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REVIEW

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The role of artificial intelligence in occupational health in radiation exposure: a scoping review of the literature

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Abstract

Introduction Artificial intelligence (AI) has the potential to significantly enhance workplace safety and mitigate occupational radiation exposure risks by improving the accuracy of assessment and management of these hazards. This study aims to review research on the use of AI in the assessment, monitoring, control, and protection of occupational radiation exposure.

Method This review was conducted according to the PRISMA guidelines. A comprehensive search was performed in the Web of Science, Scopus, and PubMed databases from inception to April 2024. The search strategy was designed based on the PICO principle and included keywords related to artificial intelligence, occupational exposure, radiation, and industry. The inclusion criteria explored the application of artificial intelligence in the assessment, monitoring, control, and protection against occupational radiation exposure. The quality of the included studies was evaluated using the MMAT critical appraisal tool.

Result In this review, the initial literature search in the Web of Science, Scopus, and PubMed databases identified 2920 articles. After removing duplicate references, screened based on title, keywords, and abstract, Ultimately, 59 eligible articles were selected, which utilized various artificial intelligence tools, such as expert systems, machine learning, deep learning, and other applied AI models. Of all the articles, 76% had high scores and were considered strong. These studies were categorized into three groups: supervision and assessment, detection and monitoring, protection, control, and personal protective equipment.

Conclusion The successful application of AI can potentially improve occupational radiation exposure management, but several key challenges must be addressed. These include the need for high-quality training data, interpretability of complex AI algorithms, alignment with safety standards, integration with existing systems, and the lack of interdisciplinary expertise. Addressing these research gaps through further study and collaboration will be crucial to realizing the benefits of AI in this domain, which has long been a critical concern in human and work environments.

Keywords Occupational Exposure, Radiation, Machine Learning, Artificial Intelligence, Deep Learning

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Introduction

Artificial intelligence (AI) is characterized by a system that can carry out cognitive tasks associated with human intelligence, such as learning and reasoning, often as well as or more proficiently than humans [1]. AI is able to considerably enhance safety monitoring and protocols across multiple industries by examining extensive empirical datasets, discerning patterns, and predicting potential hazards, which will enhance workplace safety [2]. With the advancement of AI technologies, there are opportunities to improve accuracy [3]. One of the risks in the workplace is exposure to radiation [4]. Ray or radiation is energy that spreads in the form of waves or particles in a vacuum or in a material environment. Some rays have mass, and some do not, and depending on the amount of energy, they have the power to penetrate matter [5]. The purpose of protection against radiation is to ensure that the amount absorbed by each person (except patients) is not more than the maximum allowed amount or that the minimum exposure is possible and justified [6]. The physical effects of ionizing radiation range from minor and temporary disorders in some physiological actions to serious risks such as reduced lifespan decreased immunity to diseases, reproductive issues, cataracts, blood cancer, other types of cancer, and damage to a developing fetus [4]. Occupational radiation exposure is a significant concern in various industries, including healthcare, nuclear power, and manufacturing [7, 8]. Understanding the potential risks and effects of occupational radiation exposure is crucial for protecting workers and ensuring workplace safety. This exposure can occur in industries such as healthcare [9–11]. Taking a proactive approach not only enhances worker safety but also ensures compliance with regulatory standards and reduces the likelihood of costly incidents. As AI technology continues to advance, we can expect more sophisticated solutions to further enhance radiation safety in the workplace.

A 2009 review study by Wakeford, aims to investigate the risks associated with occupational exposure to ionizing radiation, focusing on the health impacts of long-term, low-level radiation exposure. It aims to complement existing epidemiological data by examining groups such as healthcare workers, miners, and Chernobyl clean-up personnel while also evaluating the health risks from internally deposited radioactive materials, particularly alpha-particle emitters. Additionally, the study explores potential non-cancer health effects, such as heart disease and cataracts, and highlights the importance of international collaboration in deriving reliable risk estimates and establishing guidelines for radiological protection. Ultimately, this research seeks to understand better the health effects of ionizing radiation in various occupational settings [12].

Another review study conducted by Pillai et al. in 2019,,"Using Artificial Intelligence to Improve the Quality and Safety of Radiation Therapy,"examines the impact of machine learning (ML) on radiation therapy, focusing on how it can enhance treatment quality and patient safety. It discusses the shift from generalized to personalized treatment approaches, explores various applications of ML, such as outcome prediction and clinical decision support, and identifies challenges in algorithm development and integration with existing practices. Additionally, the study suggests future research directions and collaboration strategies to address these challenges and further improve the quality and safety of radiation therapy [13]. In a 2021 review, Muhammad Ikmal Ahmad et al. examined the key role of the Internet and drones in optimizing radiation monitoring systems and enhancing safety and also pointed out existing challenges and new research opportunities in this area. With this review, they sought to create a more comprehensive understanding of the applications of new technologies in radiation monitoring and security in the nuclear industry [14].

Due to the wide application of AI technology in various fields of monitoring and investigation and radiation protection and monitoring, this study was conducted as a scoping review. The purpose of this study is to review studies that discuss the use of artificial intelligence in the assessment, monitoring, control, and protection of occupational radiation exposure. These studies highlight the potential of artificial intelligence in enhancing radiation protection measures.

Materials and methods

Search strategy and study selection

This research was conducted following PRISMA guidelines. A systematic review was carried out with a comprehensive search strategy for articles without time restrictions. It includes articles from the beginning to April 2024 from Web of Science, Scopus, and PubMed Databases. The articles were searched and reviewed twice and by three researchers separately.

The search utilized the following keywords and the search strategy based on the PICO principle:

((TS = (artificial intelligence)) OR TS = (machine learning)) OR TS = (deep learning) AND ((((((((TS = (exposure)) OR TS = (assessment)) OR TS = (control)) OR TS = (monitoring)) OR TS = (effect)) OR TS = (evaluation)) OR TS = (protection)) OR TS = (prevention)) OR TS = (prediction)) OR TS = (Safety) AND ((((TS = (industry)) OR TS = (industrial)) OR TS = (occupation*)) OR TS = (work)) OR TS = (workplace) AND (TS = (radiation)) OR TS = (*ray) NOT ((((((TS = (patient*)) OR TS = (Pre-

scribe*)) OR TS = (animal*)) OR TS = (drug)) OR TS = (crime)) OR TS = (child*)) OR TS = (COVID)

Inclusion and exclusion criteria

The included studies consisted of case–control studies, cohort studies and descriptive studies that explored the application of artificial intelligence in assesment, monitoring, control and protection of occupational exposure to radiation.

Data extraction

Articles were imported into the Endnote software, duplicate studies were removed, and then screened according to the selection criteria. Data extraction included the following information: first author (year), AI tools used, purpose of the study and outcome.

Assessing the quality of articles

In this study, MMAT,[1] a critical appraisal tool, was used to assess the quality of the articles. The MMAT was developed in 2006 and was revised in 2011. The present version, 2018, was developed on the basis of findings from a literature review of critical appraisal tools, interviews with MMAT users, and an e-Delphi study with international experts. The MMAT developers are continuously seeking improvement and testing of this tool. Users' feedback is always appreciated. This document comprises a checklist (Part I) and an explanation of the criteria (Part II). In Part I, the checklist includes methodological quality criteria, which are listed in 5 categories of study designs. In Part II of this document, indicators are added for some criteria [15]. Three answers determine the scoring method for the questions in this tool:"Yes"with a score of"1","No"with a score of"0", and"Not relevant"without a score. The final score is calculated as a fraction of the sum of the 1 points over the total 0 and 1 answers. A score below 0.5 is considered weak, between 0.5 and 0.75 is considered moderate, and above 0.75 is considered strong.

Results and discussion

Search results and study selection

Two thousand nine hundred twenty articles were identified in the initial literature review using Web of Science, Scopus, and PubMed databases. After removing duplicate references, 2572 articles underwent screening based on their titles, keywords, and abstracts. Of these, 2483 articles were excluded for not meeting the inclusion criteria. The exclusion criteria were as follows: 1) the review studies. 2) Studies involving children and inhumane populations, such as animals. 3) Studies involving prescribing and taking medicine. Considering these criteria, the number of articles reached 89. Then, by reading the full text of the articles and considering the criteria for selecting studies that examine job/work/industry as one of the studied variables, the number of articles reached 59. Of all the articles, 76% had high scores and were considered strong; therefore, these studies were selected for eligibility and quality assessment, as shown in Fig. 1. The Flowchart illustrates the literature review process, detailing the identification, screening, and selection of studies that examined occupation/work/industry variables, ultimately resulting in 59 eligible articles. These studies' applied intelligence tools include expert systems and machine learning, deep learning, and other applied artificial intelligence models, as shown in Fig. 2. The applied intelligence tools in this study include expert systems**,** machine learning**,** deep learning**,** and other artificial intelligence models. Expert systems act as a model for decision-making and solving complex problems based on expert knowledge. Meanwhile, machine learning is a powerful approach in AI that allows models to learn from data and make accurate predictions without manual programming. In this context, deep learning, as a subset of machine learning, utilizes multi-layer neural networks to analyze complex data such as images and sounds. This combination of tools enables intelligent systems to perform effectively in various fields, including healthcare, business, and data analysis. In this study, according to the role of artificial intelligence in occupational health in exposure to radiation, the articles are grouped into three groups: articles related to supervision and Assessment, articles related to Detection and Monitoring, and articles related to Protection, Control, and PPE. Meanwhile, 74.14% of the studies corresponded to strong quality, 24.14% moderate quality, and 1.7% weak quality.

Figure 1 illustrates the flowchart of reviewed articles and the selection process in this review, and 2 illustrates AI tools used in studies broken down by percentage.

Application of artificial intelligence in supervision and assessment

Among the articles reviewed, 16 are related to monitoring and evaluation, which are listed in Table 1. The topics covered in these studies included the following: assisting inspections regarding radiation protection, dosimetry systems and estimation of personal equivalent dose, reviewing the effect of the mentioned absorbed dose, developing software systems to keep the dose within acceptable limits, providing an intelligent system equipped with the Internet of Things (IoT) for

[1] Mixed methods appraisal tool.

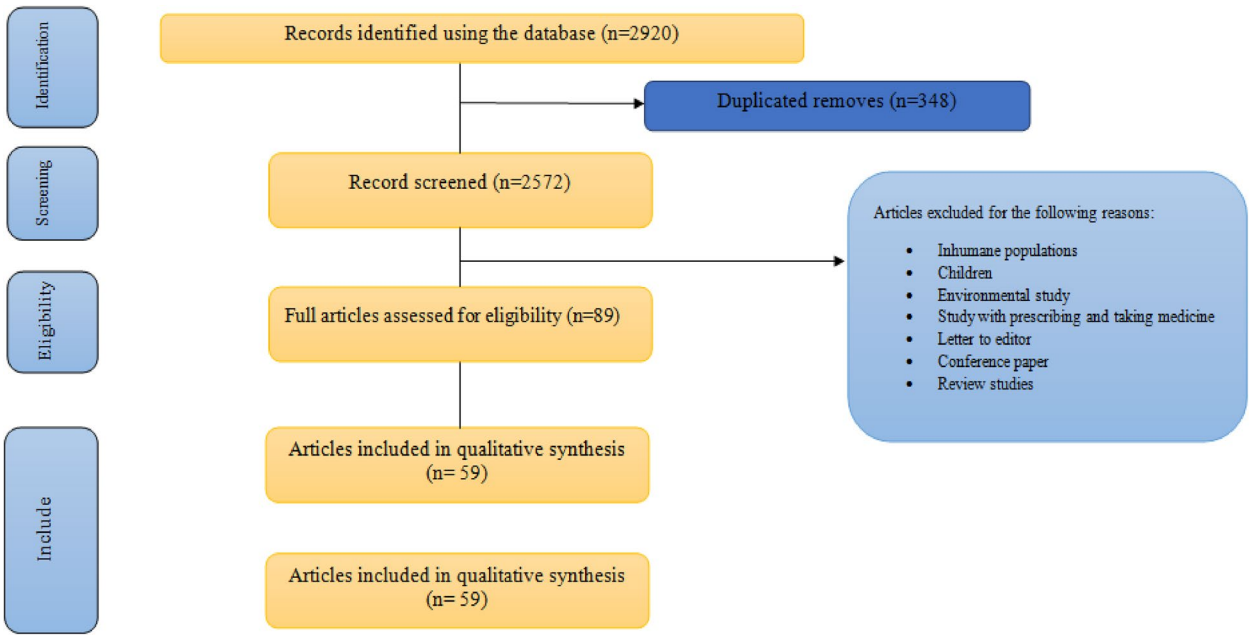

Fig. 1 Flowchart of the study selection process, following PRISMA-ScR guidelines

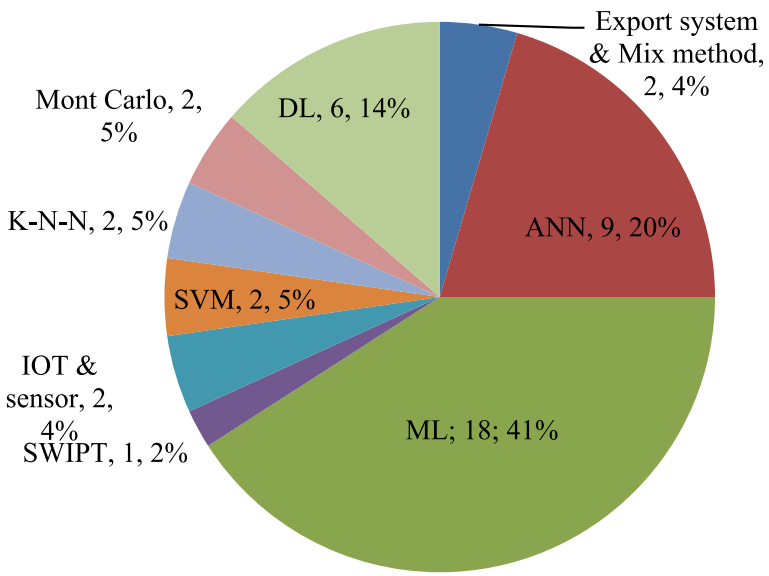

Fig. 2 Categorization of AI tools used in the studies included in this review. *SWIPT: Simultaneous Wireless Information and Power Transfer; IOT: Internet of Things; K-N–N: K-Nearest Neighbors; Mont Carlo: a computational technique that uses random sampling to obtain numerical results; An Export System refers to systems that can export data, models, or outputs generated by AI applications, Mix Method involves the use of mixed methods in machine learning and AI, combining quantitative and qualitative data; DL: Deep Learning; ANN: Artificial Neural Network; ML: Machine Learning

radiation monitoring and alerting, dose rate mapping, and radiation transfer models in nuclear power plants. Overall, these studies focus on identifying sources and predicting radiation with an emphasis on worker safety.

Application of artificial intelligence in detection and monitoring

Among the articles reviewed, 32 are related to detection and monitoring, which are listed in Table 2. The topics covered in these studies include: developing an intelligent radiation detector system for remote radiation

Table 1 Articles related to monitoring and assessment

Author	Year	Type of study	The purpose of the study	Application intelligence tools	Outcome	Quality Assessment		Ref
						Score	Quality	
Chew Lim Tan	1989	Experimental	Assisting the inspectorate in providing advice on radiation protection, licensing, and other regulatory matters	Expert system	An expert system was developed for use in radiation protection inspections under the supervision of the Singapore Ministry of Health	0.7	moderate	[16]
Lee, S. Y	2001	Modeling study	A new personal dosimetry system using alpha-Al2O3:C exploiting its optical properties	Artificial neural networks	Spectral information of X-ray and γ-ray fields can be obtained by analyzing the response of a multi-element system	0.9	strong	[17]
Mól, A. C. A	2011	Simulation study	Interpolation of radiation dose rate map in nuclear power plants	Neural networks and virtual reality	A simulation tool for evaluating radiation dose to minimize received dose	0.9	strong	[18]
Militello, A	2016	Modeling study	Radiative transfer models by integrating satellite-based radiometric data	Wearable sensors		0.2	weak	[19]
Izadi-Moud, A	2019	Cross-sectional study	Evaluating the effect of absorbed dose by overtime on blood parameters	Machine learning		0.8	strong	[20]
Troville, J	2021	Modeling study	Creating a software system to keep the dose as low as acceptable	Neural network	Monitor operating room scattered radiation and dose to staff in real- time during fluoroscopy	0.7	moderate	[21]
Psomas, C	2022	Analytical study	Presenting a complete framework for the design and analysis of far-field SWIPT under safety constraints	SWIPT	Providing insights regarding optimal design	0.8	strong	[22]
Saifullah, Muhammad	2022	Case study	IoT-Enabled Intelligent System for the Radiation Monitoring and Warning Approach	IoT-Enabled Intelligent System	The proposed system warns humans about dangerous areas with audio/visual notifications or buzzing so that they can move to a safer place	0.9	strong	[23]
Abdelhakim, A	2023	Modeling study	Identification and localization of radioactive sources	Machine learning	The proposed algorithm provides accurate source intensity estimation	0.9	strong	[24]
Gu, Z. M	2023	Modeling study	Proposing an algorithm for optimizing the ground placement strategy, which plays an important role in reducing electromagnetic radiation from the edges of the printed circuit board (PCB)	Deep Learning	The final optimization strategy obtained by the proposed algorithm has a more effective electromagnetic interference reduction	0.8	strong	[25]
Eghtesad, A	2023	Modeling study	Designed to evaluate the radiative properties of heterogeneous porous media, as well as the effects of conductive heat transfer	Artificial Neural Networks & Machine learning	The method used can improve the prediction accuracy compared to previous studies	0.8	strong	[26]
Lagerquist, R	2023	Modeling study	Estimation of full longwave and shortwave radiative transfer with neural networks of different complexity	Neural Networks	Simulation of full shortwave and longwave RRTM with all predictor variables, using worldwide data	0.9	strong	[27]
McFerran, N	2023	Modeling study	Context-Aware Roadside Radiation Measurement Testbed	Machine learning	Textual data can be combined with radiation measurement data to increase system sensitivity and accuracy in nuclear threat detection applications	0.9	strong	[28]

Table 1 (continued)

Author	Year	Type of study	The purpose of the study	Application intelligence tools	Outcome	Quality Assessment		Ref
						Score	Quality	
Stomps, J. R	2023	Modeling study	Classification of SNM radiation signatures	Machine learning	Unlabeled data can be valuable in semi-supervised non-proliferation implementations	0.8	strong	[29]
Garg, M	2024	Modeling study	Anticipating UV radiation and noise levels during welding and emphasizing worker safety	SVM and random forest	The first known application of machine learning techniques is to predict UV radiation and noise levels in arc welding processes	0.7	moderae	[30]
Pathan, M. S	2024	Modeling study	Estimation of personal equivalent dose using thermoluminescence dosimeter	Machine learning	A new method to assess radiation exposure in workers	0.8	strong	[31]

Table 2 Articles related to detection and monitoring

Author	Year	Type of study	The purpose of the study	Application intelligence tools	Outcome	Quality Assessment		Ref
						Score	Quality	
Latner, Norman	2002	Modeling study	An intelligent radiation detector system for real-time gamma radiation remote monitoring	Intelligent Radiation Detectors's	Very valuable for detecting radioactivity from moving vehicles	0.8	strong	[32]
Varley, A	2015	Modeling study	Creating an optimal detector-algorithm combination	Neural Network & Support Vector Machines	Providing the best detection capability	0.8	strong	[33]
Varley, A	2016	Modeling study	Identifying the optimal combination of the detector and spectral processing routine	Machine learning & Monte Carlo simulation	Development of a method for depth extraction and activity estimation for 226Ra contamination	0.9	strong	[34]
Aminalragia	2018	Modeling study	Revealing artificial intelligence for space radiation monitor data	Artificial Intelligence & Machine Learning	A new detection method	0.9	strong	[35]
Kang, H. H	2019	Modeling study	Prediction of radiation properties of metal substrates	Neural Network	Data-driven surrogate forecasting works precisely and comprehensively	0.9	strong	[36]
Mortazavi, SMJ	2020	Modeling study	Prediction of annual dose in health care workers exposed to different levels of ionizing radiation	Artificial neural network	Improve/facilitate the dose estimation process	0.8	strong	[37]
Sun, D. J	2020	Modeling study	Identification of representative sites among multiple environmental variables, such as elevation and land cover types	Gaussian mixture model	Capture the heterogeneity of air dose rates in a systematic manner by a minimum number of monitoring sites	0.8	strong	[38]
Bilton, K. J	2021	Modeling study	Mobile spectroscopy gamma ray source detection	Neural Network	Using simulated data from a detector	0.9	strong	[39]
Dam, R. S. D	2021	Modeling study	The method of tracking radioactive particles and optimizing the number of detectors in single-phase flow	Neural Network	The proposal is a single-phase flow RPT system	0.8	strong	[40]
Durbin, M	2021	Modeling study	Differentiation of gamma rays and neutrons in organic scintillators	K-Nearest Neighbors	This light output limit can be reduced in all six tested detector assembly combinations with the proposed method compared to conventional performance improvement methods	0.9	strong	[41]
Hashima, S	2021	Modeling study	Efficient wireless sensor network for radiation detection at nuclear sites	Machine learning	Development of wireless sensor networks that precisely monitor irregular radioactivity	0.7	moderate	[42]
Jain, S. K	2021	Modeling study	Real-time solar radiation forecast for Indore region	Machine learning	It provides solar radiation prediction with 96.9% accuracy	0.8	strong	[43]
Shao, Hong	2021	Modeling study	An improved genetic detector system to avoid"blind spots"in detector monitoring	Machine learning	Monitor the operation status of the photoelectric detection system instantly and ensure the safe and stable operation of the detector system	0.8	strong	[44]

Table 2 (continued)

Author	Year	Type of study	The purpose of the study	Application intelligence tools	Outcome	Quality Assessment		Ref
						Score	Quality	
Song, H. B	2021	Modeling study	Design of joint active and passive beams based on learning	Machine learning & Wireless Networks	Deployment of a neural network for instantaneous prediction	0.7	moderate	[45]
Wang, J. F	2021	Modeling study	Estimation of nuclear medicine exposure measures based on intelligent computer processing	The analysis module is designed in MATLAB	Use dose estimation to analyze internal exposure data in radiation management	0.8	strong	[46]
Angelone, M	2022	Modeling study	Accurate simulation of the proposed detectors by Monte Carlo technique	Monte Carlo technique	Help choose the best detector	0.7	moderate	[47]
Balanya, S. A	2022	Modeling study	Prediction of radiation dose in nuclear power plant reactors	Machine learning	These models can be used to estimate future radiation dose values in a data-driven manner	0.9	strong	[48]
Cárdenas-Montes, M	2022	Modeling study	Uncertainty estimation in predicting time series of Rn-222 radiation level	Deep learning	To predict periods of low radiation, enabling the correct planning of unshielded periods for maintenance operations	0.8	strong	[49]
Durbin, M	2022	Modeling study	Gamma-ray localization capabilities to predict real-time source locations	Machine learning	Experimental tests of gamma-ray localization	0.7	moderate	[50]
Fobar, D	2022	Modeling study	Direction estimation between a detector array and a stationary Cs-137 source	Machine learning	Multidetector array response performance for nuclear search	0.8	strong	[51]
Garankin, J	2022	Modeling study	Detection of ionizing radiation particles by the response of a plastic scintillation detector	Machine learning	The model is able to separate particles in low-energy and high-energy transfer domains	0.8	strong	[52]
Ghawaly, J. M	2022	Modeling study	Identification of unusual radioactive signatures in gamma-ray spectra collected by NaI (Tl) detectors	Deep convolutional	Automatic encoder radiation anomaly detection (ARAD)	0.8	strong	[53]
Hwang, J	2022	Modeling study	Spectrum dose prediction for plastic scintillation detector and environmental dose equivalent prediction	Deep learning	Validation of ensemble model performance for representative radioisotopes	0.8	strong	[54]
Ildefonso, A	2022	Modeling study	Reduction of single-event disturbances in RF circuits and systems	K-nearest neighbor & Machine learning	Demonstrate the potential benefits of using ML techniques in the field of radiation effects	0.7	moderate	[55]
Kavuncuoglu, E	2022	Modeling study	Performance evaluation of fiber optic scintillation detector	Neural Network	Accurate, fast, and dynamic estimation of fiber optic scintillation detector performance	0.7	moderate	[56]
Mendes, F	2022	Modeling study	Locating and identifying radioactive hotspots	Deep learning	Developing new techniques and new solutions to protect human lives	0.8	strong	[57]
Bandstra, M. S	2023	Modeling study	Detection and identification of gamma rays	Machine-learning	Identify the modifications that should be applied to adapt the methods to gamma-ray spectral data	0.8	strong	[58]

Table 2 (continued)

Author	Year	Type of study	The purpose of the study	Application intelligence tools	Outcome	Quality Assessment		Ref
						Score	Quality	
Brunet, R	2023	Modeling study	A synthetic database of infrared measurements for the inverse thermographic model	Deep learning	The proposed method can minimize the computational burden associated with models such as Monte Carlo to generate training data for real surfaces	0.8	strong	[59]
Dey, R	2023	Modeling study	Estimation of an empirical formula for germanium type detector BEGe efficiency	Machine learning	Rapid estimation of full energy peak efficiency values and verification of nominal geometric parameters	0.7	moderate	[60]
Hu, H	2023	Modeling study	An independent radiation source detection policy with generalized capability in unknown environments	Deep learning	Generalization of hierarchy control showed the best performance among independent decision policies as well as robustness and capability	0.9	strong	[61]
Paleti, B	2023	Modeling study	Identification of gamma-emitting natural isotopes in environmental sample spectra:	Convolutional neural network	Among the options for automating gamma-ray spectroscopy, pattern recognition methods are the best	0.8	strong	[62]
Pluzek, A	2023	Modeling study	Classification of partial discharges using scintillation phenomenon	Machine learning	It was possible to find out which classifier (algorithm) worked best for the task	0.7	moderate	[63]

Table 3 Articles related to protection, control, and PPE

Author	Year	Type of study	The purpose of the study	Application intelligence tools	Outcome	Quality assessment		Ref
						Score	Quality	
Kimura, Yoshitaka	1990	Modeling study	Radiation control, development of an expert system for the transfer of radioactive materials with a programming language	UTI-LISP Programming Language	Rationalization of interpretations and judgments for the transportation of radioactive materials	0.8	Strong	[64][a]
Al-Mubaid, H	2012	Modeling study	A model for extracting material properties for radiation protection	Machine learning	Identifying the most important properties related to the radiation shielding ability of materials is quite effective	0.8	strong	[65]
Duckic, P	2018	Modeling study	The sum of the factors creating equivalent environmental dose for Portland concrete	Machine learning	The sum of the factors creating the environment dose equivalent for Portland concrete slabs is calculated using the software	0.8	strong	[66]
Chen, S	2020	Modeling study	An approach to ensure the correct use of PPE in decommissioning the Fukushima nuclear power plant	Deep learning	A proposal to identify the correct use of hard hats and full-face masks	0.7	moderate	[67]
Piron, L	2021	Modeling study	Progress in preparing instantaneous control schemes for deuterium–tritium operations at JET	Machine learning	This paper deals with isotope ratio controllers to support nuclear fusion processes	0.8	strong	[68]
Tokatli, O	2021	Modeling study	Introducing advanced technologies to glove boxes	Robotics and artificial intelligence	Minimize human exposure to hazards	0.8	strong	[69]
Hou, T. Y	2022	Modeling study	Customization of orbital angular motion beams	Deep Learning	A useful reference on intelligent control of laser array systems for customizing light beams	0.7	moderate	[70]
Zhu, E. Z	2022	Modeling study	Protection against electromagnetic radiation (EM) due to its high spatial filter performance	Deep Learning	Frequency Selective Surface Inverse Design	0.8	strong	[71]
Piron, L	2023	Modeling study	A phased approach strategy towards radiation control	Machine learning	Radiation control in deuterium, tritium, and deuterium–tritium JET base plasmas	0.7	Moderate	[72]
Han, H	2024	Modeling study	Microscopic tuning of high-performance electromagnetic response mechanism of fiber-based flexible absorbers	Artificial intelligence (AI)	Enhancing the high-frequency electromagnetic damping response of flexible fiber-based wearable absorbers	0.8	strong	[73]

[a] The language of this article is in Chinese

monitoring, predicting radiation properties and the annual dose of workers, identifying representative locations among environmental variables, forecasting indoor solar radiation, tracking radioactive particles, optimizing the number of detectors, creating a wireless sensor network, designing detection systems to prevent'blind spots'in monitoring, accurately simulating detectors, radiation dose prediction, detecting ionizing radiation particles using detector responses, identifying abnormal radioactive signatures with detectors, evaluating detector performance, and locating and identifying radioactive sensitive spots, as well as estimating medical exposure control measures.

Application of artificial intelligence in protection, control and PPE

Among the studied articles, ten are related to detection and monitoring, which are mentioned in Table 3. In these studies, radiation control, the development of an expert system for the transfer of radioactive materials, a model for extracting the properties of materials for radiation protection, the factors of creating an equivalent environmental dose for the construction of protective concrete, and approaches to ensure the correct use of PPE are mentioned in these studies, excellence in preparing instantaneous control schemes, introduction of advanced technologies for glove boxes, protection against electromagnetic radiation, phased approach strategy towards radiation control, high-performance electromagnetic response mechanism of flexible absorbers.

Conclusion

Artificial intelligence (AI) has emerged as a leading in recent decades technology across various scientific and industrial fields. One area that has this technology has significantly impacted is radiation protection. A recent article by Sylvain Andresz and colleagues effectively explores the capabilities of AI and machine learning (ML) in enhancing strategies for protecting individuals and the environment from radiation exposure. Their research findings indicate that the utilization of AI can substantially improve the accuracy of radiation exposure assessments and the efficiency of risk management systems. Additionally, the authors emphasize the importance of collaboration between radiation protection professionals and data scientists, asserting that such partnerships can lead to more effective algorithm development and optimized scientific and technological outcomes. This paper will examine the applications of AI in radiation protection, along with the challenges and opportunities that arise in this field [74].

The applications of artificial intelligence (AI) are likely to enhance the quality of assessment, monitoring, control, and protection against occupational radiation exposure. AI thus holds the potential to improve protective measures against radiation. Radiation protection has been a concern for both humans and workplaces for decades. Radiation monitoring plays a critical role in preventive measures, benefiting industries, hospitals, and any activity involving radioactive materials. Beyond occupational settings, radiation monitoring is also essential for responding to emergencies. Based on the studies reviewed in this scoping review, significant research gaps exist in this field, including: 1) The need for sufficient and high-quality data. Many AI algorithms require comprehensive and high-quality training datasets, which are limited in some areas. Collecting and developing datasets related to real-world radiation exposure presents a significant challenge. 2) Interpretation and transparency of algorithms. Some AI models are complex and require greater explanation and interpretability. This presents a challenge in developing reliable and interpretable algorithms specifically for radiation applications. 3) Compliance with standards and regulations. The use of AI must align with and be validated against existing safety standards and regulations. This highlights the need to develop legal and ethical frameworks for applying AI in this domain. 4) Integration with existing systems. Incorporating AI into current monitoring and evaluation systems poses challenges and requires the development of technological infrastructures to facilitate the efficient use of AI. 5) Specialized and interdisciplinary skills, as well as more experts, are needed to become familiar with artificial intelligence and the science of radiation protection.

In a 2021 review, Gomez-Fernandez et al. examined the applications of machine learning in the nuclear industry and its potential to improve nuclear safety and radiation detection. They analyzed learning networks to determine whether domain-related features were identified. They concluded that a human-centric approach could help increase transparency and trust in the decisions of deep learning algorithms [75].

These research gaps indicate that further studies and interdisciplinary collaborations are still required. As observed in the review studies, each dealt with a part of evaluation, protection, and control. Our study's advantage is that we considered all aspects and referred to studies that had been conducted in these fields.

Abbreviations

AI	Artificial intelligence
PRISMA	Preferred Reporting Items for Systematic reviews and Meta-Analyses
PICO	Patient/Problem, Intervention, Comparison and Outcome
MMAT	Mixed methods appraisal tool
PPE	Personal protection equipment

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Authors' contributions
PA, ZF, and MS participated in the project's design. ZF and PA were responsible for searching, studying, and reviewing articles, as well as extracting data from them. ZF and PA prepared the initial draft of the article. PA, ZF, and MV assessed the quality of the articles used in the study. PA was in charge of translating, editing, revising, reviewing, and overseeing the article throughout all stages of the research. All authors have approved the final version.

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Data availability
The present study is a review, and the data are publicly available in various databases.

Declarations

Ethics approval and consent to participate
Not applicable.

Consent for publication
All authors have read this text and consent to its publication.

Competing interests
The authors declare that they have no competing interests.

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