AI-ASSISTED NUCLEAR EMERGENCY PREPAREDNESS AND RESPONSE (ERP)
Lessons from Malaysia's MySejahtera National Digital Health Strategies

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Abstract

Nuclear emergencies pose a significant threat to public health and safety, demanding rapid and effective response. Malaysia's MySejahtera app, a digital health platform successfully deployed during the COVID-19 pandemic, demonstrated the potential of AI in crisis management. This paper proposes adapting MySejahtera's AI-powered capabilities in data analysis, prediction, and resource optimization, proven effective in national digital health strategies, to enhance nuclear Emergency Preparedness and Response (EPR) within the framework of national digital health strategies. This adaptation promises faster response times by rapidly identifying affected populations, more effective resource allocation through predictive modeling of contamination zones, and improved decision-making by providing real-time radiation tracking and risk assessment. Ultimately, this approach can contribute to enhanced public safety and resilience by providing authorities with the tools to rapidly assess, respond, and manage nuclear events. Furthermore, integrating advanced AI/ML models to predict radiation spread and long-term health impacts, alongside exploring federated learning approaches to facilitate collaborative data analysis while preserving privacy and security, holds significant potential for strengthening nuclear EPR capabilities.

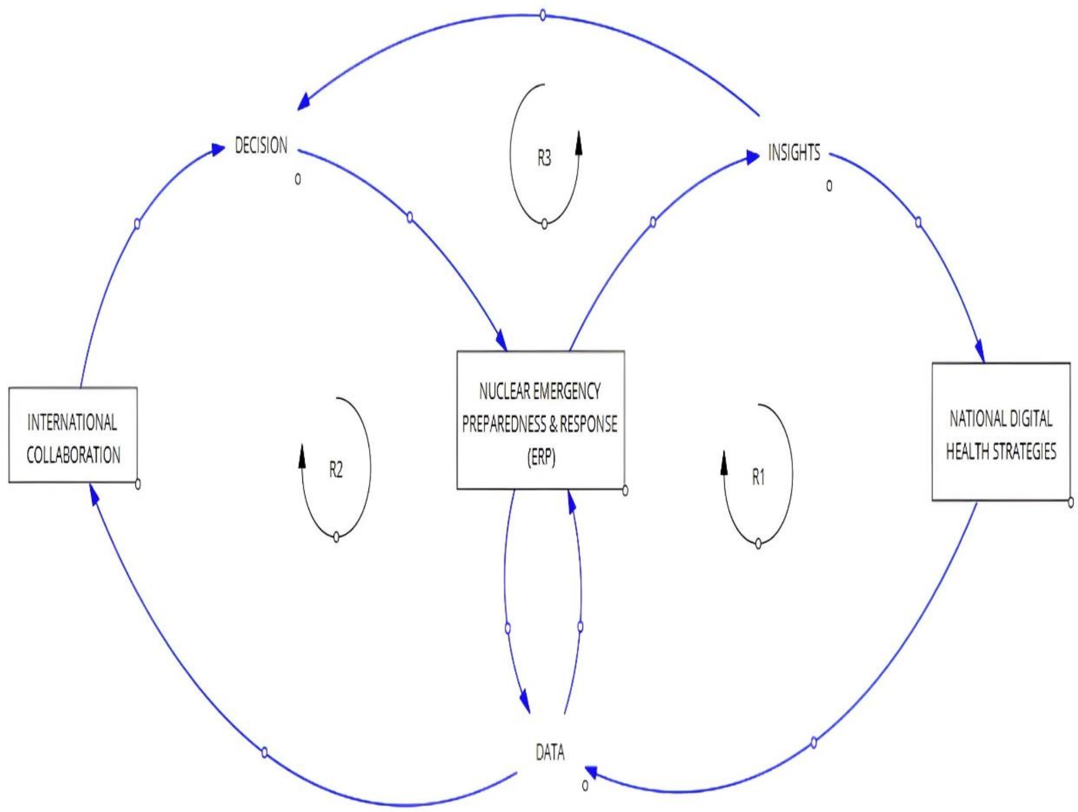

FIG. 1. Chart showing the Causal loop diagram visualizes the interconnectedness of factors contributing to effective AI-assisted Nuclear Emergency Preparedness and Response (ERP).

1. INTRODUCTION

Nuclear and radiological emergency preparedness and response (EPR) is critical in today's world [1]. The evolving technological landscape and emerging threats, such as terrorism involving radioactive materials [2], accidents at advanced nuclear power plants [3], and potential nuclear events during conflicts [4], necessitate robust EPR frameworks. While the International Atomic Energy Agency (IAEA) plays a crucial role in fostering international cooperation for nuclear EPR [5, 6, 7], traditional EPR systems often rely on outdated technologies and fragmented communication channels [8]. This hinders effective response in the face of dynamic challenges.

Integrating artificial intelligence (AI) and machine learning (ML) technologies is crucial to address these limitations and enhance preparedness for evolving threats [9, 10]. AI/ML can significantly enhance nuclear EPR by enabling rapid data analysis, predictive modelling, and optimized resource allocation [11, 12, 13]. This allows for real-time assessment, proactive risk mitigation, and ultimately, a more effective response to protect public safety [14, 15].

Malaysia's MySejahtera app, deployed during the COVID-19 pandemic, exemplifies the potential of AI in real-time data analysis, predictive modelling, and targeted interventions for managing public health crises [16, 17, 18]. By analysing infection rates, health authorities can predict outbreaks, optimize resource allocation, and implement targeted interventions to control virus spread [19, 20].

Several countries have successfully implemented national digital health initiatives, demonstrating the potential of AI-driven platforms for managing public health crises and enhancing emergency preparedness [21]. South Korea's 'Self-Quarantine Safety Protection App' uses GPS and Bluetooth technology to monitor individuals under quarantine and ensure adherence to public health guidelines [22]. Australia's 'COVIDSafe' app utilizes Bluetooth technology for contact tracing, enabling rapid identification and notification of potential exposures [23]. Israel's 'HaMagen' app uses location data to alert users about potential exposure to confirmed COVID-19 cases [24], while Saudi Arabia's 'Tawakkalna' app played a crucial role in managing the COVID-19 pandemic by providing citizens with access to vital information and services [25].

These successful implementations highlight the potential of AI-driven digital health strategies, which can be adapted to enhance nuclear EPR. By examining the similarities between managing public health emergencies and nuclear incidents, valuable insights can be gained on repurposing digital health technologies to enhance nuclear EPR capabilities [28, 29, 30].

This paper addresses the need for robust nuclear EPR systems and explores the potential of AI-driven national digital health strategies [31]. While traditional EPR systems may struggle to keep pace with the dynamic nature of nuclear and radiological events, AI-powered solutions offer significant improvements in terms of speed, accuracy, and efficiency. This paper investigates key AI-driven functionalities, including real-time data analysis, predictive modelling, and resource optimization, and examines how these can be adapted to nuclear emergencies to create a more agile and responsive EPR framework [34, 35, 36].

This paper is structured to provide a comprehensive examination of AI-driven national digital health strategies for nuclear EPR. It begins with an overview of existing digital health platforms and their successful applications in managing public health crises, using examples from various countries. The next section discusses adapting these strategies for nuclear EPR, focusing on key AI functionalities and their potential to address the challenges of nuclear emergencies. The paper then explores real-world case studies and examples of AI applications in nuclear EPR, highlighting the feasibility and benefits of this approach. It also addresses potential challenges and future enhancements for AI-driven nuclear EPR, considering factors such as data quality, privacy concerns [37], and the need for international collaboration [5, 6]. Finally, the paper concludes with a summary of key findings and a call to action, emphasizing the importance of integrating AI into national digital health strategies for enhanced nuclear EPR.

2. BACKGROUND ON MYSEJAHTERA AND ITS AI CAPABILITIES

MySejahtera, Malaysia's national digital health platform, exemplifies the potential of AI in crisis management [16, 17]. Deployed during the COVID-19 pandemic, it evolved into a multifaceted tool empowering citizens with functionalities for health self-assessments, vaccination registration, and contact tracing [16, 17]. However, its true potential lies in the sophisticated integration of AI/ML models.

Time series analysis, particularly ARIMA models [39], enabled the prediction of infection trends, facilitating proactive public health interventions [18]. Clustering algorithms like K-means and DBSCAN were instrumental in identifying potential outbreak hotspots, allowing for targeted resource allocation and containment efforts [35]. Furthermore, natural language processing (NLP) techniques analysed public sentiment to tailor communication strategies and combat misinformation [20].

Siau and Lim [17] highlight that MySejahtera's AI-powered approach is deeply rooted in its robust data infrastructure. The platform gathered and analysed large amounts of data, including case counts, demographics, and movement patterns [17]. Data preprocessing techniques ensured data quality, while feature engineering enhanced the performance of AI/ML models [25]. Real-time data updates allowed the system to adapt to the dynamic nature of the pandemic, enabling agile decision-making [18].

The impact of this AI-driven approach was tangible. Azlan et al. [16] found that MySejahtera's hotspot detection feature enabled rapid response to emerging outbreaks. Trend forecasting capabilities informed decisions on public health measures, such as lockdowns and movement restrictions [18].

Furthermore, MySejahtera's AI-powered insights contributed to optimizing vaccination strategies and managing quarantine measures [16]. The platform even enabled the generation of tailored public health advisories based on individual risk profiles [16]. These successes underscore the transformative potential of AI in predicting, mitigating, and managing crises, optimizing resource allocation, and supporting effective decision-making during emergencies [9].

This provides a compelling case for adapting MySejahtera's AI-driven approach to the unique challenges of nuclear emergency preparedness and response (EPR) [1, 5]. Imagine AI/ML models with specific capabilities to predict the spread of radiation plumes [11, 34], optimize the allocation of emergency resources [3], and analyse social media data to address misinformation after a nuclear incident [29, 30].

By integrating these AI-driven approaches into national digital health strategies, countries can significantly enhance their preparedness and response capabilities, contributing to a safer and more resilient world [15]. MySejahtera's technological foundation offers a blueprint for building robust, AI-powered EPR systems that can effectively address the complex challenges of nuclear and radiological emergencies [6, 7, 8].

3. PROPOSED ADAPTATION FOR NUCLEAR EPR

This section proposes how key components and AI-driven functionalities of national digital health platforms, inspired by MySejahtera's success, can be adapted to enhance nuclear emergency preparedness and response (EPR).

3.1. Adapting AI/ML Models

3.1.1. Radiation Plume Modelling: Predicting how radioactive plumes spread is crucial in a nuclear emergency.

Time series analysis models, such as ARIMA and Long Short-Term Memory (LSTM) networks, are effective tools for predicting patterns over time [39]. ARIMA models capture trends and changes in data, such as radiation levels, while LSTM networks, a type of recurrent neural network, excel at understanding long-term dependencies, making them ideal for modelling the spread of radiation plumes [39, 41]. Saavedra et al. [39] demonstrate the potential of combining ARIMA and LSTM for improved time series forecasting, which could be valuable for predicting the intricate behaviour of radiation plumes. These models can be trained using data from past nuclear incidents, such as Chernobyl [31] and Fukushima [4], and tested with real-time data from radiation sensors and weather monitoring systems [11, 34]. Accuracy is ensured through performance evaluation using metrics like Mean Absolute Error (MAE) and Root Mean Squared Error (RMSE) [35]. During a nuclear event, real-time data is fed into the model to predict the plume's path and intensity [34]. This information supports decision-making regarding evacuations and protective measures [1]

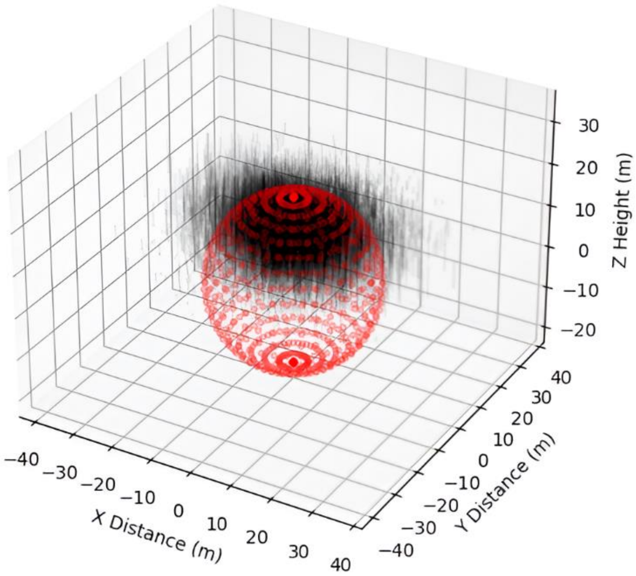

FIG. 2. 3D Radiation Plume Dispersion Model with Explosion & Gravity Simulation.

The 3D visualization shows a plume. This plume represents a simulated radiation dispersion event. The event starts with an explosion. This simulation is generated using machine learning (ML) algorithms. These algorithms predict how the radiation will spread. This prediction is based on a variety of factors. A red sphere shows the initial explosion. The plume spreads out like a cloud. Lines show the centre of the plume. The black colour of the lines simulates a dark, dense cloud, and their erratic behaviour is due to varying wind conditions and eddy diffusivity, all factored into the ML model. The tail of the plume gradually drops, simulating the effect of gravity.

3.1.2. Identifying Radiation Hotspots:

Clustering algorithms can effectively identify radiation hotspots using real-time sensor readings [36, 43]. Algorithms such as K-means and Density-Based Spatial Clustering of Applications with Noise (DBSCAN) are commonly used for this purpose [35]. K-means groups data based on distance from central points, while DBSCAN groups data points based on density and proximity [35]. DBSCAN is particularly useful for identifying outliers and is generally preferred for data with varying densities and noise [35]. Zhou et al. [43] demonstrated the effectiveness of clustering algorithms for locating radiation sources, which is directly applicable to identifying hotspots in a nuclear emergency. These algorithms can be applied to real-time radiation sensor readings to identify high-density clusters indicative of hotspots [36, 43]. Cluster quality can be evaluated using metrics like the silhouette score and Davies-Bouldin index [35].

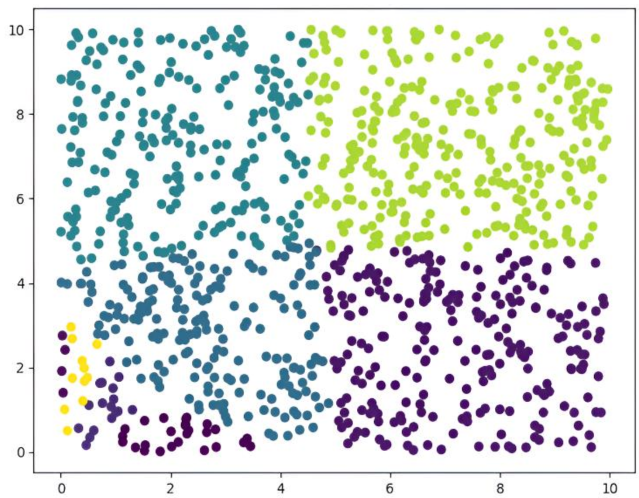

FIG. 3. Simulation of Self-Organizing Map (SOM) Ionizing Radiation Concentration.

The simulation above utilizes a Self-Organizing Map (SOM), a type of machine learning technique, to identify areas of high radiation concentration. It processes radiation measurements and presents them visually on a map, organizing the data into clusters based on similarity. This allows for easy identification of "hotspots" – areas where radiation levels are significantly elevated. This SOM approach simplifies the analysis of complex radiation data, enabling efficient interpretation and informed decision-making. By presenting the information in a clear and concise visual format, it empowers decision-makers to quickly grasp the radiation distribution and potential risks, facilitating informed and effective response strategies.

3.2. Leveraging Social Media for Situational Awareness and Public Communication

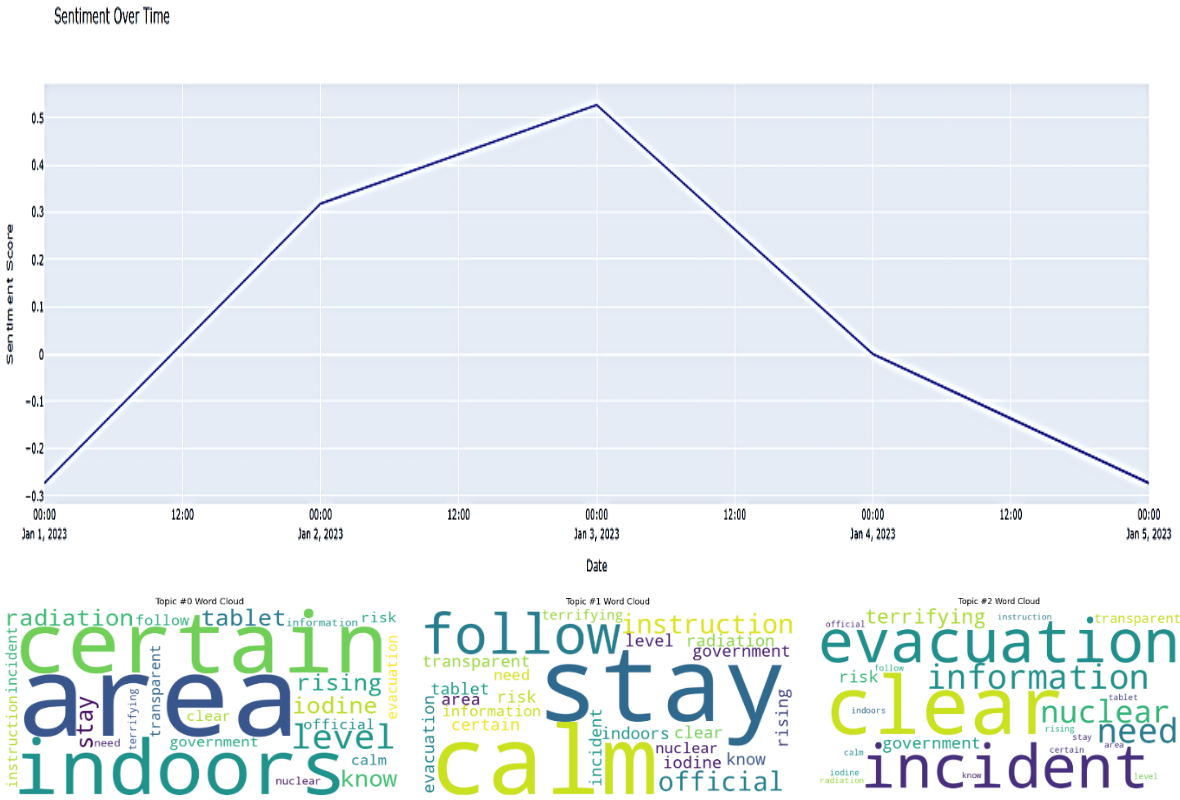

FIG. 4. Simulation of Natural Language Processing (NLP) social media activities during nuclear incident.

Social media monitoring and analysis, particularly using Natural Language Processing (NLP) techniques like sentiment analysis and topic modelling, can provide valuable situational awareness during a nuclear emergency [29, 30]. This is consistent with findings by Reuter and Kaufhold [30] in their analysis of Twitter activity during Hurricane Sandy. For instance, authorities can use sentiment analysis on tweets to track public sentiment after a radiation leak [30]. This can reveal trends, such as an initial peak in positive sentiment due to reassurance from officials, followed by a decline as anxieties increase [29]. Sentiment analysis models, trained on labelled datasets, help measure the public's emotional response [28].

Furthermore, topic modelling can generate word clouds that highlight key themes and discussions [29]. The prominence of words like "radiation," "iodine," and "evacuation" would point to specific concerns circulating online, allowing authorities to understand and address public anxieties [29]. This analysis, evaluated using coherence scores, ensures the identified topics accurately reflect the online discourse [20].

Named entity recognition can also extract crucial information from social media posts, like specific locations or organizations involved [20]. This can help identify emerging hotspots of need or misinformation [20]. By combining these NLP techniques, authorities can gain a comprehensive understanding of public reactions, tailor communication strategies to address specific concerns, and counteract misinformation effectively [2]. This proactive approach, as explored by Vieweg et al. [29] in their study of microblogging during natural hazards, helps maintain trust and facilitates informed decision-making during a crisis [2].

3.3. Data Integration and Real-time Updates

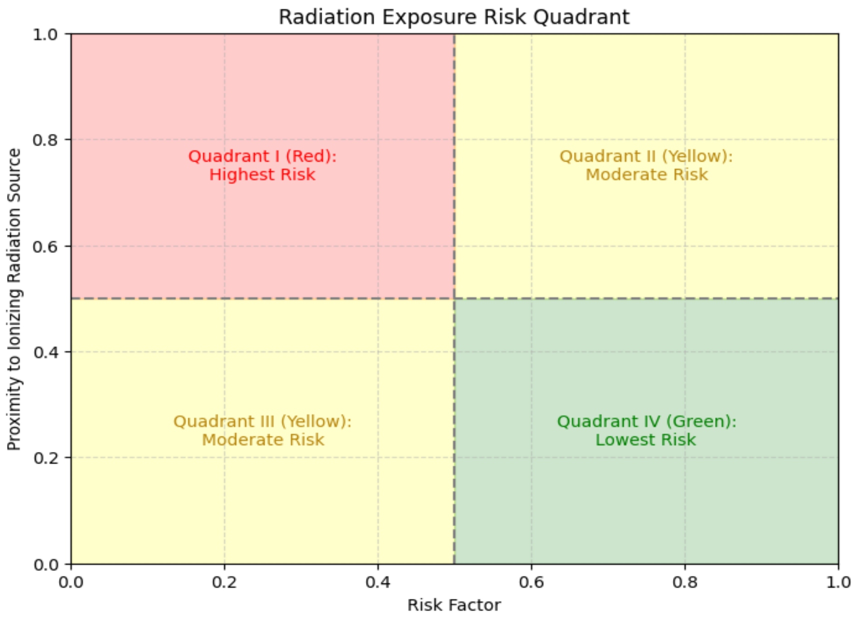

FIG. 5. Proposed quadrant of relationship between risk factor and proximity to ionizing radiation source.

Effective nuclear emergency preparedness and response (EPR) requires a robust data infrastructure [25]. Adapting national digital health strategies' data infrastructure provides a foundation for incorporating crucial nuclear EPR data streams [16, 17]. This includes integrating real-time readings from radiation sensors [36, 43], meteorological data for plume modelling [11], and historical incident records for training predictive models [4]. Real-time data updates are crucial for maintaining the accuracy and relevance of predictions, enabling the system to adapt to changing conditions [18].

International collaboration plays a crucial role in enhancing data sharing and standardization for nuclear EPR [5]. By fostering partnerships among nations, research institutions, and international organizations, data can be shared across borders, leading to improved situational awareness and more accurate predictions [5]. This collaborative effort is essential for effective data integration and real-time updates in AI-driven nuclear EPR systems [6, 7, 8].

Collaborative efforts can lead to the development of standardized data formats and protocols, facilitating seamless data exchange across borders [5]. This standardization is crucial for integrating diverse data sources, such as sensor readings and meteorological data, into AI models and ensuring interoperability between different national infrastructures [12]. International collaboration enables the establishment of common protocols and data exchange standards, benefiting all participating nations [5].

The importance of international collaboration and data sharing in nuclear emergencies is highlighted by the response to the Fukushima Daiichi disaster [4, 31]. Countries shared critical information and resources, as documented by the IAEA [31] and analysed by Kerr [4]. Countries with advanced atmospheric modelling capabilities, such as the United States (through NARAC) and France (through IRSN), provided predictions of the plume's movement and potential deposition patterns [31]. These predictions, based on meteorological data and sophisticated computer models, were crucial for assessing the potential impact of the disaster on neighbouring countries and guiding protective measures [31]. In addition, various countries and organizations aided Japan, sharing crucial information like radiation monitoring data [31]. This collaborative effort enhanced situational awareness and informed decision-making during the crisis [31].

3.3.1. Graph of Neural Network modelling

Graph Neural Networks (GNNs), capable of capturing complex relationships between interconnected entities, can be employed for advanced risk assessments in nuclear EPR [41]. Unlike traditional methods that may focus on individual risk factors in isolation, GNNs can model the interplay between various factors, such as geographical location, proximity to critical infrastructure, population density, and vulnerability to radiation exposure [13]. This holistic approach provides a more comprehensive understanding of risk and enables more targeted interventions.

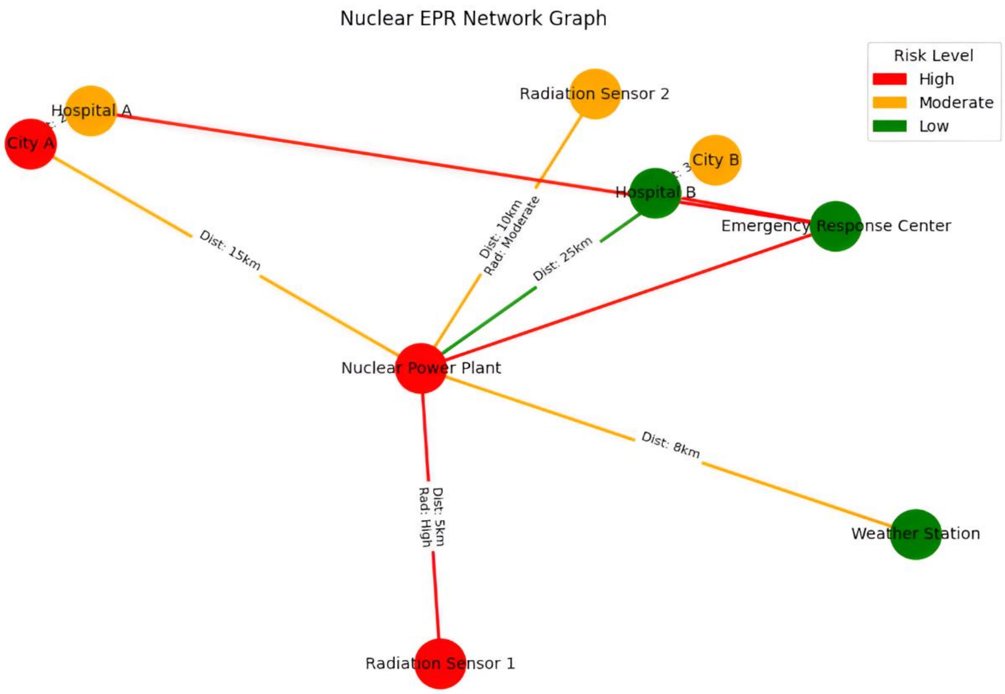

FIG. 13. Proposed Graph of Neural Network Linking EPR Scenario and Risk Zone Modelling.

Imagine a visual representation of a GNN with a central node representing a high-risk nuclear power plant. This plant is connected to various entities, including cities, hospitals, emergency response centres, weather stations, and radiation sensors. Each entity is assigned risk levels based on factors like proximity to the plant, potential radiation exposure, and population vulnerability. Thicker lines in the graph indicate stronger relationships and potentially higher impact, with color-coded lines representing different radiation levels or risk categories. This visualization aids in understanding the interconnectedness of different entities and facilitates decision-making during emergencies, enabling authorities to prioritize evacuations, allocate resources, and coordinate response efforts effectively [13].

The GNN above visually represents a nuclear EPR scenario, with the central entity being a high-risk nuclear power plant. The graph connects this plant to various entities, including cities, hospitals, emergency response centres, weather stations, and radiation sensors, each assigned risk levels based on factors like proximity and potential radiation exposure. Thicker lines indicate shorter distances and potentially higher impact, with color-coded lines representing radiation levels. This visualization aids in understanding the interconnectedness of different entities and facilitates decision-making during emergencies, enabling authorities to prioritize evacuations, allocate resources, and coordinate response efforts effectively. For instance, the graph could depict a scenario where an incident at the nuclear power plant leads to elevated radiation levels, requiring the evacuation of nearby City A and the preparation of Hospital A for potential casualties, while the Emergency Response Centre coordinates the overall response.

Beyond these specific advancements, continuous exploration of cutting-edge AI/ML techniques is crucial for staying ahead of evolving threats and challenges in nuclear EPR. This includes exploring the potential of reinforcement learning for optimizing response strategies in dynamic environments, natural language generation for automated report writing and public communication, and computer vision for damage assessment and situational awareness. By proactively embracing these advancements and integrating them into national digital health strategies, the international community can collectively enhance its preparedness for nuclear emergencies and safeguard public safety in an increasingly complex world.

3.4. Risk Assessment and Stratification

MySejahtera's AI/ML models, refined for public health crisis management, offer valuable blueprints for enhancing nuclear EPR. By drawing parallels between managing public health emergencies and nuclear incidents, key areas where existing technologies can be effectively adapted can be identified. For instance, time series analysis, adept at forecasting infection trends in MySejahtera, can be adapted to predict the dispersion of radioactive plumes following a nuclear incident [18], like how meteorological models are used to forecast weather patterns [4].

Similarly, clustering algorithms used for identifying disease hotspots can be repurposed to pinpoint areas with elevated radiation levels, aiding in targeted evacuations and resource deployment [35], much like their application in identifying environmental contamination clusters. This approach aligns with the IAEA's focus on leveraging technology to enhance response capabilities [1, 5].

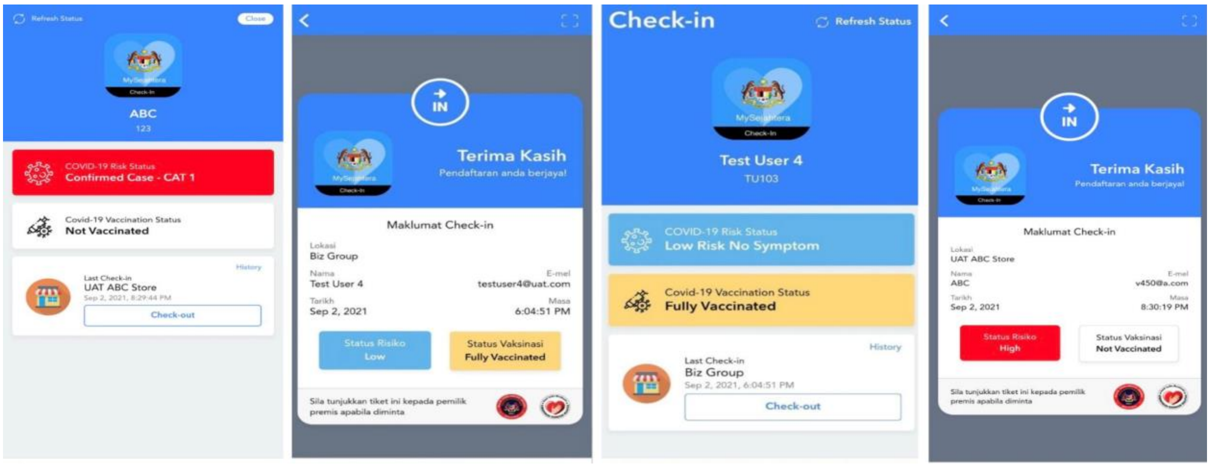

FIG. 6. Malaysia MySejahtera Digital Health risk classification overview.

MySejahtera's data infrastructure, capable of handling vast datasets on demographics and mobility, provides a foundation for incorporating crucial nuclear EPR data streams [17]. This includes real-time readings from radiation sensors [36, 43], meteorological data for plume modelling [11], and historical incident records for training predictive models [4]. The integration of diverse data sources, including real-time sensor data and demographic information, mirrors the approach used in epidemiological surveillance systems for infectious diseases [19].

MySejahtera's prediction process, refined through handling real-time health data, offers a valuable framework for nuclear EPR adaptation [18]. The model training process can be re-purposed by utilizing historical data from past nuclear incidents, such as Chernobyl [31] or Fukushima [4], to train AI models to predict the spread of radiation and potential health impacts. This involves incorporating factors like the type of incident, weather patterns, and terrain features. Furthermore, real-time updates from radiation sensors deployed across the affected area can be integrated into the system, mirroring the real-time case updates in MySejahtera [18], to provide dynamic predictions and inform ongoing response efforts. This dynamic updating process is crucial in nuclear emergencies, where the situation can change rapidly and unpredictably, as highlighted in UNSCEAR reports [45].

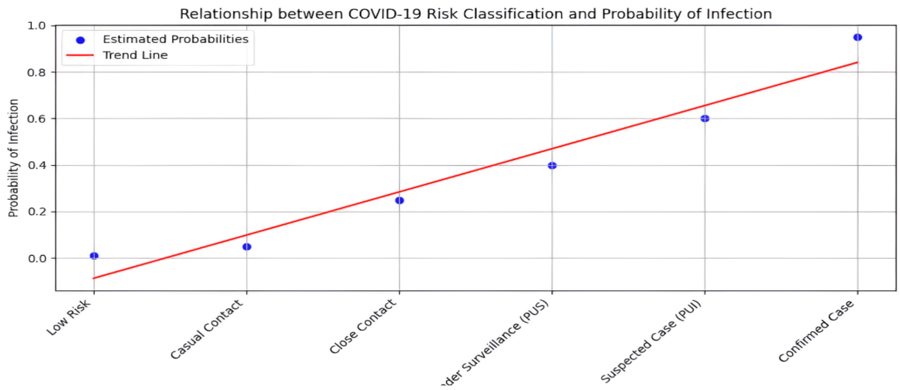

FIG. 7. Proposed regression model relationship between COVID-19 risk classification and probability of infection.

This adapted system can directly address key EPR challenges. For instance, AI-powered trend forecasts can anticipate the potential spread of radioactive material, aiding in proactive evacuations and shelter-in-place orders [1]. Hotspot detection, refined in MySejahtera for disease outbreaks [16], can be crucial in identifying areas with critically high radiation levels, guiding the deployment of specialized response teams and medical resources. Moreover, the resource allocation functionalities within MySejahtera can be adapted to guide the deployment of specialized equipment and personnel in nuclear emergencies [16]. This could involve directing radiation monitoring teams, dispatching decontamination units, or coordinating the distribution of iodine tablets, like how resources were strategically allocated during the COVID-19 pandemic [20].

By integrating these AI-driven capabilities into national digital health strategies, countries can significantly bolster their preparedness for, and response to, nuclear and radiological incidents [15]. This approach leverages existing infrastructure and fosters a unified approach to emergency management, enhancing public safety. Adapting MySejahtera's AI-driven approach into national digital health strategies can significantly enhance nuclear EPR capabilities, improving countries' ability to respond to emergencies and contributing to the IAEA's mission of a safer world [1, 5].

MySejahtera's risk stratification models, used to categorize individuals based on their vulnerability to COVID-19, can be adapted to assess the risk levels of different population groups in a nuclear emergency [16]. This could involve considering factors such as proximity to the incident, age, pre-existing health conditions, and potential for radiation exposure [42]. This approach to risk stratification aligns with the principles outlined in WHO guidelines [15]. Additionally, MySejahtera's use of NLP for analysing public sentiment and disseminating information can be invaluable in a nuclear crisis [16]. NLP algorithms can monitor social media and news reports to identify public concerns, rumours, or misinformation, allowing authorities to respond quickly and provide accurate, timely information through the platform [20]. This can help manage public anxiety and ensure effective communication during a stressful situation [2].

This paper explores the potential of enhancing AI-driven national digital health platforms to optimize healthcare provider response and improve patient outcomes during a nuclear emergency. We propose integrating a dedicated feature within these platforms to facilitate the management and tracking of patient radiation exposure. This feature would enable healthcare professionals to seamlessly record administered treatments, including medications like Potassium Iodide, Prussian Blue, and DTPA, directly into the patient's digital health record [23]. This aligns with the recommendations of Mettler and Voelz [32] for the medical management of radiation accidents, which emphasize the importance of accurate record-keeping and timely administration of appropriate treatments.

This centralized system would provide a comprehensive and readily accessible overview of each patient's treatment status, including dates and types of medications received. Furthermore, we advocate for incorporating functionalities to facilitate ongoing patient monitoring, such as automated reminders for crucial follow-up treatments and check-ups. This approach, modelled after the success of digital health platforms in managing COVID-19 vaccination records [16, 17], promises to significantly enhance public safety by streamlining access to vital patient information and ensuring timely medical interventions during a nuclear emergency. This paper aims to contribute to the ongoing discourse on strengthening nuclear emergency preparedness and response through technological advancements in healthcare [6, 7, 8].

TABLE 1. PROPOSED RADIATION RISK ASSESSMENT SCORING SYSTEM FOR NATIONAL DIGITAL HEALTH STRATEGIES.

Factor	Sub-Factor	Score	Rationale
Proximity to Incident	Immediate Zone	5	Individuals in the immediate vicinity of the incident have the highest probability of acute radiation sickness (ARS) and radiation burns.
	Near Zone	4	Individuals located within a few kilometers of the incident have an elevated probability of ARS, radiation exposure, and contamination.
	Far Zone	3	Individuals located at a significant distance from the incident have a lower probability of ARS but may still experience long-term health effects.
Exposure Pathway	Internal Contamination	5	Ingestion or inhalation of radioactive materials leads to a high probability of organ damage, cancer, and other severe health complications.
	External Exposure	3	External exposure can cause radiation burns, ARS, and long-term health effects, but the severity generally less than internal contamination.

Vulnerability Factors	High (Children, elderly, pre-existing health conditions, first responders)	5	These individuals are more susceptible to the effects of radiation and have a higher probability of severe ARS and long-term health consequences.
	Moderate	3	Individuals with moderate vulnerability have an increased probability of complications and adverse outcomes.
	Low	1	Individuals with low vulnerability are relatively less susceptible to radiation effects.

Factor	Weight
Proximity to Incident	40%
Exposure Pathway	35%
Vulnerability Factors	25%

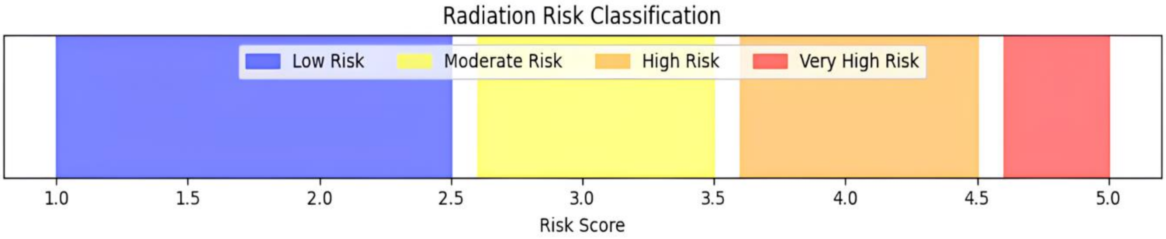

FIG. 8. Proposed Radiation Risk Assessment Scoring System for National Digital Health Strategies.

Integrating these capabilities into health strategies for enhanced nuclear emergency preparedness and response (EPR) can significantly improve public safety and resilience. By adapting MySejahtera's risk profiling system, authorities can categorize individuals based on their potential exposure to nuclear incidents. Factors such as radiation exposure levels, proximity to the incident site, health status, and evacuation orders can determine risk profiles. These profiles help identify and notify high-risk individuals. They also allow authorities to monitor health status and implement targeted interventions. Furthermore, the profiles help prioritize medical care and resources. This approach ensures a more efficient and effective response to nuclear emergencies, leveraging real-time data analysis and predictive modelling to optimize resource allocation and decision-making. By keeping their profiles updated, individuals can receive timely and accurate information, contributing to a coordinated and comprehensive emergency response. This adaptation of MySejahtera's capabilities can enhance preparedness efforts, facilitate international collaboration, and align with the overarching goals of organizations like the International Atomic Energy Agency (IAEA) for nuclear EPR.

4. CASE STUDIES AND EXAMPLES

4.1. Real-World Implementations: Existing examples of AI applications in nuclear EPR.

To further illustrate the practical applications of AI in nuclear EPR, examining real-world examples is beneficial. The Radiological Assessment Tool (RAT), developed by the Lawrence Livermore National Laboratory, uses AI to analyse sensor data and predict the spread of radioactive materials in real-time [11]. In Europe, the Decision Support System for Nuclear Emergencies (RODOS) incorporates AI models to predict the impact of nuclear accidents on public health and the environment [34]. These successful implementations demonstrate the potential of AI to significantly enhance nuclear EPR capabilities and bolster the argument for its wider adoption [6, 7, 8].

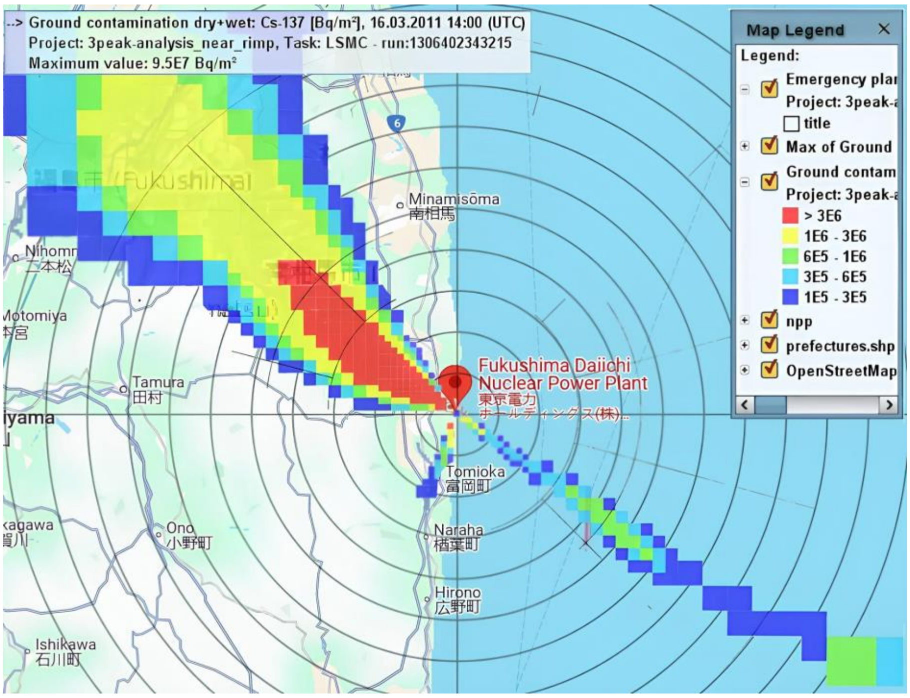

FIG. 10. Revisualization of Decision Support System for Nuclear Emergencies (RODOS) during 2011 Fukushima Daiichi nuclear disaster.

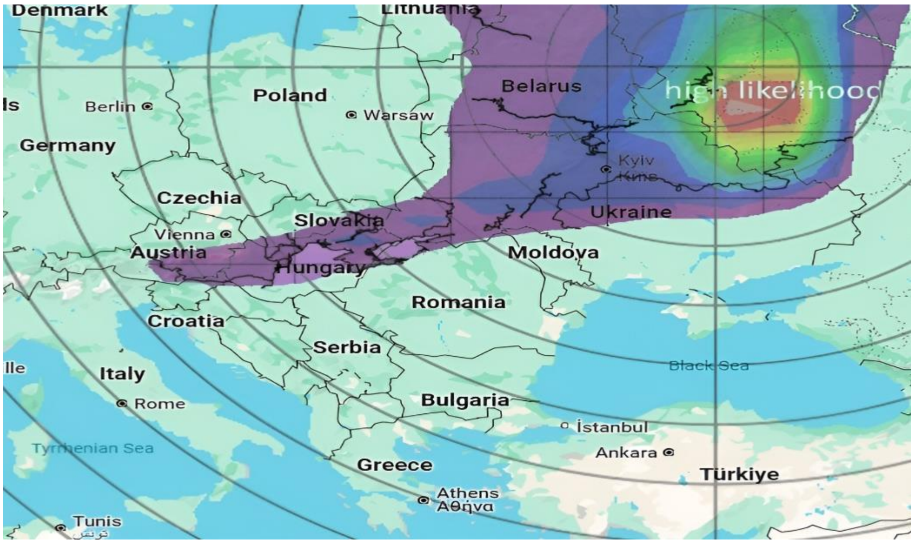

FIG. 11. Revisualization of Bayesian Statical Technique on Atmospheric Dispersion Modeling

For instance, the National Atmospheric Release Advisory Center (NARAC) used atmospheric dispersion modelling, air monitoring station data, and Bayesian statistical techniques, boosted by machine learning, to estimate the probable atmospheric sources for Ruthenium-106 detected in Europe in 2017 [11]. This analysis helped identify the likely origin of the release and assess its potential impact on the environment and public health [11]. This example highlights the power of AI in enhancing situational awareness and informing decision-making during nuclear emergencies [12].

4.2. Illustrative Scenarios: Hypothetical scenarios of nuclear incidents and demonstration of adapted MySejahtera system aid in response efforts.

Adapting MySejahtera's QR code functionality can significantly enhance AI-driven national digital health strategies for nuclear emergency preparedness and response. QR codes can track individuals' presence in specific locations during a nuclear incident, integrating this data with radiation monitoring systems to estimate individual exposure levels and assess potential health risks. Linking QR codes to medical records enables efficient tracking of decontamination procedures, medications administered, and other crucial medical interventions. This technology can also facilitate automated reminders for follow-up care. In addition, QR codes can assist in managing evacuations and shelter assignments, disseminating vital public information on radiation safety and emergency instructions, and integrating data with AI-driven platforms for analysis and resource optimization. This comprehensive approach empowers a proactive and data-driven response to nuclear emergencies, ultimately enhancing public safety and well-being. This section demonstrates how an adapted MySejahtera system could be used in various nuclear emergency scenarios.

4.2.1. Scenario 1: Urban Radiation Leak

Imagine a radiation leak at a research facility in a densely populated urban area. The adapted MySejahtera system would immediately activate, utilizing real-time data from radiation sensors and integrating it with individual location data gathered through QR code check-ins [16, 17]. This would enable rapid identification of individuals potentially exposed to radiation [36, 43], facilitating targeted evacuation orders and shelter assignments [1]. Furthermore, the system could utilize NLP techniques to monitor social media for misinformation and public concerns [29, 30], allowing authorities to provide timely and accurate information through the platform [2], mitigating panic and ensuring public safety. As Vieweg et al. [29] highlight, real-time integration of sensor data and individual location information, coupled with effective communication strategies, is crucial for rapid response and public safety in urban radiation incidents.

4.2.2. Scenario 2: Nuclear Power Plant Accident

Consider a hypothetical accident at a nuclear power plant, resulting in the release of radioactive materials. The adapted MySejahtera system would play a crucial role in managing the crisis by predicting the plume's dispersion using AI-powered models trained on historical data and real-time meteorological information [4, 11]. This would enable authorities to issue timely evacuation orders and shelter-in-place advisories to minimize public exposure [1]. MySejahtera would then disseminate these critical alerts and instructions for obtaining potassium iodide tablets rapidly to the public. [1, 16] This rapid and targeted information dissemination would leverage MySejahtera's existing infrastructure for communication and public health messaging. [16] Additionally, the system could be used to coordinate the distribution of potassium iodide tablets, ensuring that individuals within the affected area have access to this essential protective measure.

4.2.3. Scenario 3: Radiological Terrorism Incident

In the event of a radiological terrorism incident, such as the detonation of a "dirty bomb," the adapted MySejahtera system could aid in identifying individuals potentially exposed to radiation and facilitate their rapid triage and treatment [16, 17]. By linking QR code check-ins with medical records, healthcare providers could access crucial information about individuals' exposure levels and pre-existing health conditions, enabling personalized medical interventions [23]. This centralized system would also ensure efficient tracking of administered treatments and facilitate ongoing patient monitoring, enhancing the overall medical response and improving patient outcomes [32]. Integrating QR code technology with medical records and AI-powered platforms can significantly enhance the medical response to radiological terrorism incidents, enabling efficient triage, personalized treatment, and ongoing patient monitoring.

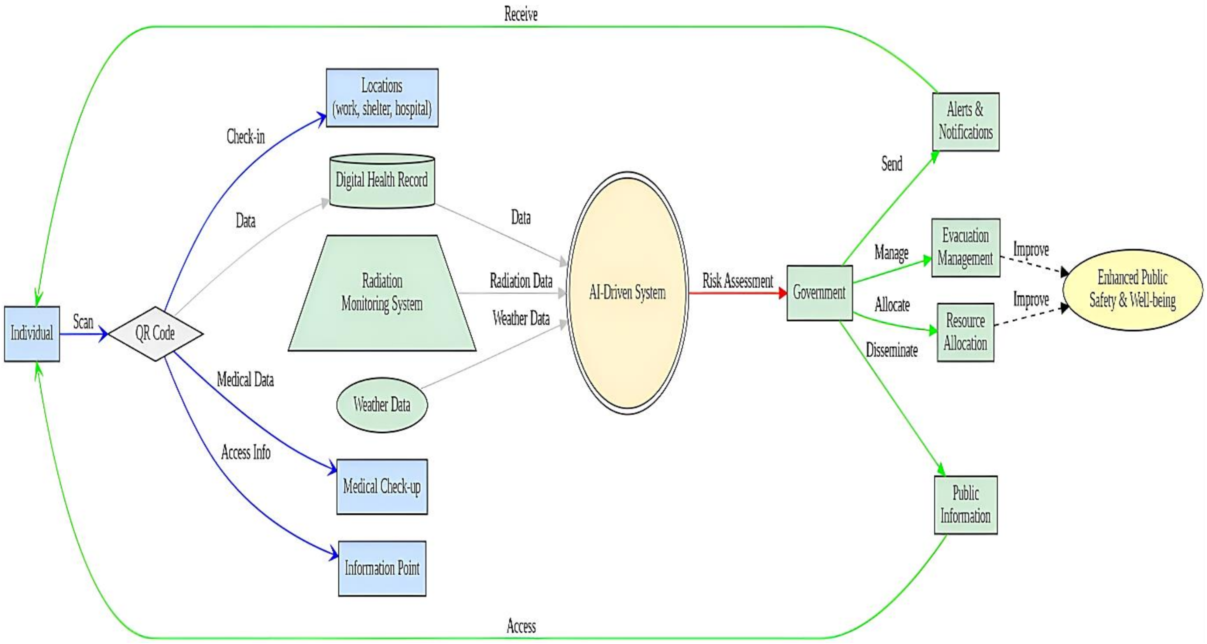

FIG. 12. QR Code Functionality for National Digital Health Strategy During Nuclear Incident

5. CHALLENGES AND FUTURE ENHANCEMENTS

While the prospect of adapting AI-driven national digital health strategies for nuclear Emergency Preparedness and Response (EPR) is promising, it is crucial to acknowledge and address the unique complexities this endeavour presents [9]. Ensuring data quality and availability is paramount for accurate predictions and reliable decision-making in nuclear emergencies [25]. Unlike the relatively structured health data in national digital health strategies, which primarily dealt with individual health records and test results, nuclear events may involve a deluge of diverse and unstructured data sources [44]. These include real-time readings from radiation sensors of varying technologies and sensitivities, meteorological data from weather stations and atmospheric models, geographical information, potentially incomplete historical incident records, and even social media feeds [44].

This heterogeneity poses a significant challenge for data interoperability and standardization [12]. To ensure effective model training and deployment, it is necessary to develop standardized data formats, implement robust data validation procedures, and utilize data fusion techniques to integrate information from these disparate sources [12]. This requires not only technical expertise but also collaboration among various stakeholders, including sensor manufacturers, data providers, and emergency response agencies, to establish common protocols and ensure seamless data exchange [5].

Furthermore, privacy concerns surrounding sensitive health and location data, already a consideration in national digital health strategies, become even more critical when incorporating data related to nuclear facilities and potential radiation exposure [23, 37]. Robust data anonymization and security protocols are essential to maintain public trust and comply with data protection regulations [37]. This is particularly important in the context of nuclear EPR, where public trust and confidence in authorities are crucial for effective response and recovery efforts [2]. Transparent data governance frameworks and clear communication about data usage are essential to address public concerns and ensure ethical data handling [23].

Another significant challenge is the potential resistance to fully embracing AI in critical safety operations [14]. Nuclear EPR often involves high-stakes decisions with potentially far-reaching consequences, and there may be reluctance to rely solely on AI-driven predictions or recommendations [8]. Building trust in these systems through rigorous testing, validation, and transparency is crucial for successful integration. Explainable AI (XAI) techniques, which provide insights into the reasoning behind AI's decisions, can help foster confidence and understanding among human operators, enabling them to make informed decisions based on AI-generated insights [9].

Ethical considerations, such as potential bias in algorithms and the need for human oversight, should be addressed to ensure responsible AI implementation [27]. Careful choice of training data and model design is needed to prevent unequal distribution of resources or protection based on factors like demographics or socioeconomic status [24]. Additionally, the implications of automated decision-making in high-stakes scenarios should be carefully evaluated to ensure human oversight and accountability [10]. A balance between AI assistance and human decision-making is crucial, especially when dealing with the potential for widespread impact in nuclear events [9].

International collaboration is paramount in addressing the multifaceted challenges of AI-driven nuclear EPR [5]. Collaborative efforts can facilitate the sharing of technical expertise, resources, and best practices, enabling countries to overcome technology limitations and accelerate the development of robust AI solutions [5]. Joint research initiatives can address ethical concerns by fostering open dialogue and establishing international standards for responsible AI development and deployment in nuclear EPR [5]. Moreover, pooling resources through international partnerships can help mitigate the costs associated with implementing AI-powered solutions, making them more accessible to countries with varying levels of technological development [5]. Federated learning offers a promising avenue for collaborative model development while preserving data privacy and national security [38]. By enabling the training of AI models on decentralized datasets without direct data sharing, federated learning allows countries to benefit from collective knowledge while respecting national sovereignty and data protection regulations [38].

Looking ahead, future enhancements can further strengthen the adaptation of national digital health strategy capabilities for nuclear EPR. Federated learning, a decentralized approach to AI model training, allows different countries to collaborate on model development without directly sharing sensitive data [38]. This approach is particularly relevant in the context of nuclear EPR, where data sensitivity and national security concerns may hinder traditional data sharing practices. Federated learning allows collaborative model development while preserving data privacy. This approach can create more robust and generalizable models by leveraging diverse datasets from various countries [38]. This aligns with the IAEA's emphasis on international cooperation and can facilitate collaborative efforts to enhance nuclear EPR capabilities globally [5].

6. CONCLUSION

This paper demonstrates how AI-driven national digital health strategies, like Malaysia's MySejahtera, can revolutionize nuclear Emergency Preparedness and Response (EPR). It proposes a framework for adapting existing technologies to improve global preparedness. The key findings underscore the transformative potential of AI in nuclear EPR. AI-powered systems can enable rapid and accurate data analysis, facilitating real-time situational awareness during nuclear events. Predictive modelling capabilities allow for forecasting the spread of radioactive plumes, identifying potential hotspots, and stratifying risk levels for individuals and communities. Furthermore, AI can optimize resource allocation, ensuring efficient deployment of medical supplies, personnel, and evacuation strategies based on data-driven predictions and risk assessments.

This AI-driven approach fosters a proactive and data-driven response to nuclear emergencies, empowering authorities with the tools to rapidly assess, manage, and respond to unfolding events. The proposed framework addresses critical gaps in current EPR systems by incorporating advanced AI/ML models, data integration capabilities, and real-time updates, ultimately contributing to enhanced public safety and resilience. Looking ahead, the paper emphasizes the importance of continuous research and development to further strengthen AI-driven EPR frameworks. This includes addressing challenges related to data quality and standardization, ensuring privacy and security, and promoting explainable AI (XAI) to foster trust and understanding. International collaboration is also crucial, particularly in facilitating data sharing and joint model development while respecting national security and privacy concerns.

The IAEA is urged to take a leading role in promoting the integration of AI into national digital health strategies for nuclear EPR. By providing guidance, fostering collaboration, and supporting member states in adapting these technologies, the IAEA can catalyse a global shift toward more robust and AI-driven EPR frameworks, contributing to a safer and more resilient future in the face of nuclear threats. In conclusion, this paper advocates for a global paradigm shift in nuclear EPR, emphasizing the integration of AI into national digital health strategies. By harnessing the power of AI, we can transform emergency preparedness and response, creating a safer world for all. International collaboration is not merely an option but a necessity in this endeavour. By working together, sharing knowledge and resources, nations can unlock the full potential of AI in nuclear EPR, ensuring a more resilient future for the global community in the face of nuclear threats.

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