

REVIEW

Next-Generation Environmental Radiation Monitoring: Advances in Sensors, Data Analytics, and Earth System Integration

Wenbing Wang

Jiangsu Qingquan Technology Co., Ltd., Nanjing 210019, China

ABSTRACT

The convergence of next-generation sensors, sophisticated data analytics, and Earth system models has fundamentally transformed the landscape of environmental radiation monitoring. These technological synergies have collectively enhanced the accuracy, spatial coverage, and real-time responsiveness of detection systems, enabling more precise identification and assessment of radiation exposure risks. This article systematically reviews recent progress in sensor technologies, including improved sensitivity and durability, alongside the growing role of machine learning algorithms in processing complex monitoring data and distinguishing anomalous radiation patterns from background noise. A central focus is the integration of radiation data into Earth system models, which facilitates the simulation of radionuclide dispersion and environmental fate, thereby supporting predictive capabilities and informed decision-making during radiological emergencies. Furthermore, the article highlights the practical benefits of real-time monitoring networks and early warning systems in strengthening disaster preparedness and safeguarding public health. Despite these notable advances, significant challenges remain, including issues related to sensor calibration, cross-platform data integration, infrastructure deployment, and cybersecurity. Looking ahead, continued research, technological innovation, and international collaboration are essential to enhance the reliability, scalability, and global interoperability of these systems. Ultimately, these developments not only contribute to reducing radiation-related risks but also align with broader sustainability objectives, particularly in supporting environmental health, climate resilience, and evidence-based policy formulation under the United Nations Sustainable Development Goals.

Keywords: Environmental Radiation; Sensors; Data Analytics; Earth System Models; Early Warning Systems

*CORRESPONDING AUTHOR:

Wenbing Wang, Jiangsu Qingquan Technology Co., Ltd., Nanjing 210019, China; Email: qliu9397@bsuc.edu.cn

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1. Introduction

The field of environmental radiation monitoring has been a mainstay of environmental health, safety and environmental protection, and it is essential in the early identification and management of radiating sources of danger^[1]. Nuclear accidents and even in our daily lives, radiation can have the capacity to influence human health as well as the ecosystems within which we operate. Historically, radiation monitoring has been based on a variety of stationary and mobile sensors to measure the level of radiation in the environment, usually related to detection and warning systems in cases of

short-term threats^[2]. Nonetheless, with the ever-changing environment and industrial landscape across the globe, there is a sense of urgency to have more advanced systems that not only identify radiation more precisely and sensitively but also have a smooth flow of the systems with large-scale environmental management systems. This changing requirement is stimulating sensor technology innovation, data analytics, and the integration of Earth systems, which is the next big jump in radiation monitoring^[3]. **Figure 1** shows the main elements and data flows—i.e., sensors, data processing, and decision support mechanisms—of a current radiation monitoring system.

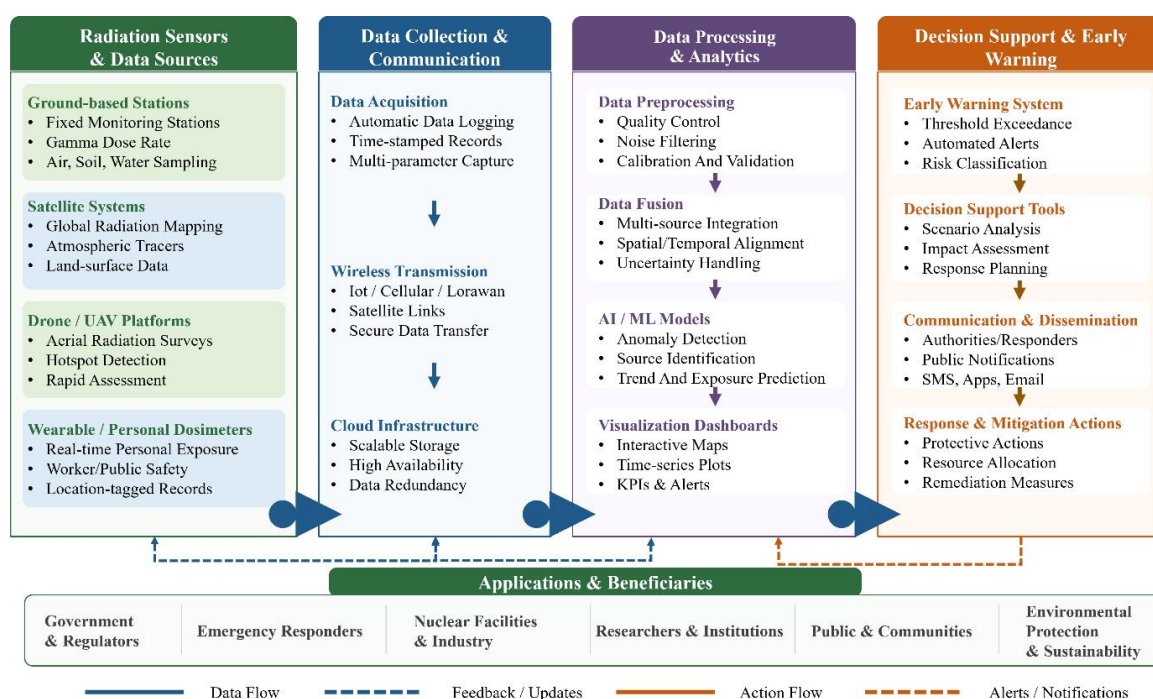


Figure 1. Overview of environmental radiation monitoring systems.

The uniqueness of this review is the analysis of the intersection of three important developments: the latest sensor technologies, the latest data analytics methods, and the inclusion of radiation monitoring in models of Earth systems^[4]. These inventions not only enhance the sensitivity and range of radiation detection but also allow real-time and dynamic reactions to environmental radiation occurrences both on a global and local level. The integration of these technologies brings forth a paradigm shift from the old, siloed monitoring systems to highly integrated, predictive and automated structures that can predict radiation events and provide actionable information to decision-makers. However, despite

these advances, current monitoring systems cannot achieve full global coverage due to infrastructure gaps in remote regions (oceans, polar areas, mountains) and sensor limitations under extreme environmental conditions.

Traditionally, radiation sensors were unwieldy and might need special equipment, lengthy calibration, and manual monitoring. The recent generation sensors, however, are transforming the world by emphasizing miniaturization, high sensitivity and portability. Graphene, organic semiconductors and improved scintillator crystals are some of the new materials that allow the creation of smaller, lightweight and more energy-efficient detectors that still offer highly

accurate measurements of radiation^[5]. Moreover, wireless communication innovations can be used to transmit sensor data in real-time, which opens the possibility of continuously operating, worldwide radiation monitoring systems^[6]. This advancement has significantly improved the spatial and temporal resolution of environmental radiation measurements, allowing better detection of radiation hotspots, especially in regions that were previously challenging to observe because of geographic remoteness or sparse infrastructure.

Along with the sensor technology developments, data analytics in radiation monitoring is being revolutionized. The amount of data produced by modern radiation sensors is enormous, especially when combined into large scale monitoring systems. This information is usually too complex and too large to process using traditional methods of data processing. Nevertheless, with the emergence of machine learning and big data analytics, it is now possible to make substantial advancements in processing and interpretation of radiation data^[7]. With improved speed and accuracy, algorithms can now be used to improve signal detection, lower noise, and detect radiation anomalies. In addition, using a combination of the data obtained with various methods, including satellite data, ground-based sensors and weather prediction, more sophisticated data fusion methods provide new opportunities to design detailed models of radiation diffusion and exposure. Such sophistication in analysis is changing radiation surveillance into a proactive, anticipatory procedure rather than a reactive one, with the capability of making anticipatory evaluations of the radiation exposure before it becomes harmful^[8].

A similarly revolutionary change is taking place in the incorporation of radiation monitoring into models of Earth systems. Complex interactions between the atmosphere, oceans, land and living organisms have long been understood using earth system models. With these models, we are able to understand more about the movement and interaction of radiation with different components of the Earth's systems by adding radiation data into these models. Radiation measurements can be incorporated into weather forecasts, climate models, and ecological simulations without interruption, providing a more comprehensive picture of the radiation processes in the environment with the help of data assimilation methods^[9]. This integration does not only increase

the precision of radiation exposure forecast but also allows the formulation of more practical risk reduction approaches, especially when dealing with ecological catastrophes like nuclear accidents, natural disasters, and the possible impact of climate change.

This capability to incorporate these technologies into real-time radiation surveillance and early warning systems may be the most interesting use of these advances^[10]. The analysis of real-time data can help detect anomalies in radiation immediately and provide the possibility of early warnings, which is essential to react to accidents and reduce their harmful consequences on the environment and human health. Real-time monitoring coupled with Earth system models can predict radiation exposure with increased accuracy, enabling more efficient emergency response plans and more informed actions to protect people. Additionally, the ubiquitous nature of mobile technologies and remote sensing additionally enables real-time monitoring of radiation, providing a level of situational awareness never seen before in circumstances of radiological emergency^[11].

This review will delve into these innovative advances in environmental radiation surveillance and how they are likely to revolutionize the scene of radiation detection and control^[3]. It will also point out the sensor technology developments that have enabled radiation detection to be more precise, mobile, and accessible, and the data analytics that have played a role in processing such large amounts of sensor data^[12]. In addition, it will talk about how Earth system models are currently being incorporated with radiation information to form more comprehensive and predictive models^[13]. Combining these developments, we will offer a comprehensive perspective on the future of radiation monitoring and the ways in which it can contribute to the well-being of people, their safety, and the sustainability of the environment.

Finally, the combination of next-generation radiation sensors, data analytics, and Earth system models is a special opportunity to not only enhance the capabilities of monitoring radiation in real-time but also learn more about its overall effects on the environment^[14]. The developments are the frontiers of radiation monitoring and have the potential to transform the way we deal with radiation safety and environmental issues in the next few decades.

2. Advances in Environmental Radiation Sensors

The development of environmental radiation sensors has been greatly enhanced in the last few decades due to the progress in materials science, engineering and methods of computation. These types of sensors play a vital role in measuring the amount of radiation in the surrounding environment, such as natural sources of radiation (cosmic radiation, radon) and artificial sources (nuclear power plants, medical facilities)^[15]. Due to the rise in global radiation exposure awareness, sensitive, reliable, and easily accessible radiation monitoring systems are in demand. This section reviews the latest advancements in environmental radiation sensors, highlighting innovations in sensor materials, miniaturization, and wireless technologies, as well as their potential to revolutionize radiation monitoring.

2.1. Evolution of Radiation Detection Technologies

The conventional techniques of radiation detection relied on large-scale equipment, including scintillation counters and Geiger-Muller (GM) counters^[16,17]. These devices were good but limited in sensitivity, portability, and energy

use. An example of such a device is the scintillation counters, which make use of fluorescent materials that fluoresce when subjected to ionizing radiation. These counters, though efficient, are usually large in size, demand a lot of power, and have an efficiency loss because of the loss of material over time. In a similar manner, Geiger counters, although very compact, do not give much information regarding the type and energy of the detected radiation, therefore, reducing their utility in more subtle environmental determinations. **Table 1** compares traditional radiation sensors (Geiger-Muller counters, scintillation detectors) to next-generation sensors, highlighting the main differences in sensitivity, portability, and power consumption.

Recent achievements in semiconductor and organic material science have created new forms of radiation detectors, including solid-state and organic scintillators^[18]. These more recent technologies not only enhance the sensitivity and resolution, but provide significant gains in size, weight and energy consumption. Detectors based on semiconductors, including silicon carbide (SiC) or cadmium telluride (CdTe), have a high energy resolution and high radiation sensitivity. These materials are especially appropriate for detecting gamma rays and X-rays, which happen to be the most pertinent in environmental monitoring.

Table 1. Comparison of traditional and next-generation radiation sensors.

Feature	Traditional Sensors	Next-Generation Sensors
Size	Bulky, requires large setups	Miniaturized, portable
Sensitivity	Limited sensitivity	Higher sensitivity, especially to specific radiation types
Energy Consumption	High, requiring significant power	Low power consumption
Accuracy	Basic accuracy, often not specific	Improved accuracy, detailed detection
Material	Often inorganic (scintillators, GM tubes)	Novel materials (graphene, organic semiconductors)
Deployment	Stationary, fixed locations	Mobile, flexible (wearable, drones, etc.)
Cost	High initial cost	Cost-effective with mass production potential

Note: This table highlights differences in size, sensitivity, power consumption, material used, deployment scenarios, and cost.

2.2. Novel Sensor Materials and Their Impact

Among the greatest changes in environmental radiation sensors has been the creation of new materials that bolster the purposes of detection. Graphene, perovskite crystals, and organic semiconductors are some of the materials that are set to transform the world of radiation sensing^[5].

Graphene is a two-dimensional material made of a single sheet of carbon atoms and it has elevated electrical conductivity and is very sensitive to ionizing radiation. Studies have revealed that graphene radiation sensors have the capa-

bility to offer high resolution and fast response times, thus making them good candidates when used in portable and real-time monitoring. Moreover, the prospect of graphene being installed on flexible materials opens opportunities to wearable radiation sensors, which will provide 24-hour surveillance to people in high-risk professions^[19].

The perovskite materials previously utilized in photovoltaics and optoelectronics are also being considered in the area of radiation sensing. Perovskites are sensitive, cheap, and simple to make, and therefore are a promising solution to environmental monitoring. Their ability to detect ionizing ra-

diation in a wide spectrum of environments is also enhanced by their high atomic number (Z), which is conducive to the detection of X-ray and gamma-ray^[20].

Another potential radiation sensor is organic semiconductors, which are both cheap to fabricate and flexible. The materials can be worked at low temperature and incorporated into large area sensors, this particularly benefits the large-scale environmental monitoring networks. Organic semiconductor detectors can also be tailored to respond to particular types of radiation, giving them flexibility in the kinds of radiation they respond to^[5].

2.3. Miniaturization and Portability

One of the most important aspects in the development of radiation sensors is miniaturization due to the growing need for portable and easy-to-use devices. Specifically, small-form-factor radiation sensors are needed to be deployed in large numbers in various locations, both urban and remote. The miniaturization trend is directly correlated with the material of more efficient sensors, especially solid-state and organic detectors^[5].

The recent developments have resulted in the design of miniature, low power devices that do not degrade the sensitivity of the larger ones, but in fact, they are improving them. A good example of this is the creation of handheld gamma spectrometers, which can measure the levels of radiation and the type of radionuclide that is present. Batteries operate these devices, and they can be used to transmit data over a distance; hence, they are suitable for field surveys, emergency response units, and long-term monitoring of environmental radiation. Their small size enables them to be deployed in locations that were not adequately covered, like remote sensing of radiation in agricultural fields, forests, or oceans, where the conventional sensors might not be practical^[21].

Miniaturization is also a key to enhancing sensor coverage and density. To illustrate, massive sensor networks may be used to track radiation levels in real time over a vast geographic region. The strategy will offer streamlined real-time, near-real-time information, which makes it more effective in identifying and monitoring sources of radiation. It also enables increased knowledge on the radiation dispersion patterns, enhancing predictive models of environmental

radiation and data on early warning systems^[2].

2.4. Wireless Communication and Real-Time Monitoring

The use of wireless communication technologies has been a key to changing the way environmental radiations are monitored. Conventional radiation detection technologies frequently involved physical connections of the sensors to central databases, which restricted the scalability and flexibility of monitoring networks. The recent introduction of wireless technologies has overcome this drawback, allowing data of radiations to be sent in real-time, both between individual sensors and centralized data processing devices^[6].

The incorporation of radiation sensors into wireless networks, i.e., Wi-Fi, Bluetooth or cellular networks enables them to continually monitor and report on the radiation level in real time. This immediate transmission of data makes it possible to make quicker decisions and to be more responsive in dealing with the risks of radiation exposure. As an example, during a nuclear disaster, real-time radiation surveillance will be able to give useful information to those in charge and the emergency department to help them make timely decisions to safeguard human health^[22].

Decentralized, self-organizing sensor networks can also be developed using wireless radiation sensors. Such networks can be implemented on a wide scale to track radiation levels in real-time and do not require a large amount of infrastructure. In cities, an example is a system of low-cost, wireless radiation sensors on buildings, streetlights and other infrastructure, which provides a continuous evaluation of radiation exposures in various locations around the city. Monitoring of other environmental parameters such as air quality and weather could also be supported by such networks, giving a more comprehensive picture of the local environment^[23]. Satellite-based radiation monitoring does not require a fixed number of satellites for basic functionality; single-satellite systems (e.g., Fermi Gamma-ray Space Telescope) provide useful data. However, constellations of 3–6 satellites optimized for radiation detection can significantly improve temporal resolution and global coverage. Beyond 10–15 satellites, additional benefits diminish due to data redundancy and processing constraints.

2.5. Integration with Mobile and Remote Sensing Technologies

Another promising boundary in environmental radiation monitoring is the use of mobile platforms and remote sensing technologies^[11]. Due to the growth of smartphones and mobile devices, a novel category of radiation sensors is now capable of being embedded into typical consumer electronics. These sensors, which are coupled with global positioning system (GPS) technology, provide the possibility of real-time and location-based radiation sensors. As an example, a mobile phone with a radiation sensor would be able to scan the level of radiation in a particular area and the information would automatically go to a database in the cloud to be analyzed and shared.

Radiation detection is also being done by use of remote sensing technologies including unmanned aerial vehicles (UAVs) and satellite-based monitoring^[24]. Radiation sensors can also be mounted on drones that can be used in dangerous areas, including around nuclear power plants, to give high-resolution radiation data without exposing human workers to these hazards. In a similar manner, radiation detection by satellite, through gamma-ray and neutron sensors, provides a global monitoring of the amount of radiation, especially in the aftermath of a nuclear accident or natural calamity.

These mobile and remote sensing technologies do more than just increase the range of radiation monitoring networks but they also offer a degree of flexibility and adaptability essential in real-time environmental monitoring. They can support quick reaction to new threats and provide monitoring of radiation in areas that have in the past been unreachable, or hard to monitor^[16].

2.6. Outlook and Open Issues

Although the innovations presented in this section represent significant advances in environmental radiation monitoring, there are still questions to address to improve sensor performance, scaling, and standardization on the monitoring platform. Although new sensor materials have the potential to be useful, barriers to commercial use, such as cost, durability, and accessibility of materials, will have to be overcome before these are widely applied in their commercial use^[25].

Moreover, the concept of incorporating sensors into large-scale surveillance systems poses challenges in data

handling, calibration, and interoperability. It is important that the sensors are aligned with the same standards and that the data they generate are compatible with other platforms, so that global radiation monitoring efforts are successful. Also, the security and privacy of radiation data will be necessary, especially in real-time monitoring systems, to sustain people's trust and confidence in them^[26].

The future of environmental radiation monitoring is increasingly promising as new materials, miniaturization, and wireless communication technologies continue to advance^[27]. The continued evolution of highly sensitive, integrated, and portable radiation sensors will open up the possibility of real-time monitoring of environmental changes and improve our ability to respond to radiation-related events and to better understand the environmental effects of radiation exposure.

3. Data Analytics in Radiation Monitoring

Sensor technology has yielded a treasure trove of environmental radiation data, yet the real promise of radiation monitoring lies in deriving actionable information from the vast, complex datasets. With the growing sophistication of radiation monitoring systems, advanced data analytics have become essential for successful radiation detection, risk evaluation, and management. Here, we examine the application of data analytics to radiation monitoring and how machine learning, data fusion, and real-time processing are improving the ability to analyze radiation data, detect anomalies, and estimate future radiation exposure levels^[26].

3.1. The Role of Big Data in Radiation Analysis

The use of next-generation radiation sensors has massively produced data that needs to be processed, stored, and analyzed. It has led to the idea of big data in radiation monitoring in which the amount, speed, and diversity of data pose challenges to the conventional techniques of data analysis^[7]. Radiation sensors have become continuous in nature and are now producing real-time data streams that demand robust, scalable systems to store and analyze. Moreover, data are usually gathered from a variety of sources, different types of sensors, environmental parameters and geographical locations and can be complicated to integrate and interpret.

Patterns, correlations and anomalies in large data sets can be identified using big data analytics. In radiation monitoring, this may be converted into the capability to identify the slightest change in radiation which may not be noticeable at once. As an example, radiation spikes due to a nuclear accident or low-level radiation exposure in urban areas necessitate sophisticated data processing applications capable of dealing with extensive and highly noisy data streams. The conventional approaches like simple statistical analysis or manual checking are inadequate in handling the amount of data produced by the current radiation sensors. On the contrary, these patterns can be easily automated by using big data techniques, which can provide real-time information about the level of radiation and possible threats^[28].

In addition, big data analytics could make it easier to integrate radiation data with other environmental monitoring systems to generate a more holistic view of the factors affecting radiation exposure. Integrating data from meteorological sensors, traffic sensors, and other environmental monitoring systems, the techniques of big data can be used to create a more comprehensive image of the movement of radiation through various environments, its interactions with other substances, and how it can be reduced^[9].

3.2. Machine Learning for Radiation Detection and Anomaly Identification

Machine learning (ML), which is one of the branches of artificial intelligence (AI), has become an influential tool to enhance the efficiency and accuracy of radiation monitoring. ML algorithms can process large bodies of data, learn from historical data, and provide predictions or classifications using new data. When applied to radiation monitoring, ML can be used to improve the detection of radiation events, detect unusual patterns, and forecast future radiation exposure levels more accurately than traditional algorithms^[7].

Anomaly detection is one of the main uses of machine learning in radiation monitoring. Through training ML models using past radiation data, systems are able to learn the normal distribution of radiation levels of a given environment or area. This allows detection of outliers or anomalies that may be suggesting a radiation event, such as suddenly increasing radiation levels caused by a nuclear accident, a natural disaster, or a radiation leak. As an example, poten-

tially dangerous spikes of radiation in real-time streams can be detected using ML algorithms and mitigated as soon as possible^[26].

The accuracy of radiation dose estimations can also be enhanced by ML. Conventional radiation sensors usually report raw counts of detected radiation, which need to be processed to estimate dose to a person or the environment. ML algorithms, especially regression models, can be trained to forecast radiation doses using sensor measurements and environmental factors. These models are able to consider various factors, such as distance to the source, weather, and terrain, and make more precise predictions of radiation exposure^[26].

Another important use of ML in radiation monitoring is classifying radiation types^[29]. Alpha, beta, and gamma radiation are different forms of radiation that have distinct physical characteristics and modes of detection. Recognizing these types of radiation is important for identifying potential health hazards and the necessary protection measures. Conventional sensors may be useful only for providing limited information about the type of radiation detected. Nevertheless, ML models can be trained to process sensor data and categorize the type of radiation based on the energy spectrum, signal time profile, and other pertinent characteristics. This would be a very valuable addition to the radiation monitoring systems, and would give more precise and specific evaluation of the radiation risks.

3.3. Data Fusion for Enhanced Radiation Monitoring

Integration of data between various types and sources of sensors is one of the main problems in environmental radiation monitoring^[12]. The radiation levels may be affected by a broad assortment of factors, such as environmental conditions, the availability of shielding materials, or the type of radiation involved in the emission. To cope with this complexity, data fusion methods are being designed to help combine the information of various sources to give a more comprehensive picture of radiation exposure and enhance the precision of radiation forecasts. The various data fusion techniques that are applied in radiation surveillance are summarized in **Table 2**, and their benefits, applications, and most important features are explained.

Table 2. Data fusion methods for radiation monitoring.

Data Fusion Method	Description	Advantages	Applications
Kalman Filter	A recursive algorithm that estimates the state of a system from noisy data	Reduces noise; optimal for linear models	Atmospheric dispersion models, sensor calibration
Ensemble Kalman Filter (EnKF)	Uses multiple model simulations to create a range of possible outcomes	Works well with non-linear models and is robust to uncertainty	Complex radiation spread modeling, uncertainty quantification
Particle Filter	Uses Monte Carlo methods to estimate the state of dynamic systems	Ideal for non-linear and non-Gaussian models	Radiation transport simulations, mobile sensor networks
Data Assimilation	Integrates real-time sensor data into existing models	Improves model accuracy, continuous updates	Real-time monitoring, forecasting radiation exposure

Data fusion is the process of integrating various data streams from various sensors or systems to form a more detailed and accurate model of what is being monitored. In radiation surveillance, this may include the incorporation of ground sensors for radiation, satellite sensors, weather stations, and even social media or citizen reporting. As an illustration, real-time radiation measurements of ground sensors can be used to forecast the spread of radiation in the atmosphere when used together with atmospheric modeling data in the case of a nuclear accident. The combination of the data presented by these various sources will allow more precise predictions of radiation dispersion, vulnerable groups, and timely preventive measures^[1].

Sensors can also be improved through data fusion in terms of calibration. Sensors can drift with time or be influenced by environmental factors and thus affect their readings. Data fusion can be used to detect inconsistency or failure of individual sensor readings by synthesising data from several sensors, resulting in more reliable and accurate measurements of radiation. Also, sensor networks with data fusion can address coverage gaps, so that even remote or inaccessible locations will be covered with radiation levels monitored continuously^[30].

3.4. Real-Time Radiation Monitoring and Decision Support Systems

Real-time radiation data analysis is a significant advancement in monitoring systems of radiation^[3]. The conventional systems were usually time consuming because manual data processing took time, thereby slowing the process of responding and the effectiveness of early warning systems. Nonetheless, radiation monitoring systems are currently able to work with data in real-time due to the creation of sophisticated data analytics tools, which allow the organization to instantly gain insight into the radiation levels and,

therefore, make decisions faster.

Data analytics can be used in real-time to identify radiation events, e.g., nuclear accidents, leaks, or natural disasters, and respond quickly to the risks to mitigate them^[31]. As an illustration, emergency responders and the general population can be notified of symptoms of radiation exposure through real-time surveillance systems that send alerts when radiation exceeds a predefined limit, enabling them to evacuate or take protective action in time. Also, real-time monitoring allows risk assessment to be dynamically adjusted based on the latest data, making management of radiation more adaptable and responsive.

A key element of real-time radiation monitoring is decision support systems (DSS). These systems combine real-time radiation information with predictive models, scenario analysis tools, and risk evaluation in case of an emergency situation to assist decision-making. DSS is able to deliver predictions of radiation exposure, prescribe protection measures (e.g., evacuation or sheltering), and optimize resource deployment based on the magnitude and site of radiation incidents. These systems can improve the decisions made by decision-makers by including real-time data to make decisions that are more informed and effective to enhance the safety of people and reduce the effects of exposure to radiation^[32].

3.5. Challenges and Opportunities in Radiation Data Analytics

Although the innovations related to radiation monitoring through data analytics are impressive, there are still a number of challenges^[26]. The quality and consistency of the data is one of the main challenges. Radiation sensors may have calibration problems, noise or interference, or may be subject to environmental influences. The quality and reliability of the data is of utmost importance to the success

of data analytics in radiation monitoring, and continuous research is being conducted to create strong data validation and calibration methods.

Enhancing the integration of heterogeneous data sources is another difficulty. Radiation data can be measured using many different sensors of various characteristics, measurement modes, and resolutions. Integrating these different data streams into a single model requires advanced data fusion algorithms and interoperability standards. The success of global radiation monitoring networks requires that radiation data may be shared and integrated across various monitoring platforms, organizations and countries in an effective manner^[33].

Nonetheless, opportunities for radiation monitoring improvement with the help of data analytics are immense despite these challenges. Machine learning, big data processing, and real-time analytics are advancing and facilitating more accurate, timely, and actionable radiation exposure insights. With the ongoing development of data analytics, the possibility to forecast radiation events, improve early warning, and aid in decisions in crises will only grow, changing how we view and handle radiation in the environment^[4].

3.6. Future Pathways for Radiation Data Analytics

As the future unfolds, data analytics in radiation monitoring is likely to be influenced by further developments in the fields of artificial intelligence, cloud computing, and sensor network developments^[7,34]. The future of autonomous radiation monitoring systems is one potential path that can be taken to achieve autonomy in systems that can monitor radiation and react to anomalies or other possible events with the help of AI, since they will analyze the data and take the necessary measures automatically, without a human operator being involved. These systems may transform radiation monitoring, especially in remote or hazardous settings, to offer real-time, continuous analysis with limited human supervision.

A different area of future development is the combination of radiation monitoring data with the wider environmental monitoring systems. When radiation data is coupled with data on air quality, climate and soil conditions, we will be able to have a more comprehensive understanding of the environmental consequences of radiation exposure. This

integrated method will play a vital role in creating relevant mitigation strategies, risk management of radiation, and safeguarding the population and the environment^[14].

4. Integration with Earth System Models

With the development of environmental radiation monitoring systems, the radiation data is becoming the subject of rising significance in their integration with Earth system models (ESMs)^[3]. Earth system models have since been applied in simulating the interactions between the atmosphere, oceans, land and ecosystems to give a complete picture of how various parts of the earth systems interact and affect one another. Radiation monitoring data can be integrated into these models to achieve a more holistic approach to the interaction of radiation with the environment and its impact on ecological and human health. In this section, the essence of radiation monitoring in Earth system models, data assimilation methods, the advantages of globalizing radiation data with atmospheric and ecological models and the consequences of these global systems on radiation exposure prediction and risk evaluation are discussed.

4.1. Overview of Earth System Models

Earth system models are computer applications that are used to model the interactions of the major components of the Earth, such as the atmosphere, hydrosphere, biosphere and geosphere. Applications in these models encompass prediction of a broad spectrum of environmental phenomena, including weather and climate, ocean currents and terrestrial ecosystems. Historically, ESMs have concentrated on forecasting natural events like weather conditions, global warming and the transportation of pollutants^[35].

The primary advantage of Earth system models is that they can model the complex interactions in various domains of the environment. By way of example, ESMs are able to simulate the effects of atmospheric conditions on ocean circulation or land use change on local ecosystems. ESMs can also be used to simulate the distribution of radiation in the atmosphere, hydrosphere and ecosystems by incorporating radiation monitoring data, which can be used to forecast effects of radiation exposure on human and ecological health^[4].

Radiation information can be incorporated into various elements of ESM such as atmospheric dispersion models, hydrological models, and ecosystem models^[36]. The integrated models can enable a better comprehension of the radiation movement and accumulation in various environments and enhance the accuracy of radiation exposure assessments.

4.2. Data Assimilation Techniques

The integration of real-time observational data (including radiation monitoring data) into predictive models to enhance the accuracy of these models is known as data assimilation. In radiation monitoring, data assimilation is the process of computing radiation measurements to update or correct predictions made by Earth system models to make sure the models are based on the best and the most recent information^[37].

Various methods of data assimilation exist, and each of them has its advantages and disadvantages as well as is applicable to various models and data. The Kalman filter is one of the most widely applied methods of environmental radiation monitoring and is a combination of real-time sensor data and model estimations to provide a more precise estimation of the amount of radiation in the environment. The Kalman filter is especially useful to systems when the observational data as well as the model prediction itself are uncertain because the algorithm has the ability to scale the relative reliability of each source and modify the model^[38].

The other method of significance is the ensemble Kalman filter (EnKF) that involves numerous model simulations to help create a list of potential outcomes and subsequently integrate the outcomes with real-time data to give a more robust forecast of the radiation dispersion^[39]. EnKF is particularly effective in the modelling of complex, non-linear processes, like radiation transport in the atmosphere, where any differences in initial conditions can cause dramatically different behaviors.

The Kalman filter and EnKF are both capable of incorporating real-time radiation monitoring data of various types of sensors, such as on-ground sensors, satellite sensors, and airborne sensors^[38,39]. These methods enable radiation monitoring systems to keep on updating projections of radiation spreads and give more precise forecasts of radiation

exposure in the short term after a radiation incident.

4.3. Coupling Radiation Data with Atmospheric Models

Atmospheric models are an important part of the Earth system models in the context of radiation movement in the atmosphere^[37]. Radiation has the ability to travel long distances and is determined by wind, temperatures and rainfall patterns. By incorporating radiation monitoring data with atmospheric models, true results can be obtained regarding the spread of radiation and these predicted results can be used to forecast the level of potential exposure in regions.

Radiation data are usually coupled with atmospheric patterns, and this is done by integrating information on wind patterns, air pressure, and temperature to model how radiation spreads in the atmosphere^[36]. To give an example, when a radiological incident or a nuclear accident occurs, real-time radiation measurements of ground sensors or orbiting satellites can be incorporated into dispersion models that are used to simulate the way the radiation will be dispersed by the wind and how it will interchange with other components of the atmosphere.

Among the greatest problems of linking radiation data to atmospheric models is the consideration of impacts of environmental variables, including temperature gradients, atmospheric turbulence, and precipitation. These characteristics are capable of affecting the flow of radiation in a manner that is not easily predictable. Nevertheless, the high-resolution atmospheric models, along with the data assimilation techniques, have yielded better predictions. In an emergency involving nuclear disaster, e.g., these models can be used to forecast radiation levels in real time, enabling immediate response to the threat to the population, e.g., evacuation or shelter-in-place^[14].

Also, radiation monitors on satellites like those used by organizations like NASA and the European Space Agency (ESA) offer a good input to atmospheric radiation models^[40]. These systems rely on gamma-ray and neutron detectors to scan the radiation levels at high altitudes and give a global image of the radiation levels and improve the power of modelling the radiation transport in the atmosphere over large areas.

4.4. Integrating Radiation Data into Ecological Models

The impact of radiation exposure to the ecosystem can be serious, such as alteration in biodiversity, ecosystem services, and health conditions of plants and animals. By modeling radiation interactions with the various environmental elements, including soil, water and vegetation, the incorporation of radiation data into ecological models can be used to evaluate these effects^[4].

Ecological models simulate the behavior of organisms and the ecosystems in response to environmental factors. By incorporating radiation data in these models, the long-term impacts that radiations would have on plant and animal populations can be predicted. As an illustration, radiation is likely to induce mutations and decrease the reproductive success or growth of plants, which subsequently influences the whole food chain. With the incorporation of radiation data, ecological models are able to forecast the distribution of these effects in various ecosystems and aid in determining the most vulnerable regions^[41].

Moreover, the radiation data can be coupled with ecosystem models to inform the restoration process of radiation-affected regions. Through the knowledge of the effects of radiation on different ecological processes, scientists can devise more effective measures of reducing its impacts on the ecosystems. This can be reforestation, soil decontamination, or even the creation of habitats that are not so vulnerable to radiation^[42]. Remote sensing devices also contribute to climate change risk mitigation by monitoring greenhouse gas emissions, tracking land-use changes, and improving atmospheric model predictions through data assimilation.

4.5. Radiation Exposure Forecasting and Risk Assessments

The incorporation of radiation surveillance data into the models of the Earth system has far-reaching consequences for radiation exposure prediction and risk evaluation^[4]. Earth system models will be used to predict the levels of radiation exposure at specific times and places, enabling risk management and decisions to be made in advance by offering a more precise picture of the radiation dispersion.

Radiation exposure prediction is critical in the case of

nuclear accidents, where predictions made on time can be used to reduce the effect on the health and safety of people^[19]. With the inclusion of real-time radiation measurements from monitoring systems, in combination with atmospheric and ecological models, precise predictions regarding radiation exposure over extensive geographical locations can be made. Such predictions could be used to make evacuation plans, protection, and resource allocation to make sure that vulnerable populations are not subjected to dangerous radiations.

In addition, incorporation of radiation data into Earth system models improves capability in carrying out risk assessment on a long-term basis. As an illustration, the levels of radiation in the ecosystem can be high years after a radiological incident, causing health hazards in the long-run to the people and the wildlife. It can be possible to model such risks to come up with long-term radiation management strategies, such as tracking the recovery of human populations and ecosystems^[35].

The use of radiation data in models that take into account various variables, including weather patterns, type of radiation, and the topography in the area, is also an advantage of risk assessment^[23]. Such a multi-faceted approach can provide a more complex perception of the radiation risks, detecting at-risk populations and ecosystems and proposing specific mitigation measures.

4.6. Challenges and Opportunities

Although there is a lot of potential in the integration of radiation monitoring data in Earth system models, a number of challenges still exist. The difficulty of combining the different sources of data with different levels of accuracy, resolution and uncertainty is one of the main challenges. Radiation data may be gathered using a variety of sensor types, such as satellite sensors, ground sensors and airborne sensors, which have drawbacks associated with each. It is important to develop high-quality data assimilation methods that can be used to balance these various sources of data to enhance the level of model accuracy^[9].

The other issue is the computational cost of executing large-scale integrated models. Real-time radiation data modeling involves many computational resources, particularly in the simulation of complex processes like radiation transport, atmospheric dispersion and ecological effects. High-performance computing and cloud-based infrastructure are

already making progress in overcoming these challenges, although more effective techniques are required in modeling to be able to execute the models in near real-time during radiation events.

Irrespective of these, addressing radiation data in Earth system models is a fascinating and a promising field of study. The capability to model radiation dispersion and exposure more accurately as radiation monitoring systems will become more sophisticated and data assimilation methods further developed will allow better decision-making and more efficient risk management strategies^[14].

5. Real-Time Radiation Monitoring and Early Warning Systems

The past few years have seen the emergence of real-time radiation monitoring systems which have had one of the most notable impacts in the sphere of environmental radiation detection. The capability to continually monitor the amount of radiation in real-time is essential in responding to radiological risks, be they natural or man-made^[3].

These technologies, together with early warning systems, will help detect radiation events quickly, manage the risks, and provide more effective measures to ensure the safety of the population. This section examines how real-time radiation monitoring systems can be developed and deployed, the importance of early warning systems, and the overall effect of the two on emergency response and disaster preparedness.

5.1. Real-Time Radiation Monitoring Networks

Real-time radiation monitoring networks entail measuring radiation levels in real-time using diverse sensors that are spread along geographical areas^[6]. These networks play a crucial role in the provision of current information about radiation exposure, both in natural sources, e.g., cosmic radiation and radon, and in anthropogenic sources, e.g., nuclear power plants or medical facilities. **Table 3** is a summary of various real-time radiation monitoring technologies, where mobile, satellite and drone-based technologies are compared based on coverage, benefits, and limitations.

Table 3. Real-time radiation monitoring technologies.

Technology	Description	Advantages	Limitations	Applications
Mobile Sensors	Portable devices for on-site radiation detection (smartphones, handheld detectors)	Low cost, flexible, immediate feedback	Limited range and sensitivity; requires user intervention	Personal radiation exposure, emergency responders
Satellite-Based Monitoring	Global radiation monitoring from space using gamma-ray and neutron detectors	Wide coverage; no need for on-ground infrastructure	Limited resolution; expensive infrastructure	Global radiation surveillance, disaster response
Drone-Based Radiation Detectors	UAVs equipped with radiation sensors for aerial radiation mapping	Access to hazardous areas, high spatial resolution	Limited battery life, requires skilled operation	Nuclear power plants, remote or dangerous environments
Fixed Station Networks	Stationary monitoring networks of radiation detectors	Continuous monitoring, ideal for high-risk areas	Fixed location limits coverage, requires significant infrastructure	Urban and industrial radiation monitoring

The main advantage of real-time monitoring is that it allows monitoring the changes in the levels of radiation and perceiving potential threats immediately after their appearance. To illustrate, during a nuclear accident, real-time surveillance is able to instantly notice that the radiation level is rising and will give the authorities the essential information on the intensity and extent of the danger. This enables emergency response teams to make the right decisions, including evacuating the affected populations or warning of shelter-in-place efforts^[14].

A real-time monitoring network may be installed in

any type of environment, both urban and remote. In cities, sensor networks can be incorporated into the surrounding infrastructure, e.g., buildings, bridges, streetlights, and radiation levels can be monitored at all times. In more isolated locations, like forests, mountains, or seas, satellite-based or mobile radiation sensors can deliver continuous data streams and give a worldwide perspective on radiation exposure^[21].

The possibility of the real-time monitoring of radiation has been significantly increased by the miniaturization of sensors, wireless communication, and energy efficiency^[27]. The sensors which were previously large and consuming a

lot of power are now reduced to miniature and low-cost devices which can be deployed on a mass scale. As an example, portable handheld devices and wearable sensors can enable individuals, first responders, and workers in hazardous settings to track real-time radiation exposure, which can enhance personal protection and environmental protection.

The wireless communication technologies are also important in facilitating real-time monitoring. Radiation sensors can send data through Wi-Fi, cellular networks, or satellite communications, allowing instant access to radiation levels anywhere in the world^[43]. Through these networks, centralized monitoring systems are able to gather and process data in real-time so that decision-makers can have the latest information on radiation exposure.

5.2. Integration with Early Warning Systems

Early warning systems (EWS) are an important aspect of contemporary disaster management that offers early warnings to help prevent the effects of events that can be hazardous. Combined with real-time radiation monitoring networks, early warning systems will give precise predictions of radiation exposure, forecast movement of radioactive materials, and allow timely interventions to safeguard the health and safety of the population^[10].

A successful early warning mechanism to monitor radiation incorporates the data of sensors, atmospheric models, and environmental variables to anticipate the distribution of radiation with time^[36]. Through real-time radiation measurements and the ability to predict the direction of the radiation, authorities can give timely warnings to the people who have been affected. Such notifications may involve evacuation, shelter-in-place instructions, and advice on safety precautions like taking potassium iodide pills to prevent radioactive iodine exposure.

More effective communication between authorities and the population can also be achieved by integrating radiation monitoring data with early warning systems. To illustrate, should the radiation levels in a given region surpass established limits, the system can automatically notify local governments, emergency responders, and the populace. Alerts may be delivered via different channels, such as short message service (SMS), social networks, radio, and television, so that the information is delivered to the people who need it the most^[44].

Besides warnings, it is also possible to use early warning systems to prioritize actions by using real-time data. An example would be in an instance where the radiation level in a given area is expected to be higher than what is deemed to be safe, the system can give suggestions on evacuation routes, resource distribution, and emergency response plans. Early warning systems can reduce the health effects of radiation exposure by supplying decision-makers with accurate and timely information to respond to such incidents and improve disaster preparedness^[32].

5.3. Mobile and Remote Sensing Technologies for Radiation Monitoring

Mobile and remote sensing technologies are increasingly becoming an important characteristic of real-time radiation monitoring systems and early warning systems^[2]. These technologies offer a high degree of flexibility, coverage and accessibility, which enables radiation monitoring in areas that might be challenging or hazardous to reach using conventional monitoring systems. **Figure 2** emphasizes the role of real-time radiation monitoring in the disaster and how response times and the safety of the population can be enhanced when the information is collected and communicated quickly.

Radiation sensors like handheld gadgets and smartphone applications have become common for real-time monitoring of radiation. These are gadgets that contain sensors of radiation and can detect radiation levels in a certain area and give the user real-time feedback on the amount of radiation he or she has been exposed to. To illustrate, mobile sensors can allow emergency responders or nuclear plant workers to monitor their radiation levels in real-time and take immediate action in case the radiation levels rise to unsafe levels^[11].

Mobile radiation monitoring can also be expanded with the introduction of radiation sensors to smartphones, which makes them even more versatile^[45]. Radiation phones can also be used to automatically capture radiation measurements, geotag the measurements using GPS positions, and send the measurements to centralized monitoring systems. This forms a distributed network of radiation sensors, which greatly enhances coverage and allows real-time data collection at a variety of locations. The general population can also use these sensors, and they will be able to offer an additional level of control in case of radiological emergencies.

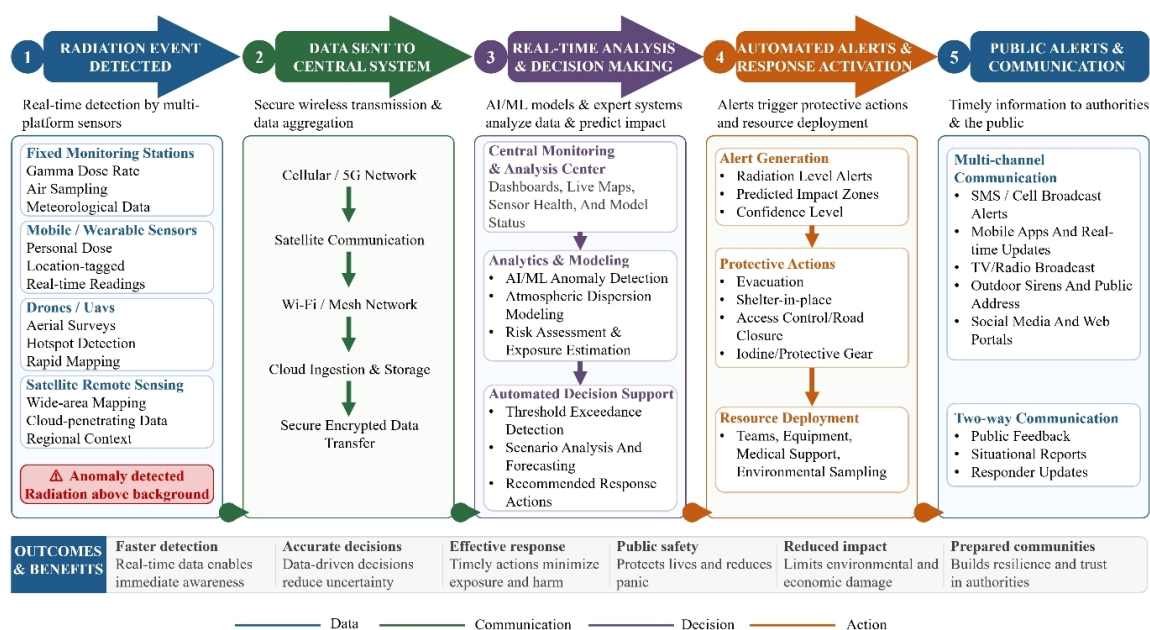


Figure 2. Impact of real-time radiation monitoring on disaster response.

The remote sensing technology such as drones and satellite-based surveillance is also vital in the real-time monitoring of radiation. Radiation detectors can be mounted on drones to survey radiation levels in dangerous areas, including nuclear power plants, disaster areas, or highly radiated areas. Drones have the ability to fly to the effected region, and offer extremely high resolution information on the amount of radiation without exposing human workers to the hazards^[24]. Also, satellite-based monitoring systems are capable of giving extensive radiation information which can be used in monitoring radiation exposure at a global level, especially during the aftermath of nuclear accidents or radiological incidents.

The combination of mobile and remote sensing technologies expands the capacity to check radiation exposure in real-time, covers it more thoroughly, and makes the early warning systems more effective.

5.4. Case Studies of Real-Time Radiation Monitoring in Response to Accidents

Radiological accidents have shown real-time radiation monitoring to be invaluable when responding to these events, and the availability of quick measurements of radiation levels, warnings, and effective mitigation strategies. A number of high-profile nuclear incidents have shown the significance of real-time monitoring and early warning systems to safeguard

the population's health and safety^[1].

The Fukushima Daiichi nuclear disaster in Japan in 2011 is one of the most striking ones. Radiation in the vicinity of the Fukushima Daiichi nuclear power plant peaked after a huge earthquake, and a tsunami caused the failure of the plant^[45]. The presence of real-time radiation monitoring devices, such as portable devices and networked sensors, played an important role in facilitating real-time data on the level of radiation. These systems allowed the authorities to make evacuation requests, establish radiation monitoring sites and provide real-time updates on the level of radiation. Their quick implementation helped reduce the risk of exposure to local people and employees participating in the cleanup.

In the same case, in the 1986 Chernobyl disaster in Ukraine, real-time radiation monitoring was not adequate to identify and manage the extent of the accident. Following the Chernobyl incident, the radiation detection and early warning systems, such as real-time monitoring networks in radiation-prone locations, were significantly enhanced. The lessons given by the Chernobyl and Fukushima have helped in the development of the current radiation monitoring systems, which are now more sophisticated, extensive, and capable of giving real-time information in case of a nuclear accident^[46].

In both instances, early warning systems were used to limit radiation exposure by providing timely information to the public and emergency responders^[2]. The systems are

now a fundamental aspect of disaster preparedness and can assist governments and organizations to be more effective in responding to nuclear accidents and other incidents of radiation.

5.5. Challenges and Limitations of Real-Time Monitoring Systems

Although real-time radiation surveillance and early warning systems offer numerous advantages, several challenges and constraints must be overcome to make them effective. The reliability and correctness of the sensors themselves is one of the main issues^[15]. Radiation sensors are prone to calibration problems, environmental interferences, and time degradation, which can influence the performance of this sensor. Sensors require regular maintenance, calibration, and testing to ensure that they deliver accurate and reliable data.

The other issue is the problem of the fusion of the data of various types of sensors and monitoring platforms. The sources of real-time radiation data can be various, such as ground-based sensors, satellites, drones, and mobile devices. To ensure that these data sources are effectively incorporated in a unified monitoring system to give complete and precise estimates of radiation exposure is of paramount importance. To overcome this challenge, data fusion, as explained in earlier sections, can help combine data from various sources and improve the system's overall accuracy^[12].

Lastly, real-time monitoring networks may be limited in scalability and coverage, particularly in remote or low-resource locations^[30]. A high density of sensors may be costly to deploy over extensive geographic areas, and the logistical challenge of keeping sensors in operation in extreme environmental conditions or in response to an emergency is also a big concern. However, these barriers are being mitigated by the development of sensor technology, wireless communication, and cloud-based data storage, which has made real-time radiation monitoring more practical and accessible.

5.6. Prospects and Pathways

The future of real-time radiation monitoring and early warning systems is promising as sensor technology, data analytics and communication systems continue to advance. With

the continued development of smaller, cheaper, and more sensitive radiation sensors, there will be more possibilities to set up large-scale monitoring networks with more coverage and more precise information. Also, the implementation of AI and machine learning in radiation monitoring systems will enable more advanced data processing, anomaly detection, and prediction^[26].

An intriguing future is the creation of autonomous radiation surveillance systems that operate on the power of artificial intelligence^[47]. These systems would be able to analyze radiation data in real-time, identify any anomalies, and respond to them automatically without human assistance. This would greatly improve the speed and efficiency of early warning facilities, especially in those locations where emergency response facilities are not readily accessible.

In the future, the real-time radiation monitoring systems will be even more integrated, flexible, and responsive with further development of technology enhancing our capacity to deal with radiation risk and safeguard the public health amidst the future challenges.

6. Challenges and Limitations

Although the developments in environmental radiation monitoring, real-time data analytics, and integration of the Earth system provide major benefits to radiation safety, various challenges and constraints remain that need to be overcome to achieve the maximum potential of such technologies^[7]. This section considers the main challenges to the deployment and implementation of next-generation radiation monitoring systems, such as sensor technology, data processing, calibration, infrastructure, and data security issues. All this is accompanied by the current studies that are being conducted in order to go round these dilemmas and enhance the overall efficiency of radiation monitoring systems.

6.1. Technical Challenges in Sensor Design

Radiation monitoring is one of the major issues in which continuous designing of highly sensitive, dependable, and durable sensors is one of the greatest challenges. In spite of the fact that there has been a great advancement of sensor technology, existing radiation sensors still have a number of limitations, especially in accuracy, range, and robustness.

To begin with, radiation sensors are prone to environ-

mental influences, including changes in temperature, humidity, and electromagnetic interference, which may undermine their performance^[12]. As an illustration, changes in temperature can alter the response of the sensor, resulting in radiation measurement errors. Likewise, sensor readings can be interfered with by surrounding electronic devices or power lines, and it is challenging to get the right data in some settings.

In addition, radiation sensors tend to drift with time, thus weakening their ability to detect and give accurate readings^[15]. Although this issue can be mitigated by periodic calibration, the requirement to continuously calibrate sensors is a logistical challenge, especially for large sensor networks. To ensure sensors remain accurate, particularly in remote or dangerous environments, ongoing investment in sensor maintenance, calibration, and replacement is essential.

Lastly, though miniaturization is a major development in the design of radiation sensors, it presents new challenges in the areas of energy efficiency and large area radiation detection. Larger sensors can be used to cover a greater area with fewer sensors at a smaller size when compared to smaller sensors, because the smaller sensors might not be able to detect as far as needed. This brings into question cost, energy usage and the requirement of a strong communication system to transmit information on these scattered sensors^[27].

6.2. Data Integration and Fusion Challenges

Another challenging issue in environmental radiation monitoring is the integration of data of various types and sources of sensors^[12]. The new radiation monitoring systems are usually based on the use of a combination of sensors, including ground-based detectors, satellite and mobile systems, to gather information. Nonetheless, there are a number of challenges in integrating these heterogeneous data sources into a unified system.

One of the main problems is that the data formats, resolutions, and accuracy of various sensors and monitoring platforms can be different^[48]. Satellite-based radiation sensors can provide coverage over large regions of the Earth, but have lower spatial resolution and time sensitivity than sensors on the ground. Likewise, smartphones or handheld devices with mobile sensors can give real-time radiation measurements, but tend to be restricted by less sensitivity and a lack of the ability to detect a given type of radiation.

The important thing to overcome these challenges is

data fusion techniques that integrate data from various sensors to form one representation of radiation exposure. But to achieve effective data fusion algorithms, complex computation resources and algorithms need to be applied that are able to reconcile differences in the data quality, scale, and uncertainty. Moreover, real-time data fusion requires high processing power, which may not be available, especially in remote locations with limited connectivity or infrastructure^[12].

The increasing amount of data collected by radiation monitoring networks makes it more urgent to have effective data integration systems and automated analytics in place. Further progress in machine learning and artificial intelligence will be relevant to enhancing the efficiency of data fusion methods, enabling more accurate and timely evaluation of radiation exposure^[26].

6.3. Calibration and Standardization Issues

Calibration is a key to the accuracy and reliability of radiation sensors^[49]. As various sensors and models can deliver different outcomes, it is important to have standardized processes of calibration among monitoring networks. Nevertheless, it is a complicated procedure to guarantee the consistency of calibration of a wide range of sensors and sensor types.

Each form of sensor has its own calibration needs and difficulties, and these needs can be different depending on the use of the sensor, where that sensor is, and what form of radiation is being encountered. In addition, radiation sensors in most cases are sensitive to environmental factors and a slight change in temperature, pressure or humidity can influence the correctness of measurements^[36]. Consequently, to maintain uniform calibration across large-scale monitoring networks, the resources, time, and expertise required are substantial.

Standardization is also essential in facilitating interoperability among sensors, monitoring systems and data platforms^[12]. It may be problematic to compare data from various sensors and systems unless they are standardized through calibration procedures. An illustrative case is that the information obtained by a satellite-based sensor and an on-the-ground monitoring station might not agree, resulting in inconsistencies in radiation exposure measurements. In order to curb this, global agencies like the International Atomic

Energy Agency (IAEA) and the International Commission on Radiological Protection (ICRP) have come up with standards of radiation monitoring, although more effort is required to enhance consistency and standardization of calibration on a global scale.

6.4. Infrastructure and Deployment Challenges

The rollout of mass radiation surveillance systems is also a considerable logistical obstacle, especially in remote or dangerous locations^[50]. The creation of a strong infrastructure that would provide the constant monitoring and transmission of data over areas with large geographic coverage would be a highly expensive undertaking in terms of equipment, manpower and maintenance.

The major infrastructure deployment issue is that it requires reliable communication networks. Radiation sensors will frequently be based on a wireless network, cellular network, or satellite connection to send the information to central monitoring stations. The effectiveness of such communication systems can be doubted in regions with low connectivity or after a natural disaster or a nuclear event. This may lead to delays in the data or even coverage gaps, lowering the efficiency of the radiation monitoring systems in giving real-time information^[51].

The cost and difficulty of installing sensors in hard-to-access areas is another challenge^[52]. In isolated or hilly areas, the use of radiation sensors requires specialized equipment and skills. Likewise, installing sensors in urban areas could require navigating complex infrastructure and regu-

latory requirements. Maintaining these networks is also a major problem, especially where resources are scarce or during the aftermath of disasters.

6.5. Privacy and Data Security Concerns

As more and more radiation monitoring systems adopt wireless communication and cloud-based data storage, data security and privacy are becoming significant issues. Radiation data, particularly when relayed in real time or a large number of sensors, may be at risk of being hacked or misused without proper security^[53].

Radiation information is also confidential, and this may be an issue when observing citizens. As an example, the implementation of the use of mobile radiation sensors built into smartphones or other gadgets consumed by people can result in privacy concerns since the gadgets can be used to track the actions and movements of individuals. This fine line between the safety of personal information and the integrity of radiation information will require the use of robust encryption, data security measures, and clear privacy policies^[54].

In addition, the security of the radiation monitoring system is indispensable for preventing malicious attacks that could compromise data integrity^[53]. For example, a cyberattack on a radiation monitoring system could lead to incorrect measurements, a breakdown in communication, or distorted data, undermining public confidence in the system and hindering an emergency response. **Table 4** highlights the main issues of radiation monitoring systems, such as sensor issues, data integration issues, infrastructure issues, and data security.

Table 4. Challenges and limitations in environmental radiation monitoring.

Challenge	Description	Impact on Radiation Monitoring	Solutions/Research Directions
Sensor Calibration	Sensors can drift over time and may not be accurate in all conditions	Inaccurate readings, reduced trust in monitoring systems	Regular recalibration, automated calibration systems
Data Integration and Fusion	Combining data from different sources (ground, satellite, drone) can be complex	Discrepancies in data quality, delays in decision-making	Development of better data fusion algorithms, standardization
Infrastructure Deployment	Installing sensors in remote or hazardous areas can be costly and challenging	Limited coverage, increased maintenance needs	Use of drones, cloud-based data storage, and decentralized systems
Security and Privacy	Real-time data transmission poses risks for data security and privacy	Vulnerability to cyberattacks, potential misuse of personal data	Enhanced encryption, privacy protocols, secure data handling

6.6. Future Research Directions

Despite the above challenges, a number of research activities are underway to enhance radiation monitoring sys-

tems. These are sensor technology development, data fusion, data calibration and system integration.

Studies of new radiation detecting materials, like

graphene-based radiation sensors and organic semiconductors, have the potential to produce a more sensitive, less expensive, and more resistant sensor. Furthermore, advancements in machine learning and artificial intelligence will enhance data analytics, enabling real-time, data-driven decision-making and anomaly detection in radiation surveillance systems^[26].

In infrastructure, scholars are looking into novel methods to implement and sustain massive sensor networks, especially in distant or risky settings. As an example, unmanned aerial vehicles (UAVs) and drones can be used to deploy sensors to provide a flexible and economical solution to radiation surveillance in regions considered difficult to access. The development of cloud computing and edge computing will also enhance data processing efficiency and reduce reliance on centralized systems^[34].

Lastly, collaboration among the international community and the formulation of uniform protocols will play a leading role in resolving the issues of calibration, standardization and data security mentioned in this section. International efforts to enhance radiation-monitoring infrastructure and guarantee the integrity and privacy of the data will be very essential in enhancing the performance of environmental radiation monitoring^[53].

7. Conclusions

The environment radiation monitoring environment has evolved tremendously through the introduction of next-generation sensors, innovative data analytics, and the use of Earth system models. This has seen the large-scale advancements in the accuracy, extent, and real-time aspects of radiation monitoring systems, which have allowed the radiation exposure to be detected and evaluated with greater accuracy. As stressed in this article, sensor technology, data fusion, and machine learning have led to improved systems of monitoring that are able not only to identify radiation but also to anticipate its spread and effects to enhance the overall response time and risk management strategies.

Integration of radiation monitoring into Earth systems models is particularly promising, with the potential to provide a holistic view of radiation movement and interactions

with the environment. These integrated systems can provide more accurate real-time predictions of radiation exposure through data assimilation and real-time forecasting, enabling more informed decisions during radiological events.

Nonetheless, like any other technological development, this one has issues that need to be addressed. Problems like sensor calibration, data integration, infrastructure deployment, and data security should be perfected to make sure that radiation-monitoring systems run smoothly and consistently on a global level. Regardless of these difficulties, the future of radiation monitoring is bright due to the future progress of sensor-based technology, artificial intelligence, and the development of infrastructure. Environmental sensors directly support sustainability by enabling real-time pollution monitoring, long-term ecological assessment, and evidence-based policy development. These technologies align with the UN Sustainable Development Goals, particularly SDG 3 (good health), SDG 13 (climate action), and SDG 15 (life on land), by providing data necessary for informed environmental stewardship. As research continues and international cooperation is established, these systems will be even more effective in their abilities to defend human health, safety and the environment against the dangers of radiation exposure.

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