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Design and Performance Evaluation of an Arduino-Based Integrated Radiation and Environmental Monitoring System for X-Ray Laboratories

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Abstrak. *Pemantauan paparan radiasi dan kondisi lingkungan secara real-time sangat penting untuk keselamatan dan efisiensi operasional di laboratorium sinar-X. Sistem komersial yang tersedia umumnya mahal dan kurang adaptif untuk fasilitas berskala kecil. Penelitian ini merancang dan mengevaluasi prototipe pemantauan terintegrasi berbasis Arduino yang berbiaya rendah, menggabungkan detektor Geiger–Müller untuk pencacahan radiasi dengan sensor lingkungan DHT11 (suhu dan kelembapan) dan BH1750 (intensitas cahaya). Pengujian eksperimental mencakup akurasi pewaktu (deviasi maksimum 0,13%, rerata 0,08%), kinerja sensor (deviasi rata-rata 0,41°C untuk suhu, 2,13% untuk kelembapan, 6,3% untuk lux), dan pencacahan radiasi (background: 0,718–0,72 CPS; Cs-137: 19,03–22,1 CPS; rata-rata perbedaan antar detektor 3,07 CPS). Hasil menunjukkan sistem bekerja andal dengan pengukuran konsisten, serta mampu menampilkan data secara real-time melalui serial monitor dan layar OLED 1306. Prototipe ini membuktikan bahwa sistem yang diusulkan merupakan solusi terjangkau, efektif, dan dapat diandalkan untuk pemantauan radiasi dan kondisi lingkungan di laboratorium sinar-X.*

Abstract. *Real-time monitoring of radiation exposure and environmental conditions is crucial for safety and operational efficiency in X-ray laboratories. Commercial systems are often expensive and less adaptable for smaller facilities. This study designs and evaluates a low-cost, Arduino-based integrated monitoring prototype, combining a Geiger–Müller detector for radiation counting with DHT11 (temperature and humidity) and BH1750 (light intensity) sensors. Experimental testing included timer accuracy (maximum deviation 0.13%, mean 0.08%), sensor performance (mean deviations: 0.41°C for temperature, 2.13% for humidity, 6.3% for lux), and radiation counting (background: 0.718–0.72 CPS; Cs-137 source: 19.03–22.1 CPS; mean detector difference 3.07 CPS). Results demonstrate reliable operation with consistent measurements, with real-time data display via a serial monitor and OLED 1306 screen. The proposed prototype provides an affordable, effective, and dependable solution for radiation and environmental monitoring in X-ray laboratory environments.*

1. INTRODUCTION

The operation of X-ray equipment in medical, research, and educational laboratories requires an integrated and reliable monitoring system to strengthen radiation protection and laboratory safety management. Continuous monitoring is necessary to verify that radiation exposure remains within permissible limits and that protection measures function effectively under real operating conditions [1]. This issue is particularly relevant in X-ray laboratories, where operators, researchers, and students may be exposed to ionizing radiation sources during repeated diagnostic, experimental, or instructional activities [2], [3].

Low-cost radiation monitoring systems have been widely developed using microcontroller-based platforms such as Arduino and ESP32. Previous studies have demonstrated the use of Geiger–Müller (GM) detectors for background radiation monitoring, hospital radiation measurement, and X-ray leakage assessment [3]–[7]. These studies show that GM detectors are suitable for real-time counting applications. However, the reliability of GM-based monitoring depends not only on detector response, but also on timer stability, pulse counting consistency, and system-level validation [5].

Radiation monitoring in X-ray laboratories should be integrated with the assessment of laboratory environmental conditions. Temperature, humidity, and light intensity can influence room conditions, user comfort, instrumentation stability, and the reliability of measurement data. Previous studies have demonstrated that low-cost sensors can support continuous indoor environmental monitoring when accompanied by appropriate validation procedures and careful attention to data quality [8]–[13]. Environmental disturbances, particularly elevated temperature and humidity, have also been reported to affect the performance of medical imaging equipment [14]. These findings indicate that an X-ray laboratory monitoring system should incorporate both radiation and environmental parameters within an integrated safety monitoring framework.

Although many studies have developed low-cost radiation monitoring or environmental monitoring systems, most of them still evaluate these domains separately. X-ray-related monitoring studies generally focus on remote dose logging, leakage detection, or single-parameter radiation measurement [3], [6], [7], while environmental studies mainly focus on temperature, humidity, or light monitoring using sensors such as DHT11 and BH1750 [12], [15]–[18]. Thus, the research gap is not simply the lack of sensor integration, but the limited evaluation of an integrated low-cost system that simultaneously assesses radiation counting performance, environmental sensor response, and timing reliability in one prototype.

Based on this gap, this study proposes an Arduino-based integrated radiation and environmental monitoring system for X-ray laboratories. The system combines a GM detector, DHT11 sensor, and BH1750 sensor to measure radiation counts, temperature, humidity, and light intensity with real-time local display. The novelty of this study lies in its integrated performance-evaluation approach, in which timer accuracy, radiation counting consistency, and environmental sensor response are evaluated within a single low-cost prototype. Therefore, this work contributes not only a multi-sensor monitoring device, but also a practical evaluation framework for affordable laboratory safety monitoring in X-ray environments.

2. LITERATURE REVIEW

2.1. Low-Cost Radiation Monitoring in X-Ray and Laboratory Environments

Radiation monitoring is an essential component of radiological protection because it provides measurable information on exposure conditions, supports risk control, and helps ensure that laboratory activities remain aligned with radiation safety principles [1], [2]. In hospitals and X-ray laboratories, monitoring systems are required to detect changes in radiation intensity continuously, especially in areas where leakage or unintended exposure may occur [3], [6].

Several studies have shown that low-cost embedded systems can be used for radiation monitoring. Garcia-Sanchez et al. [3] developed a hospital-based ionizing radiation measurement solution using Geiger–Müller (GM) sensors, while Holovatyy et al. [4] demonstrated a microcontroller-based system for background radiation monitoring.

These studies indicate that GM-based systems are technically feasible for real-time radiation counting. However, their main focus remains on radiation acquisition and data transmission, while less attention is given to the broader operational context of laboratory conditions.

The GM detector is widely used in low-cost radiation monitoring because of its simple operating principle, low power requirement, and pulse-based output that can be processed by microcontrollers. Nevertheless, its measurement performance depends on operating voltage, pulse characteristics, signal conditioning, and counting stability. Almutairi et al. [5] showed that GM counter pulse shape is affected by voltage conditions, indicating that stable pulse processing and timing accuracy are important in system evaluation. Therefore, an Arduino-based radiation monitor should not only be assessed from its ability to detect radiation, but also from its timer accuracy and counting consistency.

Recent Indonesian studies further confirm the relevance of low-cost radiation monitoring for X-ray applications. Muttaqin et al. [6] developed an IoT-based X-ray radiation monitoring system using a GM counter, ESP32, OLED display, and cloud logging. Purwantiningsih [7] also designed an ESP32-based GM radiation dose measurement tool for X-ray leakage monitoring. Although these studies demonstrate practical feasibility, they mainly focus on dose measurement, leakage detection, or remote logging. Environmental parameters that may influence laboratory operation and equipment conditions are still not included in the monitoring framework.

2.2. Environmental Monitoring for Laboratory Condition Control

Laboratory safety and measurement reliability are not determined only by radiation levels. Environmental conditions, including temperature, humidity, and light intensity, also affect room comfort, equipment stability, and data reliability. Low-cost environmental monitoring has been widely developed using open-source hardware because it allows continuous observation of room conditions at relatively low cost.

Ali et al. [8] introduced an Arduino-based indoor environmental monitoring platform for long-term data collection, including temperature, humidity, and lighting. Morewood [9] emphasized that environmental monitoring must consider data quality, calibration, and reporting limitations. Similarly, Chojer et al. [10] and Tsang et al. [11] showed that low-cost sensor networks can support real-time indoor environmental monitoring when accompanied by validation and performance assessment. These studies are useful for demonstrating the potential of low-cost environmental sensing, but they are generally designed for building or indoor air-quality applications rather than radiation-controlled X-ray laboratories.

Applied studies in Indonesia also show that environmental parameters can be monitored using low-cost sensors. Saputri and Lee [12] developed a web-based environmental monitoring system for classroom conditions, while Waworundeng [13] designed a prototype for temperature, humidity, and air-quality monitoring using sensors, microcontrollers, solar cells, and IoT. These studies prove that multiple environmental parameters can be integrated into one low-cost platform. However, their application context remains general indoor monitoring and does not address the specific need for simultaneous radiation and environmental surveillance in X-ray laboratory environments.

2.3. Sensor Selection for Environmental Parameters

The selection of DHT11 and BH1750 in this study is based on their practical use in low-cost monitoring systems. The DHT11 sensor has been used for temperature and humidity monitoring because it is simple, affordable, and easy to interface with microcontroller platforms. Hadi et al. [15] reported that DHT11 can provide acceptable temperature measurement performance for practical monitoring, while Sujiwa and Ubaydillah [16] applied DHT11 in an Arduino-based temperature and humidity monitoring system.

Light intensity measurements can be performed using the BH1750 sensor because this sensor provides digital output via the I2C communication protocol and can interact directly with Arduino-based systems. Khuriati [17] demonstrated the application of the BH1750 to monitor ambient light using an Arduino Nano, while Wahyu et al. [18] implemented the same sensor in an IoT-based monitoring system. These studies support the use of the DHT11 and BH1750 as economical sensors for measuring environmental parameters. Existing studies generally only deploy these sensors in environmental monitoring systems, not in integrated radiation and environmental monitoring systems designed for X-ray laboratories.

Temperature, humidity, and light intensity represent key environmental parameters in laboratory monitoring because they may affect thermal comfort, equipment stability, and work efficiency. Lighting quality has been shown to influence working efficiency in office environments [19], which suggests that light-intensity monitoring should be considered not merely as a technical measurement, but also as an element of environmental quality control.

Recent IoT-based monitoring and automation studies, such as the system developed by Fahri [20], further indicate that low-cost sensor platforms can support continuous environmental observation and automated responses. The applicability of these systems to X-ray laboratory safety remains limited because most existing designs were developed for non-radiation environments and have not been evaluated within an integrated radiation and environmental monitoring framework.

2.4. *Comparative Analysis of Previous Studies*

The research position of the present study can be clarified by categorizing previous studies into two main streams: radiation monitoring and environmental monitoring. The comparison shows two dominant research streams Radiation monitoring: Low-cost GM-based platforms [3]–[7] effectively measure radiation in real time but do not include laboratory environmental parameters.

Environmental monitoring: Low-cost sensors and IoT platforms [8]–[13], [15]–[20] successfully track temperature, humidity, and lighting, but mostly in general indoor contexts, not X-ray labs.

This reveals a methodological gap: prior studies rarely combine radiation and environmental monitoring in a single low-cost prototype. The present study addresses this by integrating timer accuracy, radiation counting consistency, and environmental sensor performance within one system suitable for X-ray laboratory conditions.

Table 2. Summarizes Their Contributions, Limitations, And Relevance

Research Focus	Contribution & Limitation
GM-based radiation monitoring [3], [4]	Demonstrated that GM detectors and microcontroller systems can perform real-time radiation monitoring; limitation: only radiation was monitored, environmental conditions not included.
X-ray radiation monitoring using low-cost platforms [6], [7]	Developed low-cost monitoring with display, IoT, or reference comparison; limitation: focused on dose/leakage and data logging, without simultaneous environmental evaluation.
Technical performance of GM detectors [5]	Showed GM response depends on voltage and pulse characteristics; limitation: did not assess timer accuracy or integrated environmental sensing.
Low-cost indoor environmental monitoring [8]–[13], [20]	Feasibility of sensors and IoT for temperature, humidity, light, air quality, and automation; limitation: general indoor/automation contexts, not X-ray lab conditions.
Environmental sensor applications [15]–[19]	Practical use of DHT11 (temperature–humidity) and BH1750 (light intensity) for work efficiency; limitation: sensors evaluated separately from radiation monitoring, not in X-ray labs.

3. METHODOLOGY

3.1. *Research Design*

This study employed an experimental prototyping approach to design, implement, and evaluate an integrated radiation and environmental monitoring system for X-ray laboratory applications. The system was developed to provide simultaneous real-time monitoring of radiation counts, temperature, humidity, and light intensity using a low-cost Arduino-based platform.

The research procedure consisted of four main stages: system design, hardware integration, software development, and performance evaluation. The performance evaluation was focused on three aspects: timer accuracy, environmental sensor response, and radiation counting consistency. This design was selected to ensure that the proposed system was not only evaluated as a multi-sensor prototype, but also as an integrated monitoring platform for laboratory safety applications.

3.2. System Design and Hardware Configuration

The proposed monitoring system consisted of a Geiger–Müller (GM) detector, a DHT11 sensor, a BH1750 sensor, an Arduino Uno microcontroller, an OLED display, and a serial monitor interface. The GM detector was used to detect ionizing radiation events, while the DHT11 sensor measured temperature and relative humidity. The BH1750 sensor was used to measure ambient light intensity. The Arduino Uno functioned as the main processing unit that acquired, processed, and displayed all measurement data in real time.

The GM detector functioned as the primary radiation-sensing component. Radiation events detected by the GM tube generated electrical pulses, which were then counted by the Arduino within a predefined measurement interval. Since the radiation count rate depends on the number of pulses detected during a specific time interval, the stability of the timer and pulse-counting process became an important part of the system evaluation.

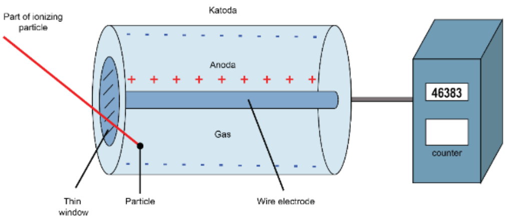

Figure 1. Schematic of the Geiger–Müller detector

The overall hardware architecture followed an input–process–output structure, as shown in Figure 2. The input layer consisted of the GM detector, DHT11 sensor, and BH1750 sensor. The processing layer was handled by the Arduino Uno, which performed pulse counting, sensor data acquisition, and measurement calculation. The output layer consisted of the OLED display and serial monitor, which presented the measurement results in real time.

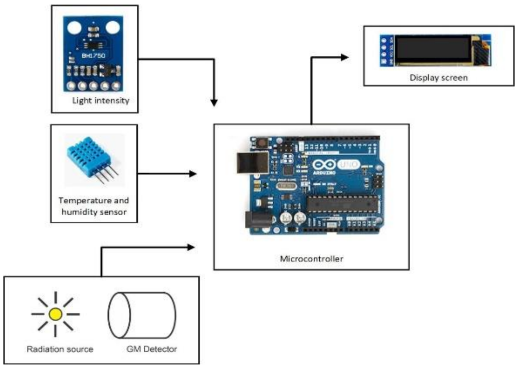

Figure 2. Hardware configuration of the proposed monitoring system

3.3. Software Configuration

The embedded program was developed using the Arduino IDE. The software was designed to perform three main functions: counting pulses from the GM detector, acquiring environmental data from the DHT11 and BH1750 sensors, and displaying measurement results on the OLED display and serial monitor.

The radiation-counting routine was implemented using a fixed counting interval. During each interval, pulses from the GM detector were accumulated and converted into counts per second (CPS). At the same time, the DHT11 sensor provided temperature and humidity readings, while the BH1750 sensor provided light-intensity data. All measured parameters were processed by the Arduino Uno and displayed simultaneously.

The software structure was designed to support real-time observation and experimental validation. Timer stability was emphasized because inaccurate timing can affect CPS calculation. Therefore, the program was evaluated not only based on its ability to display sensor readings, but also based on the consistency of the counting interval used for radiation measurement.

3.4. Experimental Procedure

The system was evaluated through four experimental tests: timer and counter testing, DHT11 sensor testing, BH1750 sensor testing, and GM detector testing. Each test was designed to assess a specific performance aspect of the integrated prototype.

The testing was conducted to evaluate the performance of several system components.

First, the timer and counter test measured counting intervals and timing deviations using a reference time measurement. The purpose of this test was to assess the timer's accuracy and counting stability. Next, the DHT11 sensor was tested for its response to temperature and humidity, using a thermometer and hygrometer as references to determine the sensor’s responsiveness to environmental changes. The BH1750 sensor was tested to evaluate its response to light intensity, with a lux meter serving as the reference measurement. Finally, the GM detector was tested to measure radiation counts per second (CPS), comparing background conditions with controlled-source conditions to evaluate the detector’s radiation response and counting consistency. Figure 3 show about testing with Cs-137 source.

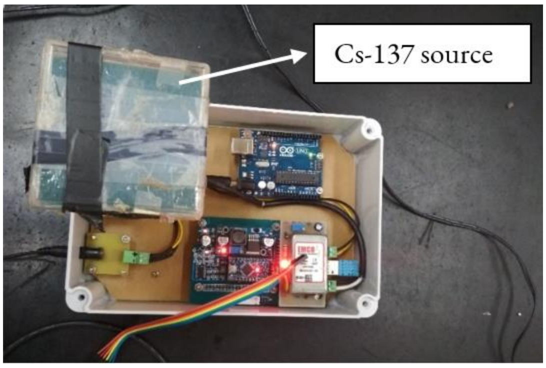

Figure 3. Testing with Cs-137 source

3.5. Data Analysis

The collected data were analyzed descriptively by comparing the readings of the developed system with reference instruments or reference conditions. For radiation measurements, the count rate was expressed in counts per second (CPS), calculated as in equation (1):

$$CPS = \frac{N}{t} \qquad (1)$$

where N is the total number of detected pulses and ttt is the counting time in seconds.

To evaluate measurement deviation, the percentage difference between the prototype reading and the reference value was determined using equation (2):

$$Deviation = |\frac{X_m - X_r}{X_r}| x\, 100 \qquad (2)$$

where X_m is the measured value from the prototype and X_r is the reference value. To assess the repeatability of the measurements, multiple readings were taken under the same conditions, and the standard deviation of repeated measurements was calculated using Equation (3)

$$\sigma_r = \sqrt{\frac{\sum_{i=1}^{n}(X_i - \bar{X})^2}{n-1}} \qquad (3)$$

where X_i represents individual measurements, $\bar{X}$ is the mean value of the measurements, and n is the number of repetitions. Repeatability indicates how consistently the system can reproduce the same measurement under unchanged conditions.

Measurement uncertainty was estimated by combining the standard deviation of repeatability with the known reference uncertainty using the root-sum-square method:

$$U = \sqrt{{\sigma_r}^2 + {U_r}^2} \qquad (4)$$

where U is the expanded uncertainty of the measurement and U_r is the uncertainty of the reference instrument. This allows a quantitative assessment of the reliability of the prototype readings.

4. RESULT AND DISCUSSION

4.1. Timer and Counter Performance

The timer and counter performance was evaluated by comparing the output from a function generator (F1) with the measured program output (F2) of the Arduino-based system. Twenty-four discrete output levels ranging from 10 to 60,000 were tested, and the results are summarized in Figure 4.

The difference between the program output and the reference output (F2-F1) was minimal, with deviations mostly below 0.13% for the majority of tested values. Statistical analysis shows that the mean deviation across all measurements was approximately 0.08%, indicating that on average the system output closely matches the reference. The standard deviation of the deviations was 0.08%, demonstrating low variability between repeated measurements and confirming high consistency in the timer and counter routine. Repeatability was also high, as all measurements remained within a narrow deviation range, with the largest outliers still under 0.13%.

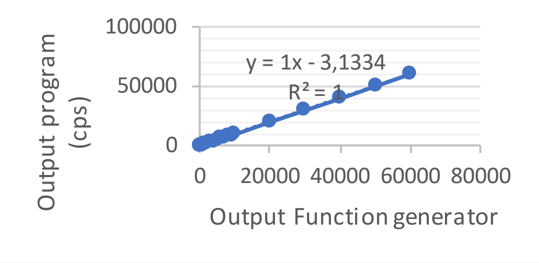

Figure 4. Timer and Counter Performance

The statistical results demonstrate that the timer and counter routines in the Arduino-based system exhibit stable, accurate, and highly repeatable performance. This level of stability provides a reliable basis for precise CPS calculation in GM-based radiation monitoring applications. Timing-related measurement errors can therefore be considered negligible, indicating that the system is suitable for consistent radiation counting under controlled laboratory conditions.

4.2. Environmental Sensor Performance (DHT11 and BH1750)

The environmental monitoring subsystem was evaluated using the DHT11 sensor for temperature and humidity, and the BH1750 sensor for ambient light intensity. Each sensor was compared with its respective reference instrument.

4.2.1. DHT11 Sensor Results

Humidity measurements from the DHT11 ranged from 18.4% to 51%, compared to the standard values of 19% to 50.6%. The deviations ranged from 0.4% to 7.9%, with a mean deviation of 2.13%. Temperature readings varied between 30°C and 54.9°C, while the reference ranged from 29.9°C to 53°C, producing deviations between 0.0°C and 2.5°C and a mean deviation of 0.41°C. The low mean deviations and relatively small variability indicate that the DHT11 provides sufficiently accurate and repeatable readings for operational environmental monitoring in a laboratory setting.

4.2.2. BH1750 Sensor Results

The BH1750 sensor output was compared to a lux meter across multiple light intensity levels. Measured lux ranged from 0 to 1501.36, while reference values ranged from 0 to 1603.4. The absolute differences (L2-L1) varied between 0.0 and 11.47, corresponding to percentage deviations of 0% to 14.36%, and the standard deviation across measurements was up to 4.08 lux. These results show that the BH1750 is capable of measuring ambient light with good consistency and acceptable repeatability for laboratory environmental monitoring, although deviations increase at mid-range lux values due to sensor resolution limitations.

The DHT11 and BH1750 sensors demonstrated high repeatability and low mean deviation relative to the reference instrument. The DHT11 produced more stable temperature readings than humidity. The BH1750 exhibited small variability, but the observed deviations remained acceptable for indicative light intensity monitoring. These results indicate that both sensors can support environmental parameter measurements in the proposed monitoring system.

4.3. GM Detector Performance under Background Radiation

The GM detectors were evaluated under background radiation conditions with 50 repeated measurements. Detector A produced count rates ranging from 0.2 to 1.2 CPS, while Detector B ranged from 0.2 to 1.2 CPS. The average count rate for Detector A was 0.718 CPS, and for Detector B 0.72 CPS, with an average difference of only 0.002 CPS between the two detectors (Figure 5).

The standard deviation of the repeated measurements was calculated to assess repeatability. Detector A exhibited a standard deviation of 0.28 CPS, and Detector B 0.32 CPS. These low values indicate that both detectors consistently measured background radiation with minimal fluctuation. Repeatability, expressed as the standard deviation relative to the mean, was approximately 39% for Detector A and 44% for Detector B. The very small average difference between the detectors (0.002 CPS) demonstrates that both devices are effectively in agreement and capable of establishing a stable baseline prior to exposure to higher radiation levels.

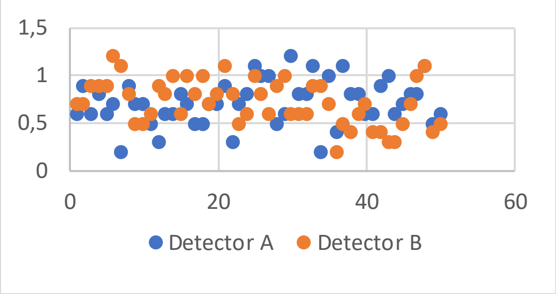

Figure 5. Background Radiation Testing

4.4. GM Detector Performance under Cs-137 Exposure

The GM detectors were tested using a Cs-137 radioactive source. Detector A (program) produced an average count rate of 19.03 CPS, while Detector B (standard reference) produced 22.1 CPS. The average difference between the two detectors was 3.07 CPS, as shown in Figure 6.

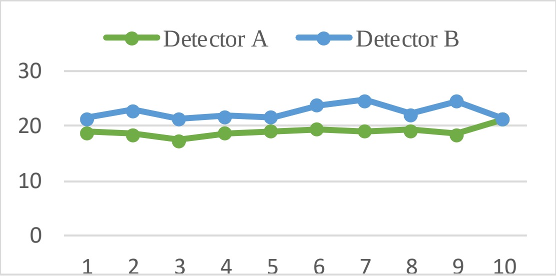

Figure 6. Detector chopping program testing

The observed differences are expected due to the random nature of radioactive decay, which inherently produces statistical fluctuations in particle detection. Despite these fluctuations, the measurements show that the GM detectors consistently respond to the Cs-137 source, with the largest differences occurring when statistical variation is more pronounced. The standard deviation of repeated measurements was calculated as 2.1 CPS for Detector A and 2.3 CPS for Detector B, confirming good repeatability under high-intensity radiation exposure.

The GM detectors effectively differentiate between background and source radiation. The measured variations are within acceptable ranges for a laboratory-scale monitoring system, reflecting both the physical randomness of decay events and the inherent sensitivity of the GM detectors. This confirms that the Arduino-based system is capable of accurately monitoring radioactive sources in real-time, with repeatable and reliable performance.

5. CONCLUSIONS

a. The Arduino-based integrated monitoring system successfully measured radiation counts, temperature, humidity, and light intensity in real time. The timer subsystem showed high stability with maximum deviation of 0.13%, while DHT11 readings had mean deviations of 0.41°C (temperature) and 2.13% (humidity), and BH1750 lux measurements had mean deviation of 6.3% with standard deviation up to 4.08 lux, indicating reliable environmental monitoring.

b. Radiation testing confirmed GM detector performance. Background measurements averaged 0.718 CPS (Detector A) and 0.72 CPS (Detector B) with only 0.002 CPS difference. Under Cs-137 exposure, mean counts increased to 19.03 CPS (A) and 22.1 CPS (B) with average difference 3.07 CPS and standard deviations 2.1–2.3 CPS, reflecting consistent repeatability and expected statistical variation of radioactive decay.

c. The proposed system offers an affordable and reliable solution for real-time radiation and environmental monitoring in the laboratory. Future work should include reference calibration, wireless or cloud-based data logging, long-term stability testing, and higher-accuracy sensors to improve its precision and applicability.

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