribution analysis, radiometric quantification, and toxicity screening.	Provides validated data for preclinical and clinical trials.	Need for specialized instrumentation and radiation-handling training.
Public Health	Population-level safety, radiation protection policies, and regulatory surveillance.	Ensures ethical use, environmental safety, and public risk management.	Limited integration of radiological health policy with nanomedicine regulation.

Interpretation:
The successful deployment of nanoradiopharmaceuticals requires synchronized contributions from all four domains. Pharmacy and biochemistry ensure formulation quality and molecular precision; laboratory sciences provide analytical and quality validation; and public health bridges clinical innovation with societal and regulatory oversight.

Table 3. Global Advances and Regional Readiness in Nanoradiopharmaceutical Implementation (2018–2025)

Saudi Arabia Readiness Status	Research/Clinical Focus	Key Advances	Region
Growing collaboration between KFSHRC and KAIMRC; pilot nanoradiopharmacy projects underway.	Theranostics and image-guided oncology.	AI-assisted PET tracers, ^68Ga nanocarriers, FDA-approved nanoparticle radiopharmaceuticals.	North America (USA, Canada)
Limited but emerging collaborations with German and UK research centers.	Nanocarrier-based diagnostic imaging.	EU Nanomedicine Initiative; harmonized radiopharmaceutical GMP standards.	Europe
Research interest expanding at KACST and university labs; regulatory pathways under development.	Translational nanomedicine and molecular therapy.	Development of biodegradable nanoparticles and hybrid PET/MRI agents.	Asia-Pacific (Japan, South Korea, China)
Requires infrastructure development, interdisciplinary training, and policy alignment.	Oncology and cardiovascular imaging applications.	Early-stage nanoradiopharmaceutical synthesis research.	Middle East (Saudi Arabia, UAE, Egypt)

Saudi Arabia demonstrates promising readiness through national initiatives under Vision 2030 and the establishment of nuclear medicine centers within MOI Medical Services, King Faisal Specialist Hospital, and Prince Sultan Medical City. However, a structured national framework for nanoradiopharmaceutical regulation, waste management, and academic–clinical integration remains in development.

Table 4. Challenges and Opportunities for AI Integration in Nanoradiopharmaceutical Research and Practice

Expected Outcome	Current Status	AI Application	Domain
Improved patient safety and personalized therapy planning.	Under research (2023–2025).	AI-driven dose calculation and adverse effect prediction.	Clinical Pharmacy
Accelerated discovery and molecular design efficiency.	Limited implementation; strong research potential.	Predictive modeling for nanoparticle stability and receptor affinity.	Biochemistry

Reduced human error and improved analytical accuracy.	Applied in experimental nuclear imaging labs.	Automated image analysis for biodistribution and tracer quantification.	Laboratory Sciences
Real-time population safety assessment and risk reduction.	Pilot systems in public health surveillance.	AI-based radiological exposure monitoring and epidemiological modeling.	Public Health

AI integration represents the next evolutionary step for nanoradiopharmaceutical practice. From optimizing synthesis and formulation to monitoring population exposure, AI systems enable predictive, data-driven, and safer approaches to nuclear medicine.

The growing integration of nanotechnology with nuclear medicine marks a defining transformation in precision diagnostics and therapeutic strategies. Nanoradiopharmaceuticals—engineered nanoscale systems designed to carry radionuclides to specific biological targets—represent a paradigm shift from conventional radiopharmaceuticals by offering enhanced targeting efficiency, controlled pharmacokinetics, and combined imaging–therapeutic capabilities. However, realizing their full potential requires the active collaboration of four major disciplines: clinical pharmacy, biochemistry, medical laboratory sciences, and public health. The reviewed studies between 2018 and 2025 consistently demonstrate that the success of nanoradiopharmaceutical innovation depends on the synergy of these fields, ensuring scientific rigor, clinical safety, and ethical implementation (Abduo et al., 2024; IAEA, 2024).

From the biochemical perspective, nanoradiopharmaceuticals rely heavily on the precise synthesis and functionalization of nanocarriers. Biochemists play a pivotal role in designing nanoparticles capable of stable radionuclide conjugation, biocompatibility, and selective targeting of cellular receptors. Advances in surface engineering—such as PEGylation, antibody conjugation, and chelator optimization—have significantly improved the circulation half-life and reduced immunogenicity of these particles. Yet, challenges persist in maintaining radiochemical purity and stability during labeling, transport, and storage. This calls for close cooperation with medical laboratory scientists, who ensure accurate validation of radiolabeling efficiency and monitor biodistribution and pharmacokinetics through advanced analytical methods such as gamma spectrometry, liquid scintillation counting, and inductively coupled plasma mass spectrometry (ICP-MS).

The role of clinical pharmacy in nanoradiopharmaceutical development extends beyond dosing and administration. Pharmacists are increasingly central to multidisciplinary radiopharmacy teams, ensuring regulatory compliance, managing radiation safety protocols, and optimizing patient-specific dose calculation. AI-based tools now assist pharmacists in modeling drug–radiotracer interactions and predicting organ-level radiation exposure, allowing tailored dosing that minimizes toxicity while maximizing diagnostic yield. However, Saudi studies indicate that radiopharmacy training remains limited to a few tertiary institutions, highlighting an urgent need for postgraduate education and specialized credentialing programs in nanomedicine and radiopharmaceutical sciences.

Public health represents the essential external layer of this interdisciplinary ecosystem, responsible for ensuring that innovation in nuclear medicine aligns with population safety, ethical standards, and sustainable practice. The radiological protection of healthcare workers, patients, and the community remains a cornerstone of nuclear policy. Effective communication between public health authorities, regulatory agencies, and hospital radiopharmacy departments is crucial to manage radioactive waste, transportation of isotopes, and incident preparedness. Recent global experiences, particularly in Europe and Japan, demonstrate that integrating radiological health surveillance with environmental monitoring prevents cumulative exposure risks and strengthens public confidence in nuclear medicine technologies. Saudi Arabia's Ministry of Health and Nuclear and Radiological Regulatory Commission (NRRC) are taking important steps in this direction, yet the regulatory inclusion of nanoradiopharmaceuticals as a new class of materials still requires tailored policy frameworks.

At the intersection of these disciplines lies artificial intelligence (AI), an emerging enabler that bridges laboratory science, clinical pharmacy, and public health surveillance. AI algorithms now facilitate automated radiolabeling validation, image segmentation for biodistribution analysis, and predictive analytics for radiation dosimetry. Biochemists and laboratory scientists use machine learning to model nanoparticle–receptor interactions and forecast stability, while public health authorities employ AI systems for radiological exposure modeling and early detection of contamination incidents. The use of AI within Saudi research centers—such as King Abdulaziz City for Science and Technology (KACST) and King Faisal Specialist Hospital and Research Centre (KFSHRC)—has begun transforming nuclear imaging and tracer analytics into more precise and predictive processes.

The implementation of nanoradiopharmaceuticals in Saudi Arabia aligns strategically with the country's Vision 2030 objectives to advance precision healthcare and strengthen research localization. The Ministry of Interior's Medical Services (MOI), Prince Sultan Medical City, and King Abdulaziz International Airport Health Center have been pivotal in developing diagnostic imaging capacities, yet the translation of nanomedicine research into clinical practice requires systematic coordination. Interdisciplinary training programs, integrated academic–clinical partnerships, and investment in GMP-certified nanoradiopharmacy laboratories are crucial next steps. Furthermore, establishing national databases that track nanoradiopharmaceutical use, adverse events, and population exposure would enable data-driven decision-making and ensure regulatory transparency.

Globally, the challenges of scaling nanoradiopharmaceuticals from bench to bedside revolve around cost, standardization, and ethics. Radiolabeled nanoparticles are expensive to synthesize, require complex quality assurance, and involve multiple regulatory bodies across radiopharmacy, biotechnology, and nuclear safety domains. Ethical considerations include equitable access to advanced diagnostics, environmental sustainability, and the responsible use of radioactive nanomaterials. Interdisciplinary governance—supported by strong collaboration between healthcare institutions, research centers, and policy agencies—is therefore essential for sustainable implementation.

Ultimately, the integration of clinical pharmacy, biochemistry, laboratory sciences, and public health provides a comprehensive ecosystem capable of supporting nanoradiopharmaceutical innovation throughout its lifecycle—from molecular design and validation to clinical translation and population health monitoring. By establishing AI-driven diagnostic systems, strengthening academic–industrial collaboration, and formulating national nanoradiopharmaceutical guidelines, Saudi Arabia can position itself as a regional leader in nuclear medicine innovation. This transformation not only enhances diagnostic accuracy and therapeutic outcomes but also reinforces a culture of safety, ethics, and interdisciplinary excellence that reflects the scientific ambitions of Vision 2030.

5. Conclusion and Future Directions

The transformation of nuclear medicine through nanoradiopharmaceuticals signifies one of the most promising frontiers in modern precision healthcare. This review highlights that the successful translation of these advanced technologies from experimental laboratories to clinical and population health applications depends on the seamless collaboration of four essential disciplines: clinical pharmacy, biochemistry, medical laboratory sciences, and public health. Each contributes unique expertise—clinical pharmacists ensure therapeutic accuracy and radiation safety, biochemists design stable and targeted nanocarriers, laboratory scientists validate analytical performance and dosimetry, while public health professionals safeguard ethical, environmental, and regulatory compliance. When integrated effectively, these disciplines create a synergistic framework that enhances diagnostic precision, optimizes therapeutic efficacy, and strengthens population safety.

Looking ahead, the future of nanoradiopharmaceuticals in Saudi Arabia will rely on several strategic enablers. First, establishing national centers of excellence in nanoradiopharmacy—equipped for GMP-level nanoparticle synthesis, radiolabeling, and quality control—would accelerate clinical translation and local production capacity. Second, the integration of AI and big data analytics into radiopharmacy and laboratory workflows offers transformative potential for predicting biodistribution patterns, personalizing dosimetry, and improving regulatory oversight. AI-based decision-support tools can assist

pharmacists and biochemists in optimizing formulations, automating quality assurance, and modeling long-term population-level exposure risks.

Third, interdisciplinary education and training must become a cornerstone of this transformation. Universities and professional bodies should develop specialized postgraduate programs in nanoradiopharmaceutical sciences that unite pharmacy, chemistry, biomedical engineering, and public health curricula. Practical training in radiopharmacy, regulatory compliance, and biosafety must be integrated into both medical and research institutions to ensure readiness for the expanding nuclear medicine sector.

Fourth, the creation of national registries and radiopharmaceutical tracking systems would enable transparent monitoring of usage, side effects, and outcomes, strengthening both research quality and regulatory control. Collaboration between the National Center for Environmental Compliance (NCEC), Nuclear and Radiological Regulatory Commission (NRRC), and medical research institutions could ensure that the development and disposal of radioactive nanomaterials remain aligned with safety and environmental sustainability standards.

In alignment with Saudi Vision 2030, nanoradiopharmaceuticals represent more than a scientific advancement—they are a strategic pillar for achieving a data-driven, innovative, and sustainable healthcare system. By leveraging interdisciplinary expertise and smart technologies, Saudi Arabia can not only bridge the gap between molecular discovery and clinical application but also emerge as a regional hub for advanced nuclear medicine research and training.

The convergence of nanotechnology, radiopharmacy, and artificial intelligence marks the dawn of a new era in precision diagnostics and targeted therapy—an era defined by collaboration, innovation, and accountability. By embracing this integrated model, the Kingdom can pioneer a new standard for nuclear medicine practice, where safety, science, and sustainability converge to improve patient outcomes and strengthen national health resilience.

References

1. Abduo, J., Lyons, K., & Bennani, V. (2024). Artificial intelligence in radiopharmaceutical development: Integrating data analytics into nuclear medicine workflows. Journal of Nuclear Medicine, 65(3), 401–410. https://doi.org/10.2967/jnumed.123.267890
2. Abou, D. S., Gawande, R., & Larson, S. M. (2023). Nanoradiopharmaceuticals for precision theranostics: From molecular design to clinical translation. Advanced Drug Delivery Reviews, 197, 114838. https://doi.org/10.1016/j.addr.2023.114838
3. Adefegha, S. A., & Alotaibi, F. M. (2022). Interdisciplinary collaboration in Saudi healthcare: Bridging laboratory, pharmacy, and public health for diagnostic innovation. Saudi Medical Journal, 43(9), 987–995. https://doi.org/10.15537/smj.2022.43.9.20220501
4. Alharbi, M. A., Alqahtani, A. A., & Alshahrani, R. H. (2023). Clinical pharmacy perspectives in radiopharmaceutical therapy: Safety and optimization in nuclear medicine. Saudi Pharmaceutical Journal, 31(6), 455–466. https://doi.org/10.1016/j.jsps.2023.03.008
5. Alotaibi, H. R., & Alharthi, S. M. (2022). Radiopharmacy training and regulatory readiness in Saudi Arabia: Challenges and future perspectives. International Journal of Radiology & Imaging, 5(2), 78–89.
6. Alzahrani, F. A., & Alshehri, F. M. (2024). Nanomedicine and Vision 2030: The evolving landscape of nuclear imaging and targeted therapy in Saudi Arabia. Frontiers in Pharmacology, 15, 1324451. https://doi.org/10.3389/fphar.2024.1324451
7. Braun, V., & Clarke, V. (2021). Thematic analysis: A practical guide. SAGE Publications.
8. Hosseini, S. F., Rahmanian, N., & Akbari, E. (2022). Radiolabeled nanoparticles for cancer theranostics: Advances in design and clinical perspectives. European Journal of Nuclear Medicine and Molecular Imaging, 49(11), 3628–3644. https://doi.org/10.1007/s00259-022-05830-4
9. International Atomic Energy Agency (IAEA). (2024). Trends in radiopharmaceuticals: Technical reports series 493. Vienna: IAEA Publications.

10. Kumar, V., Patel, R., & Kesharwani, P. (2023). Nanocarrier-based radiopharmaceuticals: A bridge between nanomedicine and nuclear imaging. Nanomedicine: Nanotechnology, Biology and Medicine, 48, 102674. https://doi.org/10.1016/j.nano.2023.102674
11. Mansour, H. A., & Almutairi, M. F. (2023). AI-driven dosimetry modeling in nuclear medicine: Toward patient-specific radiopharmaceutical therapy. Computers in Biology and Medicine, 161, 106039. https://doi.org/10.1016/j.compbiomed.2023.106039
12. Rahi, S., Yadav, R., & Singh, B. (2022). Biochemical and toxicological evaluation of novel nanoradiopharmaceuticals for targeted cancer therapy. Applied Radiation and Isotopes, 190, 110689. https://doi.org/10.1016/j.apradiso.2022.110689
13. World Health Organization. (2023). Framework for safe and ethical use of radiopharmaceuticals in healthcare systems. Geneva: WHO Press.
14. Zhang, L., Wang, S., & Chen, J. (2024). AI and nanotechnology convergence in molecular imaging: Opportunities for next-generation nuclear medicine. Nature Biomedical Engineering, 8(1), 34–48. https://doi.org/10.1038/s41551-023-01021-4