Gamma and ultraviolet radiation radiation analysis: an internet of things-based dosimetric study

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ABSTRACT

This study presents the implementation of an internet of things (IoT)-based device for the accurate and continuous measurement of gamma and ultraviolet (UV) radiation in a rural area of Sincelejo, Colombia. The device, calibrated with an error margin below 5%, allowed for the reliable collection of data during the year 2022. An average effective dose rate of gamma radiation of (0.998±0.037) mSv/year was recorded, a value that approaches the recommended limit. Additionally, the inverse square law of radiation was confirmed, observing a decrease in radiation with an increase in altitude. Concurrently, a constant risk of high to extremely high UV radiation exposure was detected throughout the year. These findings emphasize the need for constant monitoring and the implementation of UV protection measures in the region. The integration of IoT in environmental dosimetry has proven to be an invaluable tool for detailed tracking of radiation levels, significantly contributing to the understanding of radiation in rural areas. The exploration of more advanced sensors and data analysis tools in future research is recommended to further improve the accuracy and utility of these devices.

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1. INTRODUCTION

The internet of things (IoT) revolution has transformed multiple scientific disciplines, including nuclear physics, by enabling real-time monitoring and data acquisition on radiation levels, setting new standards in safety protocols, and enriching the understanding of radiation exposure in various contexts [1]. The rural area of Sincelejo, in the Department of Sucre, Colombia, is notable for its intense activity in gas extraction and exploitation, presenting unique challenges for dosimetry due to its potential repercussions on public health and the environment [2], [3]. The integration of IoT technologies into dosimetry represents a significant advancement, addressing both health protection and environmental impact analysis. Recent research has developed IoT-based systems for radiation monitoring, highlighting their low cost and ability to collect real-time data under different environmental conditions [4], [5]. These systems, which combine

Geiger counters with microcontrollers and environmental sensors, have proven to be valuable tools in assessing radiation under various weather conditions, offering a new perspective in dosimetry [6], [7].

Historically, radiation exposure in areas with intense mining activity and gas exploitation has been a growing concern due to its potential repercussions on public health and the environment. Various studies emphasize the criticality of accuracy in dosimetry, particularly in workplace, medical, outdoor activities, and in response to radiological incidents [8], [9]. These studies highlight the inherent challenges in accurately measuring radiation and the imperative need to incorporate cutting-edge technologies to optimize such accuracy [10], [11]. Despite notable progress, the effective application of these technologies in dosimetry practice, especially in complex environments like Sincelejo, continues to face challenges in terms of accuracy and reliability [12], [13]. This work is based on the premise that IoT can overcome these existing limitations, offering a unique opportunity to improve radiation measurement in specific contexts [14], [15].

This study addresses the gaps identified in the literature, proposing a highly scalable and autonomous IoT-based radiation monitoring system, specifically designed for the context of Sincelejo. Differentiating from previous research, our approach focuses on overcoming the technical challenges associated with dosimetry in rural environments, employing advanced technologies for accurate and real-time data collection. Furthermore, this work contributes to the existing body of knowledge with a detailed analysis of radiation exposure, utilizing resilient IoT detector units, representing a significant improvement in safety and public health protocols [16].

By filling the existing gap in the literature on dosimetry in the era of IoT, specifically in the Sincelejo region, this study not only stands out for its originality but also for its potential to provide valuable insights for future research and practices in the field. The following sections of the manuscript will detail the methodology used, the results obtained, and their relevance in the broader context of dosimetry. Additionally, as shown in Figure 1, an exhaustive factorial analysis of the literature from 2018 to 2023, using the search string '("internet of things" or IoT) and (dosimetry or "radiation monitoring") and (environmental or "gamma radiation" or "ultraviolet (UV) radiation")' [17], [18], has identified a trend of integrating low-power systems and IoT-based sensor nodes in dosimetry and radiation monitoring applications. This association between terms reflects a convergence between emerging technologies and the need for accuracy in radiation measurement, underscoring the relevance of the present study.

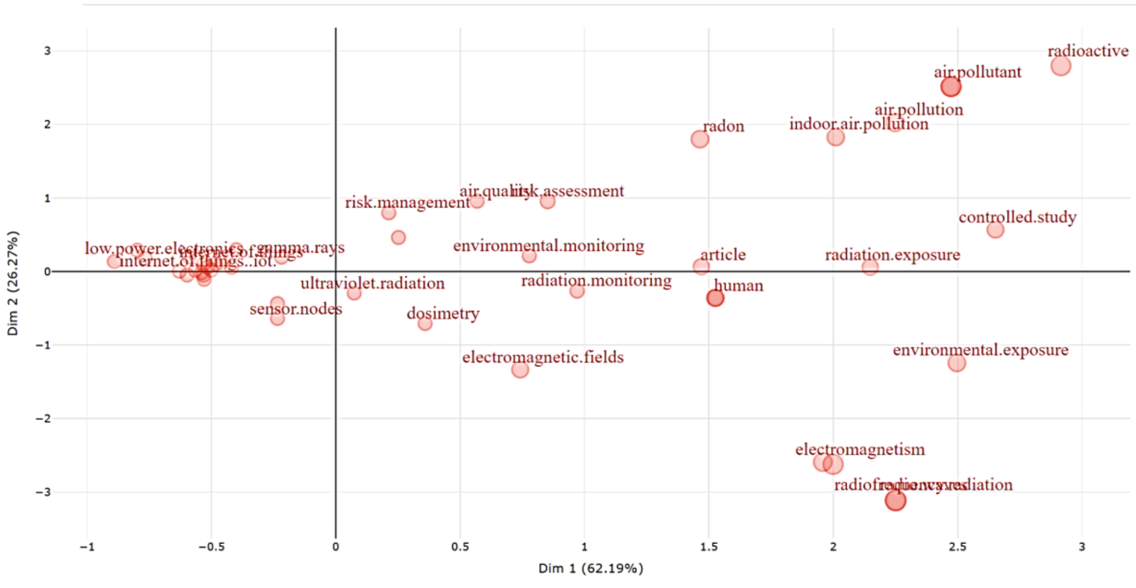

Figure 1. Factorial analysis of scientific literature on dosimetry and radiation monitoring with IoT technologies (2018-2023)

The distribution of terms such as "low power", "IoT", "gamma rays", "radiation", "sensor nodes", "dosimetry", "environmental monitoring", and "radiation mo nitoring" in the factorial analysis indicates a strong association between these concepts within recent literature. This highlights the importance of technological innovation in improving radiological monitoring and environmental safety, aligning with the current trends highlighted by this study. Table 1 (in Appendix) [16], [19]–[23] presents a selection of fundamental and highly relevant works in the field, identified through the systematic literature review of this study. These works, recognized as key references, can provide a solid starting point for future studies in this area.

Following the exhaustive review of the state of the art, as evidenced in Table 1, there is a clear need to advance the accuracy and effectiveness of radiation monitoring systems using IoT technologies. This study, set in the context of Sincelejo, Colombia, not only stands out for its innovative approach to measuring gamma and UV radiation through IoT but also for its potential to fill critical gaps identified in the current literature. The following sections will detail our unique methodology, the results obtained, and their relevance in the broader field of dosimetry and environmental monitoring. Specifically, we will focus on how our integration of IoT into environmental dosimetry proposes concrete solutions to challenges of accuracy and real-time data acquisition, establishing new directions for future research and practices in the field.

2. METHOD

At the intersection of nuclear physics and IoT technologies, our study proposes an innovative methodology for the precise monitoring of gamma and ultraviolet (UV) radiations. This research stands out for its application of emerging technologies in environmental dosimetry, demonstrating how the integration of IoT in radiation measurement can overcome the current challenges of accuracy and real-time data acquisition [19]. We have designed an advanced dosimetric system that carefully selects cutting-edge components to optimize data collection and transmission, validating its accuracy against recognized standards [24], [25]. This approach not only reflects the growing demand for accurate measurements in dynamic scenarios but also establishes a new paradigm in radiation monitoring, aligning with current research trends and the avant-garde capabilities of IoT systems [26].

The rationale for choosing IoT technologies in dosimetry lies in their ability to integrate local measurement devices with cloud services, using machine to machine (M2M)/IoT technology for remote measurements. These technologies promise improved accuracy thanks to hardware and software correction of measurement results. The adoption of advanced semiconductor sensors, based on cadmium telluride (CdTe) and cadmium zinc telluride (CdZnTe) radiation detectors, along with modern microcontroller and communication microchips, underscores the potential of emerging technologies in enhancing the accuracy and effectiveness of dosimetry [27]. Furthermore, the development of low-cost devices to measure solar UV radiation, using commercial sensors and new communication technologies, highlights the feasibility of implementing accurate and economical solutions for real-time radiation monitoring [28]. These advancements directly address the identified knowledge gaps, linking the study's objectives with the chosen techniques. The proposed method not only reflects the growing demand for accurate measurements in dynamic scenarios but also establishes a new paradigm in radiation monitoring, aligning with current research trends and the avant-garde capabilities of IoT systems.

2.1. Design and implementation of the system

The developed dosimetric system combines IoT technology with open-source hardware and software for the measurement of gamma and UV radiation, highlighting the importance of innovation in the collection and analysis of environmental data. This approach not only improves the accuracy and efficiency of real-time measurements but also optimizes operational costs. The integration of these technologies facilitates advanced and adaptable environmental monitoring, demonstrating the transformative potential of IoT in scientific research and environmental management [16], [26]. Devices were selected and calibrated considering the involved measurement parameters as follows: device selection:

- Geiger-Müller (GM) counter: the NGMC-V1 model [29], was used, equipped with a J305ß pulse-type tube with tin oxide cathode and a coaxial cylindrical structure with a wall density of (50±10) cg/cm^2. Its operational temperature range is (-40 °C to 55 °C), with an operating voltage between (380-450) V, an electrical current of (0.015 to 0.02) mA, and a sensitivity to gamma radiation of 65 μR [30].
- Humidity measurement: the DHT11 device was used, integrating an 8-bit microcontroller and allowing readings in the range of (20-95%) [31].
- Temperature measurement: a negative temperature coefficient (NTC) thermistor capable of measuring temperatures in the range of (0 °C-50 °C) was used [31].

With the integration of the application programming interface (API), the goal is to capture data from various sensors, which are then processed by a microcontroller optimized for M2M interactions. This implementation underlines the essence and potential of IoT in the digital age. Thanks to advanced connectivity capabilities, it is possible to establish real-time global communications through 2G or 3G mobile networks, thus facilitating the transmission of data between the hardware and cloud solutions.

- UV radiation measurements: the reference sensor grove 101020043 was used, detecting wavelengths between (200 to 400) nm [32].

– Atmospheric pressure measurements: the dual sensor LPS331AP was employed, capable of measuring barometric pressures from (260-1260) mbar or (26-126 kPa) with an absolute accuracy of up to ±2 mbar (0.2 kPa) and altitudes up to 10.000 meters [33], [34].

Finally, the configuration of the radiation measurement, communication, and information storage devices used in this study is presented in Figure 2. Below is a detailed description of the operational flow of the IoT dosimetric system, illustrated in Figure 3. This unified modeling language (UML) activity diagram breaks down the process from the system startup to the eventual data transmission to a NoSQL database, highlighting the automation and efficiency of the real-time data collection and analysis process.

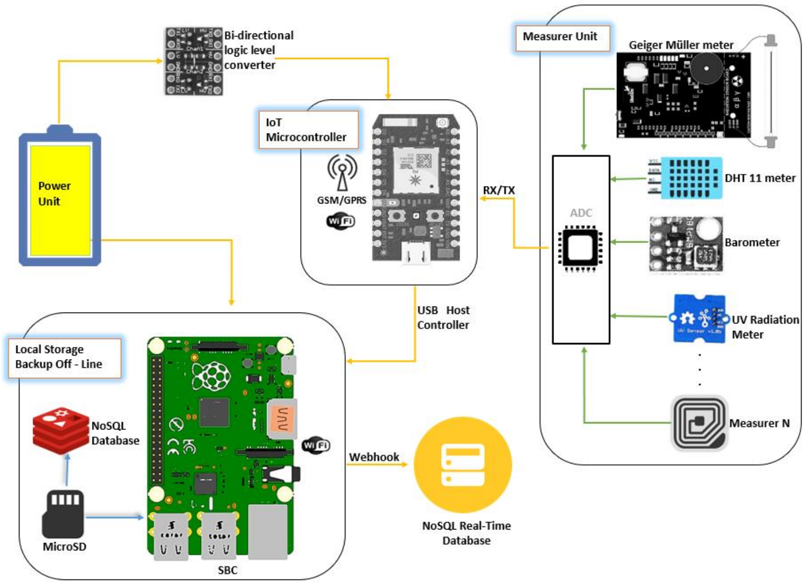

Figure 2. IoT dosimetric system configuration scheme

The diagram in Figure 3 begins with verifying the proper power supply to the system, followed by the initialization of the IoT microcontroller, which is the heart of the dosimetric system. This step is crucial to ensure that the system is ready to collect environmental data through a variety of sensors. Data collection is followed by the conversion of analog signals to digital, allowing the microcontroller to process and locally store the data before transmission. The use of a webhook to send data to the NoSQL database in real time underscores the system's capability to facilitate data analysis and remote access, a fundamental aspect for scientific research and environmental management. This cycle is continuously repeated, ensuring constant and accurate monitoring of the environment.

The process of selecting devices for our dosimetric system was based on rigorous criteria that included measurement accuracy, compatibility with IoT technologies, reliability under variable environmental conditions, and energy consumption efficiency. The deliberate choice to integrate open-source hardware and software was made to maximize the system's flexibility and facilitate adaptation to future technological innovations. This approach allowed for an effective synergy between the selected hardware components and the developed software solutions, resulting in a highly accurate and efficient dosimetric system. The integration of hardware components with software solutions was carried out through a platform that facilitates M2M communication, allowing real-time data collection and transmission over 2G or 3G mobile networks. This system not only improves the accuracy and efficiency of measurements but also optimizes operational costs by reducing the need for manual intervention and enabling advanced and adaptable environmental monitoring.

The architecture of the dosimetric system we have developed clearly illustrates the revolutionary impact of IoT technologies in critical fields such as scientific research and environmental management. By meticulously integrating advanced hardware with sophisticated software, our system not only enhances the accuracy of radiation measurements but also increases the efficiency of these processes. This integration allows for real-time data collection and deeper analysis, highlighting how the correct combination of technological components can overcome previous challenges in dosimetry, opening new avenues for environmental monitoring and radiological safety [27], [35].

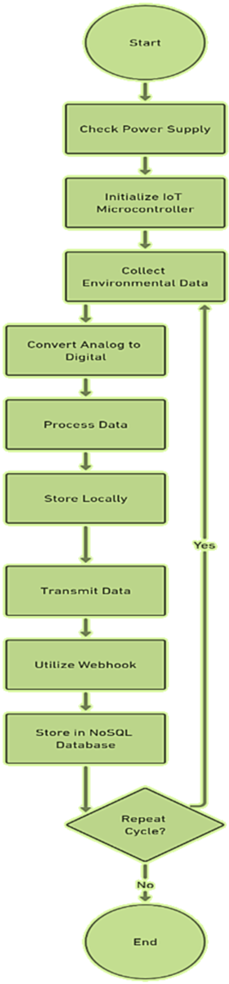

Figure 3. UML activity diagram for iot system process

2.2. Calibration of the GM dosimeter

To ensure accuracy in radiation measurements, meticulous calibration of GM digital dosimeters is crucial. This process is carried out using two specific radioactive sources: barium-133 (Ba-133), with an activity of 80.4 MBq, and americium-241 (Am-241), with an activity of 3.7 MBq. The selection of Ba-133 and Am-241 is based on their stability and their ability to emit a specific gamma energy spectrum, essential aspects for the accurate calibration of dosimeters [36], [37].

Ba-133 is notable for its wide gamma emission spectrum, which includes multiple energy peaks, facilitating detailed calibration across an extensive range of energies. In contrast, Am-241 is valued for its alpha particle emission and low gamma energy, characteristics that make it complementary to Ba-133 by allowing calibration in a different radioactive emission spectrum. The combination of these two sources provides a robust basis for dosimeter calibration, thus ensuring accuracy in detecting a wide variety of radiation types [29].

The calibration procedure involves controlled exposure of the dosimeter to these sources, adjusting the distance between the source and the dosimeter to cover a broad range of radiation intensities. This process is verified using a reference meter, ensuring that the dosimeter's measurements align with international standards. The accuracy and reliability of the measurements are crucial for applications ranging from nuclear safety to medicine and scientific research, underscoring the importance of proper calibration [38].

The distance between the source and the dosimeter varied from a minimum of 10 cm to a maximum of 100 cm. During the calibration process, an analog Geiger reference meter, calibrated by the Colombian Geological Service (INGEOMINAS), was used. This reference meter is from the LUDLUM brand, model 14C, series No. 307891. The data obtained by the digital GM dosimeter were compared with those from the reference meter to ensure the accuracy and reliability of the measurements. This calibration methodology aligns with standard protocols and has proven effective in previous research [39], [40].

The two types of meters used were calibrated, first the ionizing radiation meter and then the UV radiation meter. This was done as follows:

– Gamma radiation meter: the ionizing radiation meter was exposed to radioactive sources of Ba-133 and Am-241 with activities (A) of 80.4 MBq and 3.7 MBq respectively, placed individually at different distances from the meter, which varied in intervals of 10 cm in length up to 100 cm. The results are presented in Tables 2 and 3 and Figures 4 and 5.

Table 2. Gamma meter calibration using Ba-133 source (A=80.4 MBq) at different distances

Distance (cm)	µSv reference dosimeter	µSv calibrated dosimeter
10	60±0.02	58±0.02
20	18±0.02	17±0.02
30	10±0.03	9±0.03
40	6±0.03	5.8±0.03
50	4±0.03	3.8±0.03
60	3±0.03	2.9±0.03
70	1.5±0.04	1.4±0.03
80	1.2±0.04	1.1±0.03
90	0.6±0.03	0.5±0.03
100	0.5±0.03	0.5±0.03

Table 3. Gamma meter calibration using Am-241 source (A=3.7 MBq) at different distances

Distance (cm)	µSv reference dosimeter	µSv calibrated dosimeter
10	5±0.03	4.8±0.02
20	3±0.02	2.9±0.02
30	1.5±0.03	1.4±0.02
40	1.2±0.03	1.1±0.02
50	0.8±0.02	0.7±0.02
60	0.7±0.02	0.6±0.01
70	0.5±0.02	0.4±0.01
80	0.4±0.02	0.3±0.01
90	0.3±0.01	0.2±0.01
100	0.2±0.01	0.2±0.01

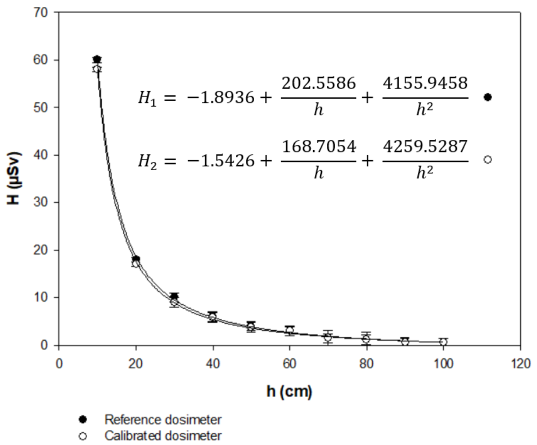

Figure 4. Gamma meter calibration utilizing a Ba-133 source with an activity level of 80.4 MBq, the meter's readings are denoted by white circles (H_2), whereas the black circles indicate the readings from the reference meter (H_1)

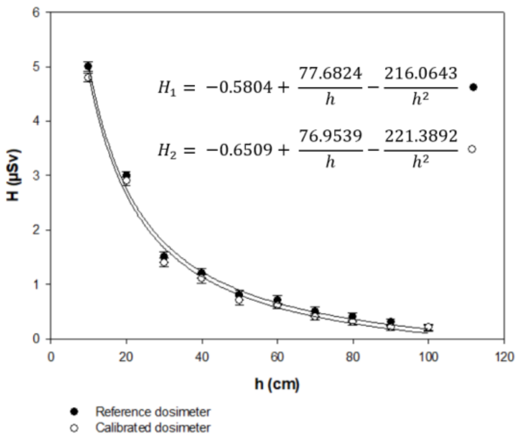

Figure 5. Gamma meter calibration utilizing a Am-241 source with an activity level of 3.7 MBq, the meter's readings are denoted by white circles (H_2), whereas the black circles indicate the readings from the reference meter (H_1)

– UV radiation meter: during the calibration process, both the UV sensor to be calibrated and the certified reference meter are prepared, ensuring that both are in optimal conditions [41]. In a controlled environment, a stabilized UV light source, UV-123 source, which has been previously calibrated to ensure consistent emission [42], is used.

The reference meter, a UV X1-RCH-108 meter calibrated by the INGEOMINAS, is placed at a predetermined distance of 10 cm from the source to obtain a standard reading. This reading is used as a reference to compare the performance of the UV sensor. Without altering the setup, the UV sensor is placed in the same position, and its reading is recorded. Table 4 illustrates the comparison process. The minimum relative error of 0.4% between the reference meter and the UV sensor indicates that the sensor is adequately calibrated and aligned with the reference standard [43].

Table 4. Comparative analysis of UV sensor and reference meter readings

Reference meter (μW/cm²)	UV IoT sensor (μW/cm²)	Relative error (%)
500	498	0.4

2.3. Ionizing radiation dose measurement

Radiation measurements were carried out in a rural area of Sincelejo (Sucre, Colombia), strategically selected for its notable altitude above sea level and its significant mining activity. This choice was based on the premise that both altitude and mining operations could influence environmental radiation levels, making this location an ideal site for study. To conduct a comprehensive assessment of how radiation dose varies with height, the dosimeter was installed at different levels, ranging from 10 meters to 100 meters above the ground, following a detailed measurement protocol that considers the influence of environmental factors such as temperature and humidity on radiation measurements [44].

This measurement process was extended over a full year, thereby capturing a comprehensive representation of temporal variations in radiation dose. This prolonged observation period was crucial to understand not only daily or seasonal fluctuations but also to identify any pattern or anomaly that could emerge throughout the different seasons of the year. The adopted methodology, which includes adjustments based on environmental conditions [45], ensures a deep understanding of radiation dynamics in the study area, providing valuable data for future research and for decision-making in terms of health and environmental safety. A recent study on measuring the environmental gamma radiation dose rate around major nuclear and radiological facilities in Bangladesh demonstrated that there is no significant exposure burden to the population due to artificial sources, underscoring the importance of continuous monitoring and safety controls at nuclear and radiological facilities [40], [46].

2.4. Measurement of ultraviolet radiation index (UVI)

Throughout the year 2022, monthly measurements of the UVI were conducted in a rural area of Sincelejo (Sucre, Colombia), with the aim of monitoring and analyzing UV radiation in this specific region. This systematic effort, which includes the calibration of instruments to adjust measurements for environmental factors such as humidity and temperature [45], has allowed for a detailed view of how the UVI varies throughout the different seasons, offering a clear perspective on the seasonal and monthly fluctuations of UV radiation. The significance of this study lies in its ability to provide essential data that aid in understanding UV radiation exposure patterns in the region, which is crucial for the development of prevention and protection strategies for the local population against the harmful effects of UV radiation. These findings not only enrich the scientific knowledge on climate and environmental variability in Sincelejo but also serve as a valuable tool for promoting public health and raising awareness about sun safety.

2.5. Theoretical justification

The selection of the GM dosimeter for this study is based on its recognized ability to detect ionizing particles with high precision, essential for effective radiation measurement in variable environments. The operation of the GM dosimeter can be described by (1) [47], [48]:

$$N = \frac{Q}{e} \tag{1}$$

where: N is the number of particles detected, Q is the total charge collected, and e is the elementary charge.

Furthermore, the inverse square law of distance, observed in our measurements, is a well-established principle in nuclear physics and has been validated in multiple studies. This law states that the intensity of radiation decreases with the square of the distance from the source [49]. This principle is vital for interpreting the collected data, allowing for a better understanding of the spatial distribution of radiation and its potential impact on health and the environment. This law can be mathematically expressed as shown in (2):

$$I = \frac{P}{4\pi r^2} \tag{2}$$

where: I is the radiation intensity at a distance r from the source, P is the total power of the radioactive source, and r is the distance from the source.

From (1) and (2) are essential for achieving the objectives of the study, providing a solid theoretical foundation for the measurement and analysis of environmental radiation in Sincelejo. Their direct application and relevance to the study's results demonstrate how precise measurements and theoretical analysis contribute to a comprehensive assessment of radiological risk, underscoring the importance of continuous monitoring and the development of effective mitigation strategies.

2.6. Applied methodology synthesis

This study has established a rigorous protocol for the detection of gamma and UV radiation in specific areas. By integrating IoT technologies with conventional measurement methods, the accuracy and reliability of the collected data are ensured. This method is not only adaptable to different scenarios but also significantly contributes to the advancement of the dosimetry field.

To ensure accuracy in radiation detection, an IoT-based procedure specifically designed to calibrate ionizing radiation devices was implemented. The process is carried out as (Figure 6):

- Selection and calibration of sources: accuracy in initial measurements is established through careful selection and calibration of sources. This step is crucial as it defines the reliability of the entire measurement process, ensuring that devices are fine-tuned to capture data with the highest accuracy possible. By calibrating the sources against recognized standards, the study is grounded on a solid and reproducible basis, indispensable for the validity of the results.
- Equipment calibration: calibrating the equipment according to international standards ensures that measurements are consistent and comparable with other global studies. This process not only validates the accuracy of the equipment but also ensures the reliability of the collected data, essential elements for the analysis and conclusions of the study. Adherence to these international standards facilitates the replicability of the study, a fundamental aspect for the scientific community.
- Data comparison: comparing the obtained data with certifications from accredited laboratories reinforces the accuracy of the measurements. This critical step confirms that the collected data accurately reflect the environmental conditions, providing a solid basis for the interpretation of the results. The rigor in this process ensures that the findings of the study are robust and reliable, significantly contributing to the existing body of knowledge. If the equipment shows an error margin of less than 5%, its calibration is confirmed [50].
- Use of calibrated device: with the equipment properly calibrated, detailed measurements are then conducted.
- Environmental dosimetry: finally, environmental dosimetry is performed to assess the radiation levels in the selected environment.

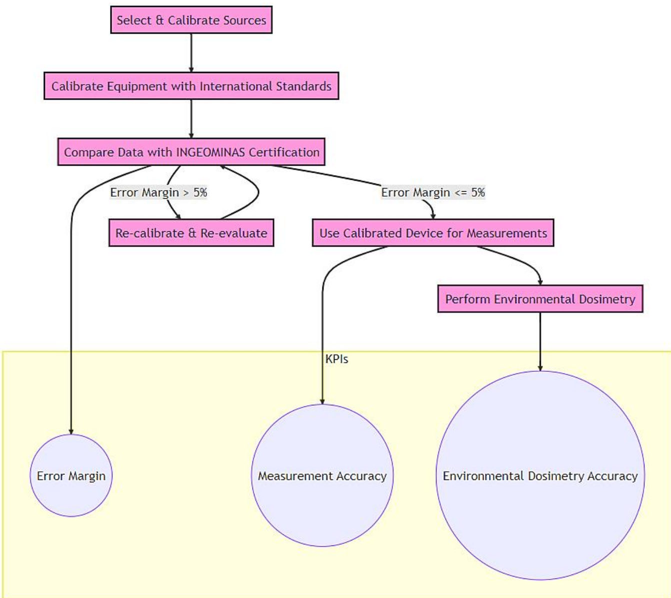

Figure 6. Flowchart of the IoT-based gamma and UV radiation detection and calibration process with associated key performance indicators (KPIs)

The KPIs in Figure 6 are essential for ensuring the radiation detection and calibration process is accurate and reliable. By monitoring these KPIs and ensuring they remain within acceptable limits, the quality and reliability of the results obtained can be guaranteed. They are described as follows:

- Error margin: this KPI refers to the margin of error between the measurements of the equipment and international standards, such as those provided by INGEOMINAS. It is crucial that this margin of error be as low as possible to ensure the accuracy of the measurements. In the context of the diagram, an error margin of 5% or less indicates that the equipment is adequately calibrated. If the error margin is higher, the equipment needs recalibration.
- Measurement accuracy: once the equipment has been calibrated, it is used to carry out measurements. This KPI assesses the accuracy of these measurements. It is essential that the measurements are accurate to ensure that the collected data are reliable and representative of the actual conditions. Measurement accuracy refers to how close a measurement is to the true value.
- Environmental dosimetry accuracy: this KPI evaluates the accuracy of environmental dosimetry measurements. Once the equipment is calibrated and used for measurements in a specific environment, it is crucial that these measurements accurately reflect the radiation levels in the studied environment. Environmental dosimetry refers to the measurement and analysis of radiation in a specific environment, and its accuracy is vital for ensuring the safety and health of people in that environment.

3. RESULTS AND DISCUSSION

Figure 7 shows the device specifically designed and assembled to carry out environmental dosimetry measurements in rural areas of Sincelejo (Sucre, Colombia). This equipment integrates IoT technologies. Table 5 presents the annual results from 2022 of the effective gamma radiation dose measurements at different heights above the surface, conducted in a rural area of Sincelejo (Sucre, Colombia). These results are visualized in Figure 8.

Figure 7. Environmental dosimetry device with IoT integration

Table 5. Gamma radiation effective dose measurements at different heights in the rural area of Sincelejo (Sucre, Colombia) during 2022

Distance (m)	Digital reading (μSv/Week)	Digital accumulated dose (μSv/Week)	Relative error (%)
10	10.98	10.98	2.90
20	3.38	14.36	3.00
30	1.78	16.14	4.40
40	1.11	17.25	4.10
50	0.66	17.91	3.80
60	0.57	18.48	3.70
70	0.27	18.75	4.10
80	0.22	18.97	3.75
90	0.12	19.09	3.50
100	0.12	19.21	3.50

In the study of radiological exposure in a specific area, it is essential to calculate the average effective dose rate measured in mSv per year. This metric provides a clear view of the dose accumulated over time [51]. Before performing any calculations, it is crucial to convert all units to a common standard to ensure accuracy. In this case, units of μSv were converted to mSv, where 1 mSv equals 1000 μSv, and weeks to years, where 1 year equals 52 weeks [52].

The average effective dose rate is calculated using a specific formula. This formula takes the adjusted accumulated dose at 100 m, multiplies it by the ratio of 1 mSv to 1000 μSv, and then multiplies the result by 52 to convert weeks into years. Mathematically, this is represented as (3):

$$Average\ measured\ effective\ dose\ rate = (Adjusted\ Accumulated\ Dose\ at\ 100\ m) \times \frac{1}{1000} \times 52 \quad (3)$$

When applying the adjusted data to this formula, it was found that the average effective dose rate measured is equal to 0.99812 mSv/year. However, to obtain an accurate measure, it is essential to consider the relative error. The relative error is calculated by taking the average of the provided relative errors, which in this case was 3.675%. This is represented as (4):

$$Average\ relative\ error = \frac{\sum Relative\ Error}{Total\ number\ of\ measurements} \quad (4)$$

Applying this relative error to the calculated value, it was found that the error in mSv is 0.0367 mSv. Therefore, the average effective dose rate measured, taking into account the relative error, is (0.99812±0.0367) mSv/year. Rounding to two significant figures, we obtain (0.998±0.037) mSv/year. Table 6 presents the average monthly UVI and their corresponding risk levels for a rural area in Sincelejo (Sucre, Colombia), which is located at an elevation of 213 meters above sea level.

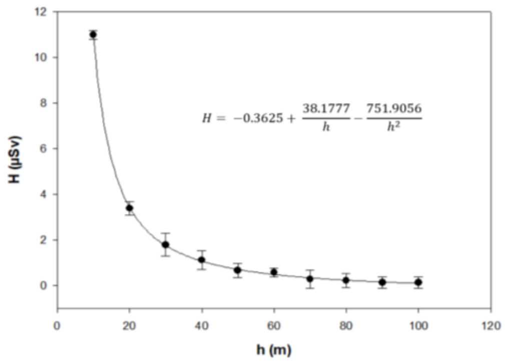

Figure 8. Effective dose of gamma radiation at different heights in the rural area of Sincelejo (Sucre, Colombia)

Table 6. Monthly average index of ultraviolet (IUV) and associated risk levels in Sincelejo (Sucre, Colombia) during 2022

Month	Average IUV	Risk level
January	10	Very high
February	10	Very high
March	11	Extremely high
April	10	Very high
May	11	Extremely high
June	7	High
July	7	High
August	10	Very high
September	9	Very high
October	9	Very high
November	11	Extremely high
December	10	Very high

Figure 8, provide valuable insights into the effective dose of gamma radiation at different heights in the rural area of Sincelejo. The measurements indicate a decrease in radiation dose with increasing height, consistent with the inverse square law of radiation [49]. This trend is crucial for understanding radiation exposure at different levels, which can inform safety measures and guidelines for residents and workers in these areas.

The calculated average effective dose rate of (0.998±0.037) mSv/year, derived from (3), falls within the range of natural background radiation levels reported in other studies [53]–[55]. Although this radiation dose is below the recommended limit, its closeness to this limit may raise some concerns. This concern is heightened if factors that could increase exposure in the future, such as an increase in industrial activity or changes in work practices, are considered. Therefore, it would be prudent to establish continuous monitoring in the area to ensure that the radiation dose does not exceed the recommended limit in the future. Additionally, considering the implementation of mitigation measures to reduce exposure, especially in specific areas or activities that significantly contribute to the total radiation dose, would be beneficial. Moreover, the average monthly UVI and associated risk levels, as shown in Table 6, reveal a consistently high to extremely high risk of UV radiation throughout the year. This finding is significant as it highlights the need for effective UV protection measures in the region, particularly during months with extremely high UVI indices [56].

The results of this study, which demonstrate variations in the effective dose of gamma radiation and UV radiation indices in Sincelejo, Colombia, underscore the importance of continuous environmental radiation monitoring. Exposure to low levels of ionizing radiation, although it does not cause immediate health effects, is a minor contributor to the overall risk of cancer, as indicated by research from the United States Environmental Protection Agency (EPA) [57]. These considerations are fundamental for long-term risk assessment in the population, especially in regions with specific geographical and climatic features that may influence natural radiation levels.

Additionally, the study by Rizzo *et al*. [58] on monitoring ambient gamma dose rates and their correlations with radon highlights the natural variability of radiation levels and their potential modification by meteorological and seismic events. This underscores the need for sensitive and accurate detection systems, such as the IoT devices used in our study, to capture these variations and their possible impacts on human health and the environment. Research by Mothersill and Seymour [59] on the health and environmental implications of low doses of ionizing radiation suggests that biological responses to low-dose radiation are complex and may include adaptive and bystander effects, challenging the linear no-threshold (LNT) model traditionally used in radiation protection. Incorporating recent advancements into our discussion, the efficiency of IoT technology in mitigating environmental-related issues, including air, and water quality monitoring, is highlighted as essential for promoting better sustainability and environmental safety [60]. These smart environmental monitoring solutions, equipped with advanced sensory devices, not only allow for the identification of pollutants but also facilitate more effective resource management, crucial in enclosed spaces like underground mines and offices, maintaining an atmosphere conducive to health and productivity [61].

IoT technology plays a crucial role in improving environmental quality, offering innovative strategies for air quality measurement and water treatment, thus contributing to a sustainable lifestyle. Moreover, the data-driven approach of IoT offers actionable insights and predictive outcomes, enhancing understanding of the environment and facilitating the implementation of significant improvements [17], [62], [63]. Water and air quality monitoring, toxic gas detection, and energy management are areas where IoT technology has proven especially effective, allowing not only real-time monitoring but also resource consumption optimization and workplace safety enhancement [64], [65]. In conclusion, this study reinforces the importance of adopting IoT technologies in environmental monitoring and dosimetry, highlighting their role in enhancing risk mitigation strategies and in formulating radiation safety policies tailored to the specific needs of each context. Looking forward, it is imperative to continue exploring and expanding the use of these technologies to effectively assess and respond to radiological risks, thus ensuring the protection and well-being of communities and the environment.

4. CONCLUSION

In this study, significant progress has been made in the measurement of environmental dosimetry in Colombia, a developing country, highlighting the effective implementation of IoT technologies for precise radiation measurements in rural areas of Sincelejo (Sucre, Colombia). This effort represents an important step toward fulfilling the United Nations Sustainable Development Goals (SDGs) in Colombia, especially goal 3, aimed at ensuring healthy lives and promoting well-being for all ages, and goal 9, which focuses on building resilient infrastructure, promoting inclusive and sustainable industrialization, and fostering innovation. The data collected during the year 2022, reflecting the measurements of the effective gamma radiation dose at different heights above the surface, have allowed for the calculation of the average effective dose rate in mSv, resulting in a value of (0.998 ± 0.037) mSv/year. This value, although within the range of natural background radiation levels and below the recommended limit, approaches this limit, highlighting the need for continuous monitoring. Additionally, it has been identified that the average monthly UVI and the associated risk levels present a consistently high to extremely high UV radiation risk throughout the year. This finding underscores the need for effective UV protection measures in the region, especially during months with extremely high UVI indices. Therefore, this study recommends the implementation of continuous monitoring in the area to ensure that the radiation dose does not exceed the recommended limit in the future. It also suggests the implementation of mitigation measures to reduce exposure, especially in specific areas or activities that significantly contribute to the total radiation dose.

This study demonstrates the potential and efficacy of integrating IoT into environmental dosimetry. The findings of this study contribute to the growing body of knowledge about radiation levels in rural areas and highlight the potential of IoT technology in advancing environmental radiation monitoring. Future work could explore the integration of more advanced sensors and data analysis tools to further improve the accuracy and utility of these devices. The exploration of AI/ML for predictive analysis and improvement in response to radiological incidents, along with advanced algorithms and low-latency communication technologies, is suggested. The current research sets a new standard in the integration of IoT for dosimetry and radiation monitoring, offering a robust and scalable platform for environmental monitoring and radiological safety, thereby contributing to the sustainable development of Colombia and the protection of its rural communities. This study is an example of how IoT technology can be used to improve the accuracy and efficiency of scientific measurements, which has significant implications for the safety and health of rural communities and contributes to the sustainable development of Colombia.

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APPENDIX

Table 1. Comparison of IoT-based radiation monitoring systems: advances and future directions

Article title	Objectives	Main contributions	Implemented technologies	Future research directions
"Ionizing radiation monitoring technology at the verge of IoT" [19].	The paper provides a systematic review of the advancements in radiation monitoring technology, emphasizing the integration of the IoT and unmanned aerial vehicles (UAVs) in this field. It discusses the classification and functionality of different radiation sensors, the application of these technologies in various domains, and the challenges faced in radiation monitoring.	– Classification of available radiation sensors based on technical functionalities. – Comprehensive review of IoT's evolutionary application in nuclear and radiation monitoring. – Exploration of IoT technologies on UAVs for radiation monitoring and summarization of current industry challenges.	– Radiation sensors (gas-filled detectors, scintillation detectors, semiconductor detectors). – IoT technologies. – UAVs or drones.	The paper suggests further research opportunities in enhancing IoT and UAV technologies for more efficient and real-time radiation monitoring, addressing the limitations of current technologies, and improving the safety and efficiency of radiation monitoring operations.
"A highly scalable and autonomous spectroscopic radiation mapping system with resilient IoT detector units for dosimetry safety and security" [16].	Developed and deployed a network of IoT-enabled gamma-ray spectrometers mounted on vehicles for real-time radiation mapping. The system autonomously collected and analyzed over 1 million gamma-ray spectra across a 1 km² urban area within a few months.	Demonstrated the ability to detect and map radiation with high spatial and temporal resolution. Highlighted the impact of construction materials on local radiation levels. Introduced a scalable, cloud-based data processing and visualization framework for radiation data.	Utilized IoT gamma-ray spectrometers, cloud computing (amazon web services (AWS) services for data processing and storage), and ArcGIS (a geographic information system) for data visualization. The system also incorporated empirical bayesian kriging for spatial data analysis.	Plans to enhance the system with advanced cloud-based analysis, implement low-latency two-way communications for dynamic data collection strategies, and expand deployment to characterize and decontaminate radiological scenarios in various urban environments.
"IoT-enabled system for detection monitoring and tracking of nuclear materials" [20].	Development of a low-cost embedded system for high-energy radiation detection, aimed at national security to detect nuclear material and send detection events to the cloud in real-time with tracking capabilities.	The paper introduces a system capable of detecting alpha particles and sending nuclear detection events to CloudMQTT servers, demonstrating more than one node with internet connection and validating the design with a standard radiation instrumentation preamplifier system.	Utilized Si-based photodetectors, trans-impedance amplifiers, ARM Cortex M4 microcontroller, ESP8266 IoT module, Message Queue Telemetry Transport (MQTT) protocol, MySQL (a relational database management system) database, and Python handler program.	Future work could explore optimizing system performance, exploring advanced algorithms for target tracking, and collaboration with security agencies for real-world evaluations, expanding data plan bandwidth as the number of nodes increases to maintain optimal performance.
"IoT-enabled intelligent system for the radiation monitoring and warning approach" [21].	Implementation of an IoT-enabled system based on machine learning for radiation monitoring and warning, focusing on classifying radiations and their effects on infants, with the system alerting humans to danger zones through audio/visual warnings.	– Development of an IoT-enabled system integrated with machine learning models for radiation detection and warning. – Utilization of various classifiers, including decision trees and adaptive boosting, to classify radiation effects with an accuracy of 81.77%. – Collection of real-time datasets for experiments and analysis of radiation effects.	– IoT technologies and electromagnetic radiation sensors. – Machine learning algorithms (decision trees, adaptive boosting, logistic regression, and support vector machines) for data analysis and classification. – Arduino Mega microcontroller for data collection and processing.	The document suggests future work could include using more advanced technologies like the Raspberry Pi microprocessor for increased system efficiency and applying hypertuning and optimization techniques to improve model performance.

Table 1. Comparison of IoT-based radiation monitoring systems: advances and future directions (continue)

Article title	Objectives	Main contributions	Implemented technologies	Future research directions
"Unmanned radiation monitoring system" [22].	Development and demonstration of a modular, UAV-compatible radiation monitoring system (radiation monitoring system, RMS-00x) designed for rapid deployment in areas affected by radiological events, to minimize radiation exposure to personnel and the public.	– Introduction of a modular radiation monitoring system optimized for use with UAVs. – Design of RMS sensor modules for comprehensive radiation detection and mapping. – Demonstration of system effectiveness in emergency planning and response at a nuclear power plant.	– Modular RMS-00x system with sensor modules for dose rate measurement, air sampling, and radiation mapping. – UAVs for deploying and operating the sensor modules in affected areas. – RMS-WASP control software for data communication and analysis. – Compatibility with various UAV carriers, highlighting the system's adaptability and scalability.	While specific future work directions were not detailed, the continuous development and enhancement of the Radiation Monitoring System (RMS) modules, including improvements in UAV integration, sensor accuracy, and operational efficiency, are implied. The system's modular nature suggests ongoing efforts to expand its capabilities and adaptability to various radiological monitoring scenarios.
"Environmental monitoring system for smart city based on secure IoT architecture" [23].	Developed an IoT-based environmental monitoring system for smart cities, focusing on secure data collection, transmission, and analysis of air and sound pollution levels.	Developed a secure IoT architecture for environmental monitoring. Implemented a system that ensures secure data transmission and authentication of IoT devices. Utilized various sensors to monitor air and sound pollution in real-time.	IoT devices and sensors for air and sound pollution. Secure data transmission protocols. Data encryption and authentication mechanisms for device security. Cloud computing for data analysis and storage.	Suggests further enhancement of the system's security features, integration with more environmental parameters for comprehensive monitoring, and the development of more advanced data analysis techniques for predictive insights.

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