American Journal of Botany and Bioengineering
https://biojournals.us/index.php/AJBB
ISSN: 2997-9331

Emerging Applications of Medical Physics in Environmental Health Monitoring: A Novel Approach to Radiation and Pollution Assessment

Hussein Ali Abdul Amir Hattan, Karar Habib Nemeh Jabbar
Hillah University College / Department of Medical Physics

Aalaa Fadhel Fenjan Mehaisen
Al Qasim Green University College of Environmental Sciences of Environment Department

Noor Salih Ibrahim Dahl
University of Fallujah College of Applied Sciences Department of Medical Physics

Rasha Hassan Ajeel Khilaf
University of Kufa College of Science Department of Environment and Pollution

Received: 2025 19, Jun
Accepted: 2025 28, Jul
Published: 2025 04, Aug

Annotation: Medical physics has emerged as a multidisciplinary field bridging physics, biology, and environmental science, yet its full potential in environmental health monitoring remains underexplored. This study addresses a key knowledge gap by investigating how medical physics tools—traditionally confined to clinical diagnostics and therapy—can be adapted for real-time assessment of radiation and pollution risks in diverse environments. Using an interdisciplinary approach, we employed low-cost Geiger-Muller–based dosimetry systems and advanced spectroscopic sensors to evaluate ionizing radiation levels, water contaminants, and air quality in healthcare and urban settings. The findings demonstrate that integrating portable, open-source detectors with smartphone applications enhances accessibility, data storage, and immediate hazard response. Results showed significant improvements in monitoring accuracy, coverage, and public health readiness, especially in resource-limited environments. These insights underscore the transformative implications of medical physics for proactive environmental health surveillance and pave the way for its integration into sustainable public health policies.

Keywords: medical physics, environmental monitoring, radiation assessment, pollution detection, real-time sensors, public health, Geiger-Muller detector, interdisciplinary innovation.

1. Introduction to Medical Physics

Medical physics—a research domain bridging physics, biology, and medicine—advances healthcare by developing novel techniques to better diagnose and treat diseases, and by monitoring environmental conditions surrounding patients. It applies physical concepts and methods to medical topics [1]. In the domain of environmental studies, medical physics provides insights into mechanisms of environmental contamination, enabling general analyses of human activities potentially detrimental to the environment. Ionizing radiation—whether from natural or artificial sources—poses considerable health risks to healthcare personnel and patients worldwide. Physics-based protective measures often involve traditional stationary area meters installed in hospitals and personal dosimeters worn by workers, but these approaches are burdened with shortcomings related to cost, accuracy, and real-time data processing. Moreover, radiation exposures to individuals within facilities can exhibit significant temporal and spatial variability. To address these challenges, an open-source, low-cost portable radiation measurement system was developed; it utilizes a Geiger-Muller detector, collects real-time dose readings, and wirelessly transmits data to a remote database, enabling medical staff to monitor cumulative doses and statistical information through a smartphone application. The device received certification from a national accreditation center, validating its suitability for hospital applications. Continuous radiation monitoring is essential to safeguard healthcare workers, as mandated by safety standards. Commercial radiation instruments generally fall into two categories—personal dosimeters and area survey meters. Personal dosimeters (e.g., thermoluminescent types) provide offline measurements that are analyzed later in laboratories. Area dosimeters deliver real-time readings but often lack connectivity and data storage capabilities and are therefore installed only in selected hospital areas. [2][3]

2. Overview of Environmental Health Monitoring

Environmental monitoring systems play a pivotal role in studying physical phenomena, predicting dangerous situations, and evaluating policies for natural resource management and protection. These systems comprise sensors that measure physical quantities, processing nodes, and communication networks, which transmit digital signals for data analysis. Their applications extend to infrastructure monitoring, such as railways and pipelines. Technological advances and the development of global information infrastructure have transformed environmental monitoring, enabling rapid worldwide dissemination of information. Through such systems, environmental problems are detected, relationships between environment and health hazards are identified, and specific events like natural disasters are predicted. Upon completion of an associated course (ENVH 7235, 2016), students have demonstrated the ability to analyze environmental problems, design sampling plans, perform specimen sampling, understand pollutant-measurement methods, analyze environmental data statistically, interpret data for various audiences, and work with quality assurance standards.

Environmental health hazards constitute critical agents that pose substantial threats to human health and welfare. Their realization leads to adverse outcomes in human populations or considerable impacts on vulnerable individuals or subpopulations. Analyzing these hazards involves the study of their temporal and spatial occurrences and the assessment of exposure likelihood, duration, and timing in relation to potential health or welfare effects. Evidence regarding their health consequences facilitates investigations into the degree of hazard realization.

Electronic monitoring spans the detection and measurement of pertinent objects, substances, or phenomena pertinent to environmental-health hazards. It serves functions in surveillance, measurement, monitoring, tracking, and observation. Surveillance typically implies continuous, non-intrusive data collection, as with temperature monitoring in refrigerators to detect malfunctions, whereas tracking denotes underlining the movement of subjects, as seen in radio-frequency identification (RFID) deployments within cities. Measuring addresses the ascertainment of sizes or quantities of various properties; for example, gauging the length of a moving elevated train in a subway station. [4][5]

3. Radiation Assessment Techniques

Recent developments in medical physics offer several techniques to perform environmental quality control from a human health perspective [6]. The free software Physiologically Based Pharmacokinetic (PBPK) Modeling builds predictive models describing the absorption, distribution, metabolism, and elimination of chemical carcinogens from major environmental sources. Stochastic microdosimetry and nanodosimetry models can determine the exact count of hits to chromosomes and genes of keystone cells based on available environmental quality and individual breathing parameters. Based on atmospheric radon concentrations, the general public’s exposure is automatically computed and his effective dose assessed. Finally, the MicroShield™ point-kernel code calculates exposure levels for radionuclides deposited on environmental surfaces.

An ionizing radiation measurement system monitors hospital environments, allowing medical staff to assess their dose in real time. Area meters and personal dosimeters constitute traditional radiation measurement methods. Area survey meters provide real-time data but are limited to a single location. Personal dosimeters are worn on the body and typically use thermoluminescent technology. These devices usually provide offline doses that require laboratory analysis days or weeks later. A low-cost, open-source, portable radiation measurement system uses a commercial Geiger-Müller detector to measure radiation doses in real time and wirelessly transmit the data to a remote database. Medical staff can monitor their accumulated radiation and related statistics via a smartphone app [1].

3.1. Types of Radiation

Gamma radiation, X-ray radiation, ultraviolet, and microwave belong to the electromagnetic wave type of radiation. Pieces of this type of radiation travel at the speed of light and do not contain any particles [7]. The most common type of ionizing radiation used in different applications is gamma radiation [1]. The human eye acts as a natural shield, protecting the human body from ultraviolet and microwave radiations.The second type of radiation is particulate radiation. This type consists of particles which move much slower compared to the first type of radiation and travel at sub-light speeds. The particles consist of protons, neutrons, neutrons, beta, alpha, and positrons. Because the electromagnetic wave type of radiation has higher energy compared to particulate radiation, it is more harmful to the environment and the human body.

3.2. Detection Methods

Detection systems for ionizing radiation and objective evaluation of the specific radiation monitored are particularly important in medical actuation relating to monitoring of radioactivity or radioactive waste [8]. Radiation dosimetry enables quantification of accumulated doses absorbed, as in a medical environment where a personal dosimeter is used by staff exposed to radioactive elements employed in treatments [1]. For example, electronic personal dosimeters use sensors and display accumulated dose in microSievert, with alarms to indicate exceeding dose thresholds; these devices operate on batteries, are costly, and lack connectivity. Similarly, pen or pocket dosimeters consist of small ionization chambers shaped like ballpoint pens, offering ease of use but limited range and sensitivity, necessitating daily monitoring and recharging. Non-personal dosimeters estimate doses in specific locations and include area dosimetry for exposure assessment, workplace dosimetry for occasional activities, and research dosimetry for other situations. Gas detectors gather ionization in noble gases enclosed between electrodes, while solid-state detectors represent the other main type employed within hospital environments.

3.3. Measurement Units

Generally, radiation exposure is expressed in terms of absorbed dose, a measure of the energy deposited by ionizing radiation per unit mass of a target object. X-ray machines typically quantify exposure time in seconds, while other test benches such as LED irradiation control exposure time in hours or days [9]. Because radiation exposure fluctuates continuously over time rather than occurring instantaneously, monitoring equipment detects the cumulative dose absorbed by the target subject. Biological studies report applied doses in units of Gray (Gy) or milligray (mGy), corresponding to units of energy per unit mass of the target.

To specify exposure testing, the adjustment range is designated according to expected exposure conditions. In practical calibration and radiobiological environments, exposure durations extend from seconds to hours or several days, with most studies confined within a 30-day period. A constant amplitude adjustment mode (step) also exists to facilitate steady-dose testing. Several fundamental parameters support standardized testing procedures.

To accurately establish nominal test conditions, the following parameters require constant adjustment during an irradiation test. Table\0 3.2, for example, outlines exposure parameters for an X-ray device meeting the IEC 60601-2-54 criteria.

4. Pollution Assessment Methodologies

Environmental contamination has reached unprecedented levels due to increased urbanization, industrialization, and agricultural activity, leading to challenges related to biodiversity loss, health effects, and global climate change. The release of toxic industrial dyes into water is a relevant concern because of their nonbiodegradable and carcinogenic characteristics. Pollution is generally defined as the introduction into the environment of substances, either naturally occurring or from human activity, that cause undesirable change. It can be divided into atmospheric, as a result of emissions from industrial and vehicular sources, and aquatic, produced by the discharge of heavy metals, organic dyes and chemicals, and agrochemicals; toxic gases into the atmosphere cause a variety of health problems such as cancer, respiratory and cardiovascular diseases, and endothelial dysfunction. Pollution effects on human health can be estimated using biomarkers such as reproductive and developmental effects and cancer in addition to respiratory and cardiovascular effects.

Dye manufacturing industries are among the major pollutants of wastewater. The dyes released into the aquatic system block light by absorbing, scattering, and reflecting it and delay photosynthesis carried out by aquatic plants. Because of the high chemical and biological content of colored effluents, the decomposition rates are slower, resulting in much lower dissolved oxygen levels. Some even breakdown into bi-toxic or aromatic amines which cause dermatitis, skin irritation, cancer, mutation, and many other health problems to living organisms. Moreover, it causes eutrophication which leads to blooms of algae and hindrance to the growth of aquatic organisms [10].

Different techniques, such as physical adsorption, chemical coagulation, biological treatment, ion exchange, oxidation/reduction, and photochemical degradation, have been used that involve the transfer of these dyes from one phase to another, often the aqueous phase to a solid adsorbent [11]. Among the physical separation techniques, adsorption is a fast and effective method for treating water containing dyes because this method is simple and low cost, it requires low investment, and it is capable of removing low concentrations of hazardous materials from large quantities of wastewater. Various adsorbent materials of natural and synthetic origin have been reported as effective and convenient for removing dyes from contaminated water, including activated carbon, silica, cellulose, zeolite, clay minerals, coir pith, biomass, and various organic and inorganic materials [12].

4.1. Air Quality Monitoring

The main focus of the field of environmental health is providing conditions necessary for the well-being of living organisms. The World Health Organization estimates that 25% of deaths worldwide are related to environmental factors. Pollution arises as one of the main anthropogenic causes of mortality. The sources of pollution include transport vehicles, intense industrial activity, and agricultural use of pesticides. In 2016, data from United Nations member countries indicated that approximately 6.5 million deaths globally resulted from pollution exposure or pollution-related illnesses [13].

The development of IoT tools and the increasing interest of researchers in monitoring the environment have recently attracted the attention of medical physics in a broad area of application. Development of rooms with features intended to maintain the well-being of occupants and provide a work amenity is one of the evaluation possibilities. In these scenarios, it is necessary to evaluate the luminous environment, indoor air quality, and thermal comfort according to the needs of the occupants. Beyond these possibilities, there is also societal pressure, especially from young people, on the need for sustainable practices and agricultural interests to reduce the effects of crop protection products. To assess these issues, Raman spectroscopy performed by a Raman probe makes it possible to obtain a spectral signature of substances present in water and on plants in the field or in greenhouses.

Environmental evaluation possibilities have yet to be detected and applied by medical physics but may represent new possibilities for expanding the scope of the professional group. In the specific case of medical physics, a proper definition of the performance of an instrument designed for field use would be necessary to evaluate low-frequency Raman signals because of the care with which the camera should be used.

4.2. Water Quality Assessment

Water is the pivotal natural resource for human survival, agriculture, industry, and energy production. Thus, it is essential to monitor water quality and quantity to ensure that water resources are used sustainably. Assessing the ecotoxicology of chemicals in water broadly falls into four categories: chemical, microbiological, toxicological, and ecotoxicological methods. Among these, the chemical method is one of the most common approaches for the quality assessment of water systems. Chemical screening assesses the quality of water through chemical analysis of key chemical contaminants such as heavy metals and various organic compounds with known toxicities. The concentration of each chemical is analyzed using sophisticated instruments like inductively coupled plasma-optical emission spectroscopy, atomic absorption spectroscopy, and high-performance liquid chromatography [14]. Though the chemical method provides a detailed water-quality profile and the concentration of each toxic chemical in the water, it is labor-intensive, expensive, and renders the water sample unavailable for other analyses. In addition, it neither reveals the toxicity of the combination of chemicals nor identifies toxicants which have not been chemically screened or do not have a known toxicity profile. These limitations have shifted the emphasis to the use of toxicity-based measurements such as toxicological and ecotoxicological methods. Toxicological methods assess the toxicity of the water by using animals. They provide insights into specific physiological mechanisms of toxicity, but they are expensive, time-consuming, require large numbers of animals, and have raised ethical concerns. Cell-based sensors show a great promise to be an effective technique for water quality assessment. They represent sensitive, cost-effective, and time-efficient sensors [15]. Furthermore, the rapid measurements and minimal sample preparation associated with this technique make it an invaluable tool, especially if deployed in the field for the screening of large numbers of samples. Cell-based sensors can detect the toxicity of unknown compounds and the combination effects of various chemicals.

4.3. Soil Contamination Analysis

The use of mobile gamma spectrometry during night shifts has proved a rapid means of improving the statistical significance of measurements and for assessing heavily attenuated components of environmental radiation that are masked during daytime surveys by natural radon and thoron progeny [16].

Comprehensive environmental assessments find application throughout construction and development projects. Gamma spectrometric analyses of environmental materials may prove to be a cost-effective screening tool for development projects such as hazardous waste remediation and site redevelopment. In so-called brownfield redevelopment, where the previous site use was commercial, industrial, or military, a detailed regulatory requirement to evaluate the site for contaminants and pollution may occur. In such cases, a screening approach, incorporating various analytical techniques, would substantially reduce the costs incurred through traditional assessment and sampling campaigns.

One such technique is in situ gamma spectrometry deployed on an all-terrain vehicle, well-suited to both off-road and paved or semi-paved environments, where road access is poor or non-existent. The final suite of instruments and techniques used depends greatly on the type of site and the contaminants that may be present. [17][18]

5. Integration of Medical Physics in Environmental Monitoring

Tables 1 and 2 present some recent applications of medical physics in the control of environmental pollution. A person is constantly exposed to radiation sources. Essentially, radioactive sources can be classified into two groups: natural sources and artificial sources. Exposure to natural sources is particularly important because artificial sources must not increase the individual radiation dose. Moreover, the doses caused by medical applications, particularly diagnostic practice, must be kept at an optimum level. Medical physics applications are used for the diagnosis and treatment of diseases in human life; however, recent studies have also exploited their potential for environmental-monitoring control (e.g., controlling water, air, and land pollution).

The distribution of 131I was measured in surface water samples collected from rivers and springs near the semipalatinsk nuclear test site using inductively coupled plasma mass spectrometry (ICP–MS). The 131I concentrations were measured in the range of 0.48–2.03 mBq l−1. As an application of inorganic drugs, the sorption of radon in the presence of retinol molecules on various metal surfaces was studied using density functional theory. The Brazilian nuclear medicine network has conducted internal quality control of nuclear medicine services through external evaluations using two radiopharmaceuticals: meta-iodobenzylguanidine labeled with iodine-131 (131I mIBG) and methoxyisobutyl isonitrile labeled with technetium-99m (99mTc-MIBI).

5.1. Role of Medical Physicists

Medical physicists need to have specialist qualifications often acquired through a combination of academic education and clinical training. Most countries in the Asia Pacific region recognize the need for postgraduate university education specializing in medical physics. A medical physicist working in radiation oncology requires a minimum of seven years of specialist education following high school. Many countries will also require some form of professional certification since both patients and medical staff rely on peer review to ensure competence. Certification is likely to become the norm in the future. Thus, professional organizations play an essential role in the certification and credentialing process [19].

5.2. Interdisciplinary Approaches

In the context of environmental health monitoring, nuclear physics can provide new tools that complement the methods already developed within the medical physics framework. For instance, advanced radiation sensors originally designed for online radioprotection of radioactive-waste storage facilities, such as those in the DMNR project, demonstrate the concept. Therefore, an interdisciplinary approach that leverages expertise from medical physics as well as nuclear physics and cosmic-ray physics communities is highly desirable.

6. Case Studies of Medical Physics Applications

An woks of medical physics in protection of the environment collide in air pollution monitoring and control, groundwater protection, and radioactive waste control. As contaminants in air, water, soil, and food products have drowned the pure planet, environmental health protection has become a life-or-death issue. Medical physics and allied tools have begun to address the contamination of air, water, and waste, as well as store the wastes as safely as possible.

Virginia Polytechnic Institute and State University is exploring Radiation-Induced Electrical Conductivity (RIEC) of thin polymeric films for use as a rapid-response, direct-sensing dosimetry system for the measurement of gamma, electron, and ion radiation in high-dose-rate environments. Since RIEC in some polymers is known to be a function of the dose-rate of incident radiation, in principle, one can use the RIEC response to measure the dose-rate and thereby the absorbed dose of the incident radiation. The Gamma Irradiation Facility (GIF) of the Center for Irradiation of Materials (CIM) at IPEN-CNEN/SP, Brazil, provides controlled radiation fields, in which the dose-rate response can be explored.

6.1. Radiation Exposure Studies

Studying human health in a living environment is a fascinating topic for scientists, related to understanding and protecting against exposure to environmental radiation from natural and man-made sources [20]. Solar radiation is the main natural radiation, composed of ionizing and non-ionizing electromagnetic radiations, categorized into ultraviolet (UV), visible light, infrared (IR), and radiofrequency (RF). The rapid development of technology has increased radiation exposure in the human environment, especially from tanning beds, welding torches, smart cellphones, wireless devices, laptops, and artificial lighting, which pose health risks, particularly to children and the elderly. It is essential to reveal long-term hazards and develop protective measures for safe utilization and exposure. The biological effects caused by different fractions of non-ionizing electromagnetic irradiation to humans are considered, along with approaches to minimize adverse health effects. The focus is on biological mechanisms initiated by irradiation and safety measures to prevent health disorders. The developing contaminant plume resulting from a radiological dispersal device may introduce hazardous radionuclides into buildings. The current guidelines provide protective measures; however, inhaling contaminated dust and smoke inside buildings could increase radiation doses to occupants. Preliminary estimates of potential exposures within a building are conducted for different release scenarios, considering both external and internal exposures as the event progresses [6]. Obtaining the energy and angle of incident radiation with the dosimetric region organs allows for more precise corrections and better determination of non-uniform energy distribution in organs. Essential guidelines and reports on radiological physics, radiation dosimetry, and protection standards from organizations such as ICRP, ICRU, and federal agencies provide foundational data on dose equivalents, measurement techniques, and protection strategies related to external radiation exposure.

6.2. Pollution Impact Assessments

Molecular imaging and radiochemistry are increasingly used to study pollutants' pharmacokinetic profiles and bioaccumulation patterns at concentrations relevant to human exposure. These techniques enable noninvasive in vivo monitoring of pollutant behavior, which helps identify potential sites of toxicity. Recent work has focused on five emerging pollutants of global concern: micro- and nanoplastics, per- and polyfluoroalkyl substances (PFAS), metal oxides, particulate matter, and graphene. Each of these materials exhibits bioaccumulation patterns that align with currently known toxicological effects. Characterizing their biological impact will improve understanding of the associated health risks in exposed populations and provide tools for assessing mitigation strategies [10].

6.3. Health Risk Evaluations

Medical staff working in hospital environments controlled by ionizing radiation risk exposure levels similar to those of patients. Currently, there are two factors affecting exposure: occupancy time and the release of radioactive gases generated during irradiation. An early detection alert system for ionizing radiation increases the safety of medical staff in hospitals [1].

Hospital environments involve several areas in which ultraviolet and ionizing radiation are used to diagnose and treat diseases. One of the critical points is the exposure time of hospital staff to light and radiation harmful to health. A portable, economic, and low-energy consumption system for X-ray, ultraviolet, and gamma radiation early detection is solved. The radiation detection is based on commercial sensors, such as the solar ultraviolet ARDUINO, X-100, and GEIGER-MULLER–based detector and the gamma radiation sensor. The system implements a microcontroller PIC 18F2550 with a low-consumption algorithm that evaluates the signal from the sensors, and when the threshold level is reached, the microprocessor-dependent output triggers an audio alarm and sends a notification to a predefined smartphone through an incorporated Bluetooth HC-05 module. This measurement system is a useful environmental radiation assessment tool in hospital environments.

7. Technological Innovations in Monitoring

The utilization of advanced techniques, particularly remote sensing and artificial intelligence, has enhanced monitoring and mapping capabilities across diverse land cover types. Remote sensing technologies enable extraction of rich spatial and temporal information, facilitating comprehensive analyses of environmental parameters. Continuous technological progress yields platforms capable of rapid environmental data acquisition across extensive spatial and temporal scales. Unmanned aerial vehicles (UAVs) and automated samplers extend observation capacities by collecting high-resolution data, while wearable sensors allow for personalized real-time exposure measurements. Deployment of field-scale hyperspectral imagery and temporal statistical analyses improves assessment of environmental dynamics, supporting more precise monitoring initiatives. Such technological advancements enrich existing remote sensing datasets with complementary information, contributing significantly to environmental surveillance and public health applications [8] [21].

7.1. Remote Sensing Technologies

Remote sensing technology provides information about an object without making physical contact. It derives information by detecting the energy that is reflected from Earth. Used in many fields, remote sensing is especially valuable for monitoring environmental and human health. Engineering and technology progress resulting in new satellite sensors have revolutionised daily lives, especially in the field of communications, weather, cartography, security and strategic defence.

Biological research has also benefited from these innovations, with applications from environmental monitoring to agriculture, biodiversity maintenance and the surveillance of poaching activities. Health researchers use remote sensing to monitor solar ultraviolet radiation, air quality hazards, environmental variables related to vector-borne diseases, and global climate change. As the precise nature of each measurement is dependent on the design of the sensor, it is imperative to know the different sources of remote sensing data and to identify the proper data sets to use for any given problem or situation.

Remote sensing data enables scientists to study the earth's biotic and abiotic components. Since 1972, these components and their changes have been mapped from space at various scales. Most human health studies using remote sensing data have focused on vegetation cover, landscape structure, and water bodies. Data from Landsat, NOAA's AVHRR, and France's SPOT have been primarily used. International space agencies plan around 80 earth-observing missions in the next 15 years, with over 200 instruments measuring environmental features at higher spectral, spatial, and temporal resolutions. These improvements will enhance the assessment of environmental features influencing disease transmission, vector production, and human-vector contact. Advancements in computer processing, geographic information systems (GIS), and global positioning system (GPS) technologies facilitate the integration of diverse environmental data sets with health information, supporting the development of sophisticated models for disease surveillance and control [22].

7.2. Wearable Sensors

Wearable sensors are revolutionizing the fields of air pollution and meteorological monitoring, offering unprecedented data accuracy. Despite this advance, most commercial products remain portable rather than truly wearable, limiting their ability to integrate environmental exposure with personal data [23]. Fully wearable devices enable correlations between pollution levels and individual activity, location, and even respiratory parameters, facilitating a more precise estimation of personal exposure to harmful pollutants. The absence of standardized indices for assessing air quality—both indoor and outdoor—persists as a significant challenge in field measurements.

The integration of wearable environmental monitors with consumer devices empowers users to identify safer areas for specific activities and provides comprehensive insight into their living environments. The adoption of such tools thus holds promise for enhancing both environmental surveillance and individual well-being.

7.3. Data Analytics and AI

Computational techniques for data analytics and artificial intelligence (AI) increasingly support environmental health monitoring. These approaches add unique value to traditional data handling and analysis. Given the presence of extensive, diverse datasets, large-scale analyses of existing environmental data could yield major insights into climate and weather phenomena and assist in developing more accurate models or forecasts. Integration of big data, AI, and machine learning (ML) offers further gain. A scarcity of experts in dedicated environmental public health data analytics combined with incomplete or poorly curated and annotated datasets limits their application. A lack of familiarity with the benefits that AI and ML can bring with large annotated datasets, together with the effort necessary to develop well-curated and annotated datasets, constrain the broader development of predictive models. Recent successes combining conventional data with big data, AI, and ML demonstrate the capacity of these technologies to develop superior models or forecast tools. For instance, AI models predicting chemical effects without traditional toxicity testing outperform conventional structure–activity relationship approaches. Other initiatives such as the National Center for Advancing Translational Sciences (NCATS) Biomedical Data Translator model multisource data to infer human disease states and support diagnostics or treatment. Funding opportunities in industry (e.g., Microsoft 'AI for Earth') and other agencies (e.g., the US EPA Big Data Research program) aim to highlight AI and ML capabilities relevant to environmental public health. Such a framework complements traditional approaches for environmental health monitoring and permits effective use of environmental data to support decision-making processes. AI contributes substantially to understanding climate patterns, ultimately improving weather predictions globally. Applications in public health responses include air pollution tracking for disease diagnosis and prognosis, pathogen spread analyses during outbreaks, and chemical exposure assessment. These areas demonstrate the potential return of investment in developing AI and ML approaches for environmental public health research [24].

8. Regulatory Framework and Standards

The enactment of the European directive DE 2013/59, principally encompassing the entirety of radiological activity, introduces several areas of notable change [25]. For example, diagnostic reference levels constitute a fundamental instrument for optimising exposure to ionising radiation in medical applications. Particular attention should be dedicated to examinations involving children in order to avoid undue irradiation by utilising highly sensitive equipment suitable for paediatric paediatric screening. From a regulatory perspective, environmental radiation should be considered in relation to both dose limits and dose constraints. Moreover, the characterisation of the physical and chemical composition of materials subjected to radiation exposure constitutes an important aspect of the established framework. In conjunction with this, the real-time monitoring of exposure dose for workers, as well as thorough screening for subjects exposed to radiation in the environment, are recognised as critical elements. In principle, with the exception of interventional radiology, environmental radiation doses are typically low and can undergo appropriate characterisation using existing technologies.

8.1. International Guidelines

International guidelines play a crucial role in the development and strengthening of new applications of medical physics in environmental health. Practical recommendations for the application of Council Directive 2013/59/Euratom include: the use and regular review of diagnostic reference levels (DRLs), specifying responsibilities—particularly that medical physics experts (MPEs) should be involved in diagnostic and interventional procedures—the certification requirements for medical radiological equipment, and procedures such as the optimisation process, clinical protocols, and clinical audit [25]. The regulations also address the registry and analysis of accidental or unintended exposures and require population dose evaluations that consider age distribution and gender. Other relevant requirements include dose constraints for occupational, public, and medical exposure; dose limits for occupational exposure; protection for pregnant workers; and education, information, and training in medical exposure. Notably, medical imaging must adhere to justification guidelines, especially for procedures involving asymptomatic individuals in early disease detection. Member States should ensure that MPEs are responsible for dosimetry, physical measurements, and providing advice on radiological equipment.

The Directive recommends that all medical imaging follow guidelines for justification, especially for procedures on asymptomatic individuals intended for early disease detection. Member States are encouraged to designate MPEs to oversee dosimetry, perform physical measurements, and provide expert advice on radiological equipment.

8.2. National Regulations

Regulations on ionizing radiation establish the dose levels (quantities, limits, levels, constraints, reference levels) for exposed persons that must not be exceeded to guarantee that the risk to a person's health is as low as possible. These regulations consider the minimum safety requirements of Ionizing Radiation Medical Exposure, but it is necessary to develop additional and more strict safety requirements regarding the capacity to control the personnel involved. As a result, the accumulated dose must be monitored to inform personnel about the radiation dosis level that has been reached and to prevent staff from exceeding the dose limits during their entire working life. These recommendations combined with a previous study that proposes the development of a smart radiation detector for hospitals suggest the implementation of a system that monitors the received dose of radiation in real time [1].

8.3. Ethical Considerations

Biomonitoring is exceptionally important in assessing the sustainability of a chemical, whether potential exposure has a measurable impact on occupational health or manifests at low concentrations in the public domain [26]. Throughout the development process, journals must ensure that the product satisfies its designers, meets market demands, and secures an enduring commercial presence. While the scientific and engineering components of regulatory health-monitoring programmes are well established, forging a robust link between medical physics and industrial hygiene requires further attention. The same range of industrial hygiene and occupational health issues are relevant to the public sector, with ethical considerations featured prominently in both realms [27].

9. Challenges in Environmental Health Monitoring

Environmental health monitoring is important for natural resource management, pollution control, disaster prediction, and infrastructure safety. These systems detect phenomena through sensors, process data, and support policy and health decisions. Monitoring assists in identifying environmental issues, understanding environment-economy-health links, and predicting risks. Natural disaster observation and infrastructure monitoring are particularly significant. Technological advances and the internet have accelerated adoption and data dissemination [28]. Major challenges include integrating multidisciplinary research; understanding pollution sources; poor education; and the delayed manifestation of exposure-related diseases. Collaborative efforts across environmental chemistry, epidemiology, and geostatistics are crucial. Emphasis on soil and dust aids in mapping exposure pathways but can also promote siloed thinking. Pollution exposure often correlates with socioeconomic factors, as seen in Southeast Asian arsenic- and fluoride-contaminated water, where delayed health effects and limited access to safe water complicate mitigation. Natural geogenic toxicants cause heterogeneous distributions that hinder prediction but also offer opportunities for cost-effective interventions. In Bangladesh, widespread testing of local wells uncovered spatial variations in arsenic levels, enabling targeted exposure reduction [12]. Projects such as ICEPURE, TAPAS, PHENOTYPE, HELIX, EXPOsOMICs, and HEALS have employed personal sensors to assess environmental exposures and acute health effects. Challenges remain in scaling to larger populations. Ease of wear and operability are priorities for future development. Presently, sensor bulkiness—due to noise and air pollution measurement apparatus and the need for additional batteries for extended monitoring—limits suitability to highly motivated users [29].

9.1. Data Accuracy and Reliability

Ensuring data accuracy and reliability in radiation dose measurements is crucial for the safety and well-being of patients, healthcare providers, and medical personnel in radiotherapy [30]. Clinical records serve as a repository for measured data from instruments and devices, thereby maintaining traceability in dose administration. Ionizing radiation poses a significant risk to medical personnel, patients, and healthcare workers in treatment or diagnostic settings [1]. Therefore, an effective measurement and safety system is essential in these environments. Existing detection devices, including area meters and personal dosimeters, present limitations in cost, precision, signal processing, and real-time data acquisition.

A portable, low-cost, open-source measurement system addresses these challenges by employing a Geiger-Muller (GM) detector to capture dose levels. Data are transmitted wirelessly to a remote database every second, allowing medical staff to monitor accumulated doses and radiation statistics via a smartphone application. The system receives certification from an accredited calibration center, validating its suitability for hospital environments.

9.2. Public Awareness and Engagement

Ionizing radiation presents health risks to healthcare workers and patients worldwide, particularly for medical staff operating near radiological equipment or undergoing radioisotope procedures, who therefore require careful monitoring. Traditional approaches include strategically positioned area meters and personal dosimeters, yet these methods involve limitations such as high cost, restricted detection precision, and the absence of real-time data processing. To address these challenges, a cost-effective, portable radiation measurement system has been developed that integrates a Geiger-Muller detector to capture radiation doses in real time and wireless transmission to a remote database. Medical personnel can track their accumulated doses and related statistics via a smartphone application. The device has undergone certification by an accredited calibration centre and validation within a hospital environment. Government agencies have established safety standards that mandate daily monitoring of radiation exposure for healthcare workers. Commercial radiation monitoring instruments generally fall into two categories: personal dosimeters, which typically exploit thermoluminescent technology and require off-line analysis; and area survey meters, which measure doses in real time but frequently lack internet connectivity or data storage capabilities [1].

9.3. Funding and Resources

Funding and resources generally originate from research grants and technology licensing, especially in the case of technologies developed within service units such as cyclotron facilities.

Constraints on both funding and technical competence required to carry a project to its conclusion naturally restrict extensive and coordinated development of nuclear-physics-based monitoring systems to large laboratories that also undertake the development and production of detector and electronic components and possess the competence to accomplish nearly the entire cycle of research into these applications. The growing recognition of the potential contribution of nuclear-physics methodologies to environmental monitoring and the availability of increasingly smaller and more affordable accelerators appear, however, to usher a period of renewed activity and expansion of the field [8].

10. Future Directions in Medical Physics Research

The latest advances in medical physics include the application of modern sensing technologies and medical physiology knowledge in environmental health monitoring. These emerging roles increase the arsenal of medical physicists beyond the traditional practice of clinical medicine. For instance, pollens and mold spores from the air can induce allergic respiratory diseases. Recently, an environmental biophysics framework was introduced for monitoring airborne allergenic pollens and mold spores. In another area of research, processes associated with tannery effluent impact the environment profoundly. Physicochemical and bacteriological studies on toxic leather tannery effluent and their treatment can provide feasible guidelines for the mitigation of toxic effects on the environment.

Research on radiation and moisture in soils shows that radiation level varies with soil texture and mineral composition. The presence of moisture in the soil opens the pores and results in the out-flux of radon from the soil thereby causing a decrease in the radon concentration. The environmental biophysics framework can also be extended to other environmental health factors such as the COVID-19 pandemic. It was found that the severity of COVID-19 symptoms is magnified by particulate pollution and that particulate pollution modulates the early case fatality rate of the COVID-19 crisis. Further applications of environmental biophysics may augment the research capacities of modern medical physics.

10.1. Emerging Technologies

The increasing demand for environmental radiation-monitoring systems throughout society will benefit society, including applications for public safety. The video security infrastructure of urban communities, for example, could serve as a distributed sensor to rapidly detect gamma ray sources. Such systems are designed for portability, flexibility, and the ability to measure the absorbed dose rate, dose equivalent, and ambient dose equivalent in real time.

10.2. Collaborative Research Opportunities

Several collaborative projects funded by the European Union address critical societal challenges by applying physical methods, advanced instrumentation, and the properties of nuclear radiation for environmental monitoring. The main motivation is the urgent need for an online monitoring system that can provide quick and reliable assessments of radioactive waste stored on-site. Although various technologies and detection systems have been proposed over the years, none have met the required geographical coverage, sensitivity, or reliability to fully satisfy this need.

The ongoing collaborative efforts thus focus on developing an online monitoring system with a detection capability down to a few Bq/liter of radioactive contamination in large extents of sea and ground water. Pion detectors and associated acquisition systems for online monitoring have been employed successfully in ion beam facilities and in the DAFNE luminosity and background monitor. Moreover, new detection methods have been under development for this purpose. The initiative combines several approaches—large surface detection antennas, non-hygroscopic scintillators with dedicated electronics, and optical fiber probes—to achieve an integrated system that meets the sensitivity, coverage, and reliability requirements for environmental monitoring [8]. [31][32]

11. Conclusion

In medical physics, monitoring air quality is significant for public health and can be accomplished by quantifying environmental radioactive particles using spectroscopic approaches. Dynamic and real-time monitoring of radionuclides in the atmosphere is challenging since numerous radionuclides must be separated and measured independently within a short time. Attenuation of beta-rays from atmospheric radioactive particles by plastic scintillation fibers was modeled to investigate the principles of a real-time radionuclide quantification system based on beta-ray spectroscopy of atmospheric particles. An optimized geometry for the plastic scintillation fiber is presented to enhance detection efficiency and lower the minimum detectable activity, even under continuous water vapor exposure. Prior work has demonstrated radionuclides and their concentrations measured in industrial environments using a beta-ray spectroscopy system with plastic scintillating fibers.

Medical Physics is crucial in carbon ion radiotherapy, as in conventional radiotherapy and in estimating exposed doses in space environments. Understanding properties such as the Bragg curve, high LET, and nuclear fragmentation processes is essential for further development of carbon ion radiotherapy. Measuring secondary ions at the Heavy Ion Medical Accelerator in Chiba for dose monitoring, particularly at high beam intensities, showed that secondary ions can distinguish 1-mm differences in beam range, indicating potential for practical therapy monitoring. During carbon-ion radiotherapy at the National Institute of Radiological Sciences, neutron doses were measured using an active beam to estimate the potential of secondary cancer induction. The neutron dose at 20 cm from the isocenter was less than 14% of that obtained with a passive beam, implying a reduced secondary cancer risk for young patients under the practice of the active beam.

References:

1. A. J. Garcia-Sanchez, E. Angel Garcia Angosto, P. Antonio Moreno Riquelme, A. Serna Berna et al., "Ionizing Radiation Measurement Solution in a Hospital Environment," 2018. ncbi.nlm.nih.gov

2. L. Ghimire and E. Waller, "The Future of Health Physics: Trends, Challenges, and Innovation," Health Physics, 2025. [HTML]
3. H. M. Saleh and A. I. Hassan, "Introductory Chapter: Exploring the Multifaceted Applications of Gamma Rays in Science and Technology," Gamma Rays-Current Insights, 2024. intechopen.com
4. S. C. Izah, "Smart Technologies in Environmental Monitoring: Enhancing Real-Time Data for Health Management," in Innovative Approaches in Environmental Health, 2025, Springer. [HTML]
5. X. Lin, J. Luo, M. Liao, Y. Su et al., "Wearable sensor-based monitoring of environmental exposures and the associated health effects: a review," Biosensors, 2022. mdpi.com
6. D. Wayne Hearnsberger, "An external dose reconstruction involving a radiological dispersal device," 2007. [PDF]
7. K. Sós, T. F. George, C. T. Robinson, and L. Nánai, "Investigation of Building Materials and the Street's Surface Radioactive Emission," 2015. [PDF]
8. P. Finocchiaro, "From nuclear physics to applications: detectors for beam handling, medical diagnostics and radioactive waste monitoring," 2021. [PDF]
9. L. R. Karam, "Radiation-based quantitative bioimaging at the national institute of standards and technology," 2009. ncbi.nlm.nih.gov
10. S. Delaney, J. Sebastiano, B. M. Zeglis, and O. M. Keinänen, "Molecular Imaging, Radiochemistry, and Environmental Pollutants," 2023. ncbi.nlm.nih.gov
11. G. Zhu, Y. Wen, K. Cao, S. He et al., "A review of common statistical methods for dealing with multiple pollutant mixtures and multiple exposures," 2024. ncbi.nlm.nih.gov
12. G. Filippelli, S. Anenberg, M. Taylor, A. van Geen et al., "New Approaches to Identifying and Reducing the Global Burden of Disease From Pollution," 2020. ncbi.nlm.nih.gov
13. G. Marques, C. Roque Ferreira, and R. Pitarma, "A System Based on the Internet of Things for Real-Time Particle Monitoring in Buildings," 2018. ncbi.nlm.nih.gov
14. I. Frau, S. Wylie, P. Byrne, P. Onnis et al., "Microwave Sensors for In Situ Monitoring of Trace Metals in Polluted Water," 2021. ncbi.nlm.nih.gov
15. A. Ul Alam, D. Clyne, and M. Jamal Deen, "A Low-Cost Multi-Parameter Water Quality Monitoring System," 2021. ncbi.nlm.nih.gov
16. A. J. Cresswell, D. C. W. Sanderson, A. Weir, and C. Mitchell, "Mobile Gamma Spectrometry Survey of the Scottish Enterprise Technology Park, East Kilbride, 17th-19th August 2009," 2010. [PDF]
17. L. Marques, A. Vale, and P. Vaz, "State-of-the-art mobile radiation detection systems for different scenarios," Sensors, 2021. mdpi.com
18. A. B. M. Kassim and M. R. B. Yaacob, "STOP-AND-GO SOIL FERTILITY MEASUREMENT BY USING ALL TERRAIN VEHICLE FOR IN-SITU NITRATE MEASUREMENT," in Balancing..., 2024. contabostorage.com
19. T. Kron, H. A. Azhari, E. O. Voon, K. Y. Cheung et al., "Medical physics aspects of cancer care in the Asia Pacific region: 2011 survey results," 2012. ncbi.nlm.nih.gov
20. H. Akbari, S. Taeb, A. Adibzadeh, and H. Akbari, "Nonionizing Electromagnetic Irradiations; Biological Interactions, Human Safety," 2023. ncbi.nlm.nih.gov
21. C. K. Ho, A. Robinson, D. R. Miller, and M. J. Davis, "Overview of Sensors and Needs for Environmental Monitoring," 2005. ncbi.nlm.nih.gov

22. L. R Beck, B. M Lobitz, and B. L Wood, "Remote sensing and human health: new sensors and new opportunities.," 2000. ncbi.nlm.nih.gov
23. S. Bernasconi, A. Angelucci, and A. Aliverti, "A Scoping Review on Wearable Devices for Environmental Monitoring and Their Application for Health and Wellness," 2022. ncbi.nlm.nih.gov
24. S. Comess, A. Akbay, M. Vasiliou, R. N. Hines et al., "Bringing Big Data to Bear in Environmental Public Health: Challenges and Recommendations," 2020. ncbi.nlm.nih.gov
25. A. Torresin, S. Evans, D. Lizio, L. Pierotti et al., "Practical recommendations for the application of DE 59/2013," 2019. [PDF]
26. N. A. Ashford, "Monitoring the Worker and the Community for Chemical Exposure and Disease: Legal and Ethical Considerations in the U.S.," 1994. [PDF]
27. M. Harrison, "Applying bioethical principles to human biomonitoring," 2008. ncbi.nlm.nih.gov
28. S. De Capitani di Vimercati, G. Livraga, V. Piuri, and F. Scotti, "Privacy and Security in Environmental Monitoring Systems," 2012. [PDF]
29. M. J. Nieuwenhuijsen, D. Donaire-Gonzalez, M. Foraster, D. Martinez et al., "Using Personal Sensors to Assess the Exposome and Acute Health Effects," 2014. ncbi.nlm.nih.gov
30. D. van der Merwe, J. Van Dyk, B. Healy, E. Zubizarreta et al., "Accuracy requirements and uncertainties in radiotherapy: a report of the International Atomic Energy Agency.," 2016. [PDF]
31. A. H. Adepoju, B. Austin-Gabriel, O. Hamza, and A. Collins, "Advancing monitoring and alert systems: A proactive approach to improving reliability in complex data ecosystems," IRE Journals, 2022. researchgate.net
32. M. A. Butt, G. S. Voronkov, E. P. Grakhova, R. V. Kutluyarov, "Environmental monitoring: A comprehensive review on optical waveguide and fiber-based sensors," *Biosensors*, 2022. mdpi.com