



## Design, construction and performance evaluation of an Arduino Uno-based radiation detector

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### Abstract

Radiation monitoring is essential for environmental protection and occupational safety, yet many commercial radiation monitoring systems are costly and technically demanding, limiting their accessibility for routine field applications, particularly in developing countries. This study developed and evaluated a low-cost, portable, and in-situ radiation detector for real-time environmental radiation monitoring. The system integrated a Geiger–Müller (GM) tube, Arduino Uno microcontroller, ESP32 wireless communication module, display components, and supporting electronic circuits, with a mobile application for real-time data presentation. Field measurements were conducted at two locations within Ladoke Akintola University of Technology (LAUTECH), Ogbomoso, Nigeria, and compared with measurements obtained using a commercial LK3600 radiation survey meter. Performance was assessed using Mean Square Error (MSE), Root Mean Square Error (RMSE), and Mean Percentage Error (MPE). The developed detector successfully detected and monitored background radiation and exhibited measurement trends comparable to the reference instrument, although it generally recorded higher dose rates. MSE values were 0.000473 and 0.000675, RMSE values were 0.02174 and 0.02598  $\mu\text{Sv/h}$ , and MPE values were 136.36% and 209.70% for Locations 1 and 2, respectively. The study demonstrated the feasibility of an affordable, portable, and real-time radiation monitoring system, providing a potentially accessible alternative for preliminary environmental radiation assessment. Further calibration, optimization, and validation against multiple reference instruments under varied environmental conditions are recommended.

**Keywords:** In-situ radiation detector, Geiger Muller (GM) tube, Environmental radiation monitoring, Arduino uno, and Radiation dose rate

### Introduction

Radiation is a form of energy that travels through space or a medium as waves or particles. It occurs naturally in the environment and can also be produced artificially through human activities, with important applications in medicine, industry, agriculture, and scientific research (Apte and Bhide, 2024; Vardhan and Shukla, 2017) <sup>[11]</sup>. Radiation is broadly classified into non- ionising and ionising radiation. Ionising radiation has sufficient energy to remove electrons from atoms and is widely used in medical imaging and cancer treatment. However, excessive exposure can damage living tissues and cells and increase the risk of diseases such as cancer (Benke and Ralph., 2024 <sup>[3]</sup>; Alashban and Alghamdi, 2024; Talapko *et al.*, 2024) <sup>[2, 8]</sup>. Therefore, reliable radiation monitoring is essential for radiation protection and safety.

Radiation detectors are used to measure the presence and intensity, and in some cases the type, of radiation. They are important in radiation protection, environmental monitoring, medical diagnostics, and nuclear research (Boukhalfa, 2021). The performance of a radiation detector depends on several factors, including the interaction cross-section, detector mass, noise, sensing volume, detector material, and the thickness of protective materials. Excessive protective material can reduce the amount of radiation reaching the sensing element and consequently affect detector sensitivity (Tsoulfanidis and Landsberger, 2021; Kang *et al.*, 2020).

In-situ radiation detectors provide the advantage of measuring radiation directly at the location of interest without the need to transport samples for laboratory analysis. This allows real- time monitoring, reduces delays in obtaining measurements, and facilitates continuous observation

of radiation levels. However, the design and construction of such detectors require consideration of sensitivity, accuracy, durability, portability, cost, environmental conditions, and ease of operation and maintenance. The increasing application of ionising radiation in medicine, industry, research, and environmental monitoring creates a need for reliable and accessible radiation measurement systems.

Commercial radiation detectors may be expensive, require specialised expertise, or have limited suitability for routine field monitoring. In addition, limited real-time monitoring and wireless data transmission can restrict timely access to radiation information. These challenges highlight the need for a simple, portable, and cost-effective in-situ radiation detector capable of reliable real-time measurement. Therefore, this study focuses on the design, construction, and performance evaluation of an in-situ radiation detector based on an Arduino Uno microcontroller. The performance of the developed detector is evaluated using mean square error (MSE), root mean square error (RMSE), and percentage error (%E).

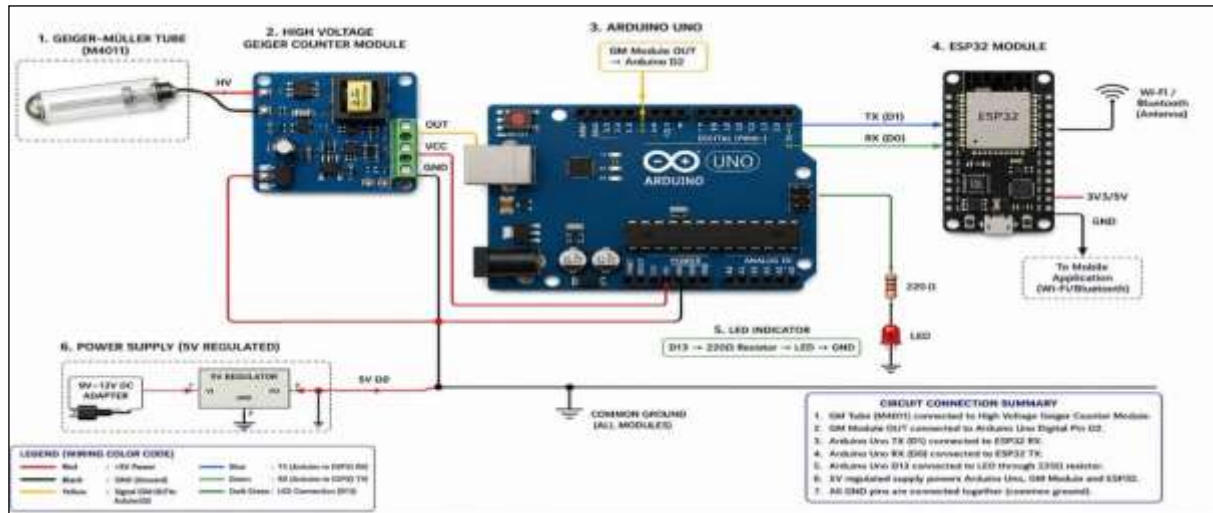
### Materials and Methods

#### 1. Circuit Design

The circuit (Fig 1) was designed using the Arduino Uno as the main controller of the system. The Arduino program was written, compiled, and uploaded into the microcontroller using the Arduino Integrated Development Environment (IDE). The code used for the design is presented at the appendix. Thereafter, it was connected to an Arduino DIY Geiger–Müller counter, an ESP32 module, an LED, and a regulated power supply. The Geiger–Müller counter was

used to detect ionising radiation. Whenever radiation particles passed through the Geiger tube, electrical pulses were generated and sent to the Arduino Uno for processing. The Arduino counted these pulses over a period of time and converted the readings from counts per minute (CPM) to dose rate in microsieverts per hour ( $\mu\text{Sv/h}$ ) using the conversion factor for the M4011 Geiger tube. To enable wireless communication,

the ESP32 module was connected to the Arduino through serial communication (UART). The ESP32 transmitted the processed radiation readings to the mobile application through Wi-Fi or Bluetooth. An LED was also included in the circuit to provide a visual indication whenever radiation was detected. The entire circuit was powered using a 5 V regulated power supply to ensure stable operation throughout the testing process.



**Fig 1:** Circuit Diagram of Arduino Uno Based In-Situ Radiation Detector

## 2. Detector Construction

The construction of the radiation detector was carried out in stages (Fig 2). First, all the required components were obtained and checked to ensure that they were working properly. After that, the Arduino Uno, Geiger-Müller counter, ESP32 module, LED, and other components were connected on a breadboard according to the circuit design. The Arduino Uno was then programmed using the Arduino IDE. The construction was tested several times to ensure that it could correctly count the radiation pulses and convert them into meaningful radiation values. After confirming that the Arduino was working properly, the ESP32 module was connected to enable wireless communication between the detector and the mobile application. The LED indicator was also tested to ensure that it responded whenever radiation was detected.

## 3. Materials Used

The materials used for the construction of the radiation detector are described below:

- 1. Arduino Uno Microcontroller:** The Arduino Uno served as the detector's central processing unit, receiving pulses from the Geiger-Müller tube, calculating count rate, converting the measurements to radiation dose rate ( $\mu\text{Sv/h}$ ), and transmitting the processed data to the ESP32 module, with its selection based on simplicity, reliability, low power consumption, and sensor compatibility.
- 2. ESP32:** The ESP32 module provided wireless communication between the radiation detector and mobile application, transmitting radiation measurements in real time via Wi-Fi for remote monitoring and display of radiation levels on an Android device.

- 3. Arduino DIY Geiger-Müller counter:** The Arduino DIY Geiger-Müller Counter served as the radiation sensing unit, with the Geiger-Müller tube detecting ionising radiation through electrical pulses generated by interactions within its gas-filled chamber, which were counted by the Arduino Uno for radiation measurement.

- 4. Light Emitting Diode (LED):** Light Emitting Diodes (LEDs) provided visual indication of radiation detection by producing a brief flash for each detected radiation event, allowing immediate confirmation of the detector's operation.

- 5. Power supply unit:** A rechargeable battery pack provided stable electrical power to the detector, enabling portable field operation without reliance on mains electricity.

- 6. Connecting wires:** Male-to-male and female-to-female jumper wires connected the Arduino Uno, ESP32 module, Geiger-Müller counter, LEDs, and other components, ensuring stable signal transmission and power distribution within the circuit.

- 7. Breadboard:** A solderless breadboard was used for prototype construction, allowing easy assembly, testing, troubleshooting, and modification of the circuit before finalising the detector.

## 4. Software Used

Different software packages were used in this research. The Arduino IDE was used to write and upload the program to the Arduino Uno. The program was responsible for reading the pulses from the Geiger-Müller counter, calculating the radiation level, converting the readings into dose rate, and sending the data to the ESP32 module. Visual Studio Code

was used as the main code editor during software development because it provides useful tools for editing and managing source code. Android Studio was used to test and debug the mobile application before installation on an Android device. Flutter SDK, together with the Dart programming language, was used to develop the mobile application. The application was designed to receive radiation readings from the ESP32 and display the values in a simple and user-friendly interface for real-time monitoring.

## 5. Performance Evaluation

The performance of the developed detector was assessed by comparing its readings with those obtained from the commercial LK3600 radiation survey meter. The performance evaluation indices obtained by comparing the dose-rate measurements recorded by the developed radiation detector (Adrad) with those measured by the commercial LK3600 survey meter at the two study locations. The evaluation was based on the Mean Square Error (MSE) (Equation 3.1), Root Mean Square Error (RMSE) (Equation 3.2), and Mean Percentage Error (Equation 3.3), which collectively provide an indication of how closely the developed detector agreed with the reference instrument.

$$\text{Mean Square Error MSE} = \frac{1}{n} \sum_{i=1}^n (m_i - t_i)^2 \quad (3.1)$$

where  $n$  is total number of paired observations used in the analysis (22),  $i$  is observation index, where  $i=1,2,3,\dots,n$ ,  $M_i$  is dose-rate measurement recorded by the developed radiation detector (Adrad) at the  $i$ th observation ( $\mu\text{Sv/h}$ ),  $T_i$  is corresponding dose-rate measurement recorded by the reference radiation detector (LK3600) at the  $i$ th observation ( $\mu\text{Sv/h}$ ), and  $(M_i - T_i)$  is difference between the measurement obtained from the developed detector and that obtained from the reference detector,  $(M_i - T_i)^2$  is squared difference between the two corresponding measurements. Root Mean Square Error

$$(\text{RMSE}): \sqrt{\frac{1}{n} \sum_{i=1}^n (m_i - t_i)^2} \quad (3.2)$$

where  $\sqrt{\phantom{x}}$  is square root operator,  $n$  is total number of paired observations,  $i$  is observation number,  $M_i$  is dose-rate measurement obtained from the developed detector at the  $i$ th observation ( $\mu\text{Sv/h}$ ),  $T_i$  is corresponding dose-rate measurement obtained from the LK3600 reference detector at the  $i$ th observation ( $\mu\text{Sv/h}$ ) and  $(M_i - T_i)^2$  is squared difference between the two corresponding measurements.

$$\text{Percentage Error (\%E)} = \frac{\text{LK3600} - \text{Adrad}}{\text{LK3600}} \times 100 \quad (3.3)$$

where LK3600 ( $T_i$ ) is dose-rate measurement obtained from the commercial LK3600 radiation survey meter ( $\mu\text{Sv/h}$ ), Adrad ( $M_i$ ) is Dose-rate measurement obtained from the developed Arduino-based radiation detector ( $\mu\text{Sv/h}$ ),  $(T_i - M_i)$  is difference between the reference measurement and the developed detector measurement, and 100 is Conversion factor used to express the error as a percentage.

## Results and Discussion

### 1. The Constructed In-Situ Radiation Detector

Plate 1 presents the constructed In-Situ Radiation Detector, which illustrates the architecture and operational flow of the

system. The detector continuously monitors environmental ionising radiation using an M4011 Geiger–Müller (GM) tube supplied with approximately 400– 500 V DC from a high-voltage module. Radiation detection produces electrical pulses that are counted by an Arduino Uno (ATmega328P) over a defined time interval to obtain Counts Per Minute (CPM), which are converted to radiation dose rate ( $\mu\text{Sv/h}$ ) using a calibration factor. A Light Emitting Diode (LED) provides visual indication of each detected radiation event, while the processed measurements are transmitted via UART to an ESP32 module for wireless communication with a Flutter-based Android application. The application displays the measured Counts Per Minute (CPM), radiation dose rate ( $\mu\text{Sv/h}$ ), and the radiation safety status. It also supports real-time monitoring and can optionally store historical radiation data for future analysis and record keeping.



Plate 1: Stage of Construction

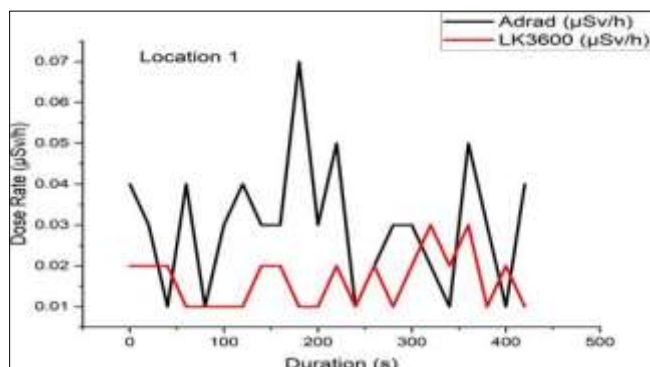
### 2. Ambient Dose Rate Measurements at Location 1

Fig 2 shows the variation in ambient gamma dose rate measured at Location 1 using the Adrad and LK3600 portable radiation survey meters over approximately 420 s. The Adrad recorded dose rates of  $0.01\text{--}0.07 \mu\text{Sv h}^{-1}$ , while the LK3600 recorded  $0.01\text{--}0.03 \mu\text{Sv h}^{-1}$ , with both instruments showing low background radiation throughout the monitoring period (UNSCEAR, 2015) [9]. The Adrad exhibited greater short-term fluctuations, reaching  $0.07 \mu\text{Sv h}^{-1}$  at approximately 180 s and about  $0.05 \mu\text{Sv h}^{-1}$  at subsequent intervals, whereas the LK3600 showed a more stable response, with most readings between  $0.01$  and  $0.02 \mu\text{Sv h}^{-1}$  and brief increases to  $0.03 \mu\text{Sv h}^{-1}$ . These variations may result from the random nature of radioactive decay, counting statistics, detector orientation, local environmental conditions, and differences in detector sensitivity, calibration, signal processing, and integration time (Wilds, 2013; Terashima *et al.*, 2015) [9]. Although Adrad consistently recorded higher dose rates, both instruments showed similar trends without a sustained increase, suggesting that the observed differences were more likely related to detector characteristics and calibration than to changes in the radiation field (Terashima *et al.*, 2015) [9]. The measured values remained within the reported range of natural background radiation, with no persistent elevation indicative of an abnormal radiation source (UNSCEAR, 2015 [9]; Petoussi-Henß *et al.*, 2020).

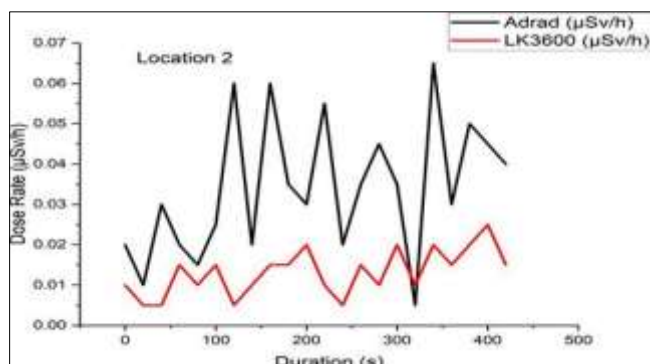
### 3. Ambient Dose Rate Measurement at Location 2

Presented in Fig 3 is the variation in ambient dose rate measured at Location 2 (LAUTECH Sculpture, Fine and Applied Arts Section) over a monitoring period of approximately 420 s using the developed Arduino-based radiation detector (Adrad) and the commercial LK3600

radiation survey meter. The Adrad recorded dose rates of approximately  $0.005 - 0.065 \mu\text{Sv h}^{-1}$ , compared with  $0.005 - 0.025 \mu\text{Sv h}^{-1}$  for the LK3600, with both instruments showing similar patterns of increase and decrease despite the consistently higher Adrad readings. The observed fluctuations are characteristic of environmental radiation measurements and may result from the random nature of radioactive decay, terrestrial radionuclides, cosmic radiation, local environmental conditions, and photon scattering (UNSCEAR, 2022; Wilds, 2013). Adrad showed notable peaks around 120, 160, 220, 340, and 380 s, reaching approximately  $0.060 - 0.065 \mu\text{Sv h}^{-1}$ , while the LK3600 exhibited smaller corresponding increases. Such variations are consistent with the Poisson statistics of radiation detection and do not necessarily indicate detector instability (Knoll, 2010; Tsoulfanidis and Landsberger, 2021). The smoother response of the LK3600 may be associated with its factory calibration and optimized signal processing, whereas the higher readings and fluctuations from Adrad may reflect differences in calibration, detector efficiency, electronic noise, dead-time effects, and Geiger-Müller tube response (Wilds, 2013; Knoll, 2010). Despite these differences, Adrad maintained a stable response without evident signal drift or interruption and successfully tracked changes in the ambient radiation field. Further calibration with certified reference sources and appropriate calibration factors may improve agreement with the commercial instrument and support its application in continuous in situ environmental radiation monitoring.



**Fig 2:** Ambient Dose Rate Measurements at Location 1



**Fig 3:** Ambient Dose Rate Measurement at Location 2

#### 4. Statistical Analysis for Ambient Dose Rate at Location 1

Presented in Table 1 are the descriptive statistics and one-sample *t*-test results for the 22 ambient dose-rate measurements obtained at Location 1 using the Adrad and

LK3600 radiation survey meters. The Adrad recorded a mean dose rate of  $0.030 \pm 0.01543 \mu\text{Sv h}^{-1}$ , compared with  $0.01636 \pm 0.00658 \mu\text{Sv h}^{-1}$  for the LK3600, indicating that Adrad recorded a higher mean dose rate and greater variability during the measurement period. The observed variation may be influenced by counting statistics, detector sensitivity, counting time, local environmental conditions, and the random nature of radioactive decay (Wilds, 2013), as well as differences in detector design, calibration, energy response, and signal processing. The one-sample *t*-test yielded  $t = 9.11921$  for Adrad and  $t = 11.66533$  for LK3600, with  $p < 0.0001$  for both instruments, indicating that the mean dose rates measured by each instrument were significantly different from the test mean of  $0 \mu\text{Sv h}^{-1}$  at the 0.05 significance level (Field, 2018). This finding confirms that measurable ambient radiation was present at Location 1, however, the test does not determine whether the two instruments differed significantly from each other. The higher mean and variability observed with Adrad may reflect differences in detector response and calibration, whereas the lower standard deviation of the LK3600 indicates a more stable measurement response. The measured dose rates represent environmental background radiation, which varies with local geological and environmental conditions (UNSCEAR, 2015).

**Table 1:** Statistical Analysis for Ambient Dose Rate at Location 1

| Location 1                  | N  | Mean    | SD      | t Statistic | Prob> t |
|-----------------------------|----|---------|---------|-------------|---------|
| Adrad ( $\mu\text{Sv/h}$ )  | 22 | 0.03    | 0.01543 | 9.11921     | <0.0001 |
| LK3600 ( $\mu\text{Sv/h}$ ) | 22 | 0.01636 | 0.00658 | 11.66533    | <0.0001 |

Adrad ( $\mu\text{Sv/h}$ ): At the 0.05 level, the population mean is significantly different from the test mean (0).

LK3600 ( $\mu\text{Sv/h}$ ): At the 0.05 level, the population mean is significantly different from the test mean (0).

#### 5. Statistical Analysis for Ambient Dose Rate at Location 2

Presented in Table 2 are the descriptive statistics and one-sample *t*-test results for the 22 ambient gamma dose-rate measurements obtained at Location 2 using the Adrad and LK3600 radiation survey meters. The Adrad recorded a mean dose rate of  $0.03409 \pm 0.01688 \mu\text{Sv h}^{-1}$ , compared with  $0.01318 \pm 0.00568 \mu\text{Sv h}^{-1}$  for the LK3600, indicating that Adrad recorded a higher mean dose rate and greater variability during the measurement period. The observed variation may be influenced by counting statistics, detector orientation, local environmental conditions, and the random nature of radioactive decay (Wilds, 2013), as well as differences in detector design, calibration, energy response, and signal processing (Terashima *et al.*, 2015). The one-sample *t*-test yielded  $t = 9.47421$  for Adrad and  $t = 10.88716$  for LK3600, with  $p < 0.0001$  for both instruments, indicating that the mean dose rates measured by each instrument were significantly different from the test mean of  $0 \mu\text{Sv h}^{-1}$  at the 0.05 significance level (Field, 2018). This finding confirms that measurable ambient gamma radiation was present at Location 2; however, the test does not determine whether the two instruments differed significantly from each other. The higher mean and variability recorded by Adrad may therefore be associated with differences in detector response and calibration, while the lower variability of the LK3600 indicates a more stable response under the conditions of the study. The measured dose rates represent environmental

background radiation, which varies with local geological and environmental conditions (UNSCEAR, 2015).

**Table 2:** Statistical Analysis for Ambient Dose Rate at Location 2

| Location 2     | N  | Mean    | SD      | t Statistic | Prob> t |
|----------------|----|---------|---------|-------------|---------|
| Adrad (μSv/h)  | 22 | 0.03409 | 0.01688 | 9.47421     | <0.0001 |
| LK3600 (μSv/h) | 22 | 0.01318 | 0.00568 | 10.88716    | <0.0001 |

Adrad (μSv/h): At the 0.05 level, the population mean is significantly different from the test mean (0).

LK3600 (μSv/h): At the 0.05 level, the population mean is significantly different from the test mean (0).

## 6. Performance Evaluation

The performance of the developed detector was assessed by comparing its readings with those obtained from the commercial LK3600 radiation survey meter. Table 3 presents the performance evaluation indices obtained by comparing the dose-rate measurements recorded by the developed radiation detector (Adrad) with those measured by the commercial LK3600 survey meter at the two study locations.

**Table 3:** Performance Metric

| Performance Metric            | Location 1 | Location 2 |
|-------------------------------|------------|------------|
| Mean Square Error (MSE)       | 0.000473   | 0.000675   |
| Root Mean Square Error (RMSE) | 0.02174    | 0.02598    |
| Mean Percentage Error (%)     | 136.36     | 209.70     |

The Mean Square Error (MSE) values were 0.000473 for Location 1 and 0.000675 for Location 2, while the corresponding Root Mean Square Error (RMSE) values were 0.02174 μSv/h and 0.02598 μSv/h, respectively. These relatively low absolute error values indicate that the developed detector produced measurements that were reasonably close to those of the reference instrument, although slightly greater deviations were observed at Location 2. The RMSE values show that the average absolute difference was approximately 0.02 μSv/h at both locations, which represents a modest difference within the low dose-rate range associated with environmental background radiation. The observed deviations may be associated with local environmental conditions, detector response characteristics, or calibration differences, as similar deviations can occur during the evaluation of prototype radiation monitoring systems before final calibration adjustments (Knoll, 2010; Tsoulfanidis and Landsberger, 2021).

The Mean Percentage Error (MPE) was 136.36% for Location 1 and 209.70% for Location

2. These relatively high percentage errors should be interpreted with caution because percentage- based error measures become highly sensitive when reference values are very small, as several LK3600 measurements ranged from 0.005 to 0.020 μSv/h. Thus, small absolute differences between the instruments can result in disproportionately large percentage errors. This limitation has been recognized in measurement science, where error measures expressed in the original measurement units, such as RMSE, are often considered more informative than percentage-based metrics when dealing with low-magnitude observations (Willmott & Matsuura, 2005)<sup>[15]</sup>. The results indicated that the developed detector maintained consistent responses at both locations, although the slightly higher errors at Location 2 suggest some increase in measurement variability. Further calibration using certified radiation reference sources is recommended to

reduce systematic differences and improve agreement with commercial survey instruments for environmental radiation monitoring applications.

## Conclusion

This study successfully designed, constructed, and evaluated a low-cost, portable, in-situ radiation detector for environmental radiation monitoring. The detector, which integrates a Geiger–Müller tube, microcontroller, display module, and supporting electronic circuits, was tested at two locations within Ladoke Akintola University of Technology, Ogbomoso, and compared with a calibrated LK3600 radiation survey meter. The results confirmed that the detector could measure environmental background radiation and follow similar measurement trends to the reference instrument, although it consistently recorded higher dose rates. The relatively low MSE and RMSE values indicate small absolute differences, while the high percentage errors were largely influenced by the low reference dose rates. Although further calibration is required to improve accuracy and reduce systematic bias, the developed detector demonstrates the feasibility of locally designed radiation monitoring instruments for routine environmental measurements, research, teaching, and preliminary radiation surveys.

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