



Application of TLD Dosimeters (CaSO₄:Dy and LiF:Mg,Ti) for Environmental Assessment of H*(10) in Field Studies.

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Abstract: The increasing use of ionizing radiation across various sectors of society underscores the need for effective monitoring of occupationally exposed individuals (OEIs), the public, and the environment. Within this framework, environmental radiation protection programs adopt the ambient dose equivalent H*(10) as the operational quantity, as defined by the International Commission on Radiological Protection (ICRP) and recommended by the International Atomic Energy Agency (IAEA), due to its suitability for estimating the risk of external exposure under field conditions. This study assessed the ambient dose equivalent H*(10) through a field survey conducted around the perimeter of the IPEN facilities. Eight monitoring points were selected near thirteen already existing environmental sampling stations, covering approximately 60% of the area. The monitoring was structured in three stages: (i) a comparative analysis between monthly and quarterly measurements using CaSO₄:Dy thermoluminescent detectors (TLDs), which showed proportional responses; (ii) a comparison between quarterly measurements with CaSO₄:Dy and LiF:Mg,Ti TLDs, which demonstrated equivalent results; and (iii) a comparison between the quarterly CaSO₄:Dy data from this study and those obtained in the Environmental Radiological Monitoring Program of the Center for Metrology of Ionizing Radiations of IPEN (ERMP/CEMRI-IPEN), which indicated consistent and satisfactory results, confirming the reliability of using H*(10) in the applied monitoring system. Statistical and uncertainty analyses further confirmed the robustness of the environmental monitoring with thermoluminescent dosimeters. Proper detector selection remains essential to ensure accuracy, minimize variability, and enhance environmental radiation monitoring programs.

Keywords: dosimetry; thermoluminescence; environmental monitoring; field research



Aplicação de dosímetros TLD (CaSO₄:Dy e LiF:Mg,Ti) para avaliação ambiental de H*(10) em estudos de campo

Resumo: O uso crescente da radiação ionizante em diversos setores da sociedade evidencia a necessidade de um monitoramento eficaz de indivíduos ocupacionalmente expostos (IOEs), do público em geral e do meio ambiente. Nesse contexto, os programas de proteção radiológica ambiental adotam a grandeza operacional equivalente de dose ambiente H*(10), conforme definida pela Comissão Internacional de Proteção Radiológica (ICRP) e recomendada pela Agência Internacional de Energia Atômica (IAEA), devido à sua adequação para estimar o risco de exposição externa em condições de campo. Este estudo avaliou o equivalente de dose ambiente H*(10) por meio de uma pesquisa de campo realizada ao redor do perímetro das instalações do IPEN. Oito pontos de monitoramento foram selecionados próximos a treze estações de amostragem ambiental já existentes, cobrindo aproximadamente 60% da área. O monitoramento foi estruturado em três etapas: (i) uma análise comparativa entre medições mensais e trimestrais utilizando detectores termoluminescentes (TLDs) de CaSO₄:Dy, que apresentaram respostas proporcionais; (ii) uma comparação entre medições trimestrais com TLDs de CaSO₄:Dy e LiF:Mg,Ti, que demonstraram resultados equivalentes; e (iii) uma comparação entre os dados trimestrais de CaSO₄:Dy deste estudo e aqueles obtidos no Programa de Monitoramento Radiológico Ambiental do Centro de Metrologia das Radiações Ionizantes do IPEN (PMRA/CEMRI-IPEN), que indicaram resultados consistentes e satisfatórios, confirmando a confiabilidade do uso de H*(10) no sistema de monitoramento aplicado. As análises estatísticas e de incerteza confirmaram a robustez do monitoramento ambiental com dosímetros termoluminescentes. A seleção adequada do detector permanece essencial para garantir precisão, reduzir a variabilidade e fortalecer os programas de monitoramento radiológico ambiental.

Palavras-chave: dosimetria, termoluminescência; monitoração ambiental; pesquisa de campo

1. INTRODUCTION

Currently, there is a significant increase in the application of ionizing radiation in various sectors of society, including industry for production purposes and medicine for diagnosis and treatment of diseases. Consequently, there has also been an increase in monitoring workers and the environment to ensure continuous verification of radiation levels, with the aim of mitigating potential impacts on both the environment and individuals [1, 2, 3].

Given the necessity of such monitoring, establishing a radiological protection program is essential to ensure the proper use of ionizing radiation, thus preventing harm to human health and the environment [4, 5, 6].

According to the recommendations of the International Commission on Radiological Protection (ICRP 26), the Radiological Protection Program should be proportional to the degree of risk associated with the use of ionizing radiation, to ensure the effective management of necessary measures for the protection of individuals, their workplaces, and the environment [1, 3, 4, 6].

Radiological protection aims to provide an appropriate standard of protection for individuals and the environment without inhibiting beneficial activities that may lead to increased radiation exposure (ICRP, 1990) [2]. The primary objective of implementing monitoring programs is to assess the radiological conditions of the workplace and ensure they are acceptably safe and satisfactory for individuals exposed to them. [2, 3, 7, 8, 9].

In Brazil, the control over the use of radiation sources is carried out by the Brazilian Nuclear Energy Commission (CNEN), linked to the Ministry of Science, Technology, and Innovation. This control is exercised in accordance with the CNEN Standard NN 3.01 [10], which addresses the Basic Requirements for Radiological Protection and Radiation Source Safety. This standard applies to planned, emergency, and existing exposure situations. The types of exposure considered in the standard include occupational, public, and medical

exposures. The regulation establishes the basic requirements for the radiological protection of individuals and the environment from exposure to ionizing radiation, including the safety of ionizing radiation sources [10].

Although alternative operational quantities exist—such as $H'(0.07)$, primarily used for skin and extremity monitoring, and $H_p(d)$, employed for individual monitoring of occupationally exposed workers—these are not directly applicable to the environmental context of this study. In contrast, $H(10)^*$ specifically addresses the needs of ambient monitoring, allowing for direct comparison with international recommendations and regulatory limits. Accordingly, we emphasize that the use of $H(10)^*$ in this work ensures both methodological robustness and alignment with international radiation protection standards for environmental surveillance. [10, 11, 12].

The Environmental Radiological Monitoring Program (ERMP) is an integral part of the Radiological Protection Plan and must be established and implemented considering the pre-operational, operational, and post-operational phases. The ERMP is intended to assess the impact resulting from the use of ionizing radiation [10, 11, 12].

Environmental monitoring consists of measuring radiation levels in the environment; for this purpose, thermoluminescent dosimeters (TLDs) [12] can be used at locations defined as representative of critical radiation pathways, both during normal operations and in the event of accidents involving the release of radioactive materials into the environment [10, 12]. According to ICRU Report 85 [12], the operational quantity $H^*(10)$ is recommended for environmental monitoring, as it provides a conservative estimate of effective dose for strongly penetrating radiation fields.

Thermoluminescent materials are generally non-conducting crystals that contain impurities or defects in their crystalline structure, which act as traps for charge carriers. The simplest way to understand the role of these traps is through the band model [13, 14, 15].

The choice of IPEN is also relevant because it represents a nuclear installation located within a densely populated urban area, which reinforces the importance of continuous assessments of the ambient dose equivalent, $H^*(10)$, for environmental radiation protection. Thus, conducting this research at IPEN not only strengthens the reliability of existing monitoring programs but also contributes to consolidating TLDs as robust and comparable tools for field studies.

The Environmental Radiological Monitoring Program (ERMP), currently carried out by IPEN, uses only $\text{CaSO}_4\text{:Dy}$ detectors on a quarterly basis in its verification routine. The present research, which aims to expand environmental monitoring options, employed two types of thermoluminescent detectors — $\text{CaSO}_4\text{:Dy}$ and LiF:Mg,Ti — to determine the ambient dose equivalent, $H^*(10)$, for use in environmental monitoring [11, 16].

2. MATERIALS AND METHODS

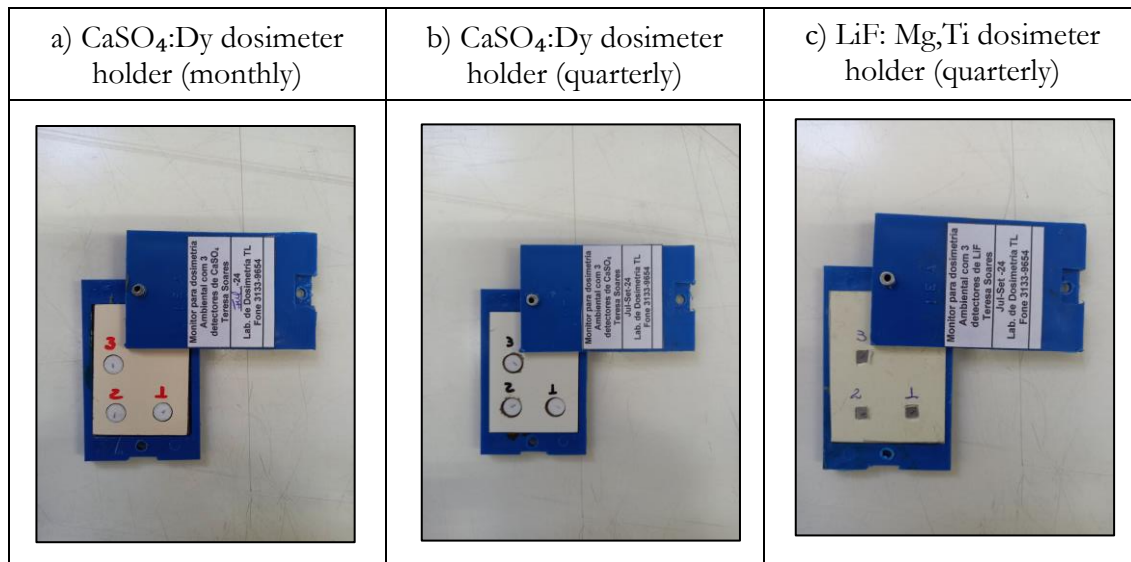
2.1. Materials

The study employed $\text{CaSO}_4\text{:Dy}$ and LiF:Mg,Ti detectors, each with specific requirements. $\text{CaSO}_4\text{:Dy}$ offers high sensitivity to gamma radiation but requires controlled humidity storage due to its hygroscopic nature. LiF:Mg,Ti , although less sensitive, provides near tissue equivalence and reduced fading, making it a robust reference material. For both detectors, standard protocols were followed, including annealing prior to reuse, light-protected storage, and calibration with reference gamma fields (e.g., Cs-137), ensuring reliable and comparable results.

In this study, two thermoluminescent detectors were used: $\text{CaSO}_4\text{:Dy}$ pellets, monthly (Figure 1a) and quarterly (Figure 1b); and LiF:Mg,Ti pellets (Figure 1c). These detectors, which belong to CEMRI/IPEN and were provided for the present research, were placed in

a dosimeter holder, as shown in Figure 1. The $\text{CaSO}_4\text{:Dy}$ dosimeter holders have three types of filters: plastic, Pb with a hole, and total Pb. The LiF:Mg,Ti dosimeter holder has only plastic.

Figure 1 - Dosimeter holders used as supports for $\text{CaSO}_4\text{:Dy}$ and LiF:Mg,Ti pellets.



For the thermal treatment of the dosimetric detectors, the following equipment was used: Heatech muffle furnace, model 4814 – 1 (for both LiF:Mg,Ti and $\text{CaSO}_4\text{:Dy}$ detectors); and the Sterilifer surgery oven, model SX 1.0 DTME, used only for LiF:Mg,Ti . The irradiations were performed in the $\text{H}^*(10)$ quantity, using the Hopewell panoramic irradiator with a ^{137}Cs source, model SC 1015G, activity: 3.7×10^{10} Bq (1Ci). The equipment used for thermal treatment and irradiation belongs to CEMRI and the Radiation Technology Center (CTR), both part of IPEN.

2.2. Dosimeter preparation

The preparation of the detectors for field insertion followed the specific requirements of the dosimetric materials [16, 17, 18]. The detectors were given a pre-dose in the $\text{H}^*(10)$ quantity, using ^{137}Cs at 2mSv in the panoramic irradiator. After irradiation, the thermal treatment of the LiF:Mg,Ti pellets was performed in a muffle furnace at 400 °C for 1 hour,

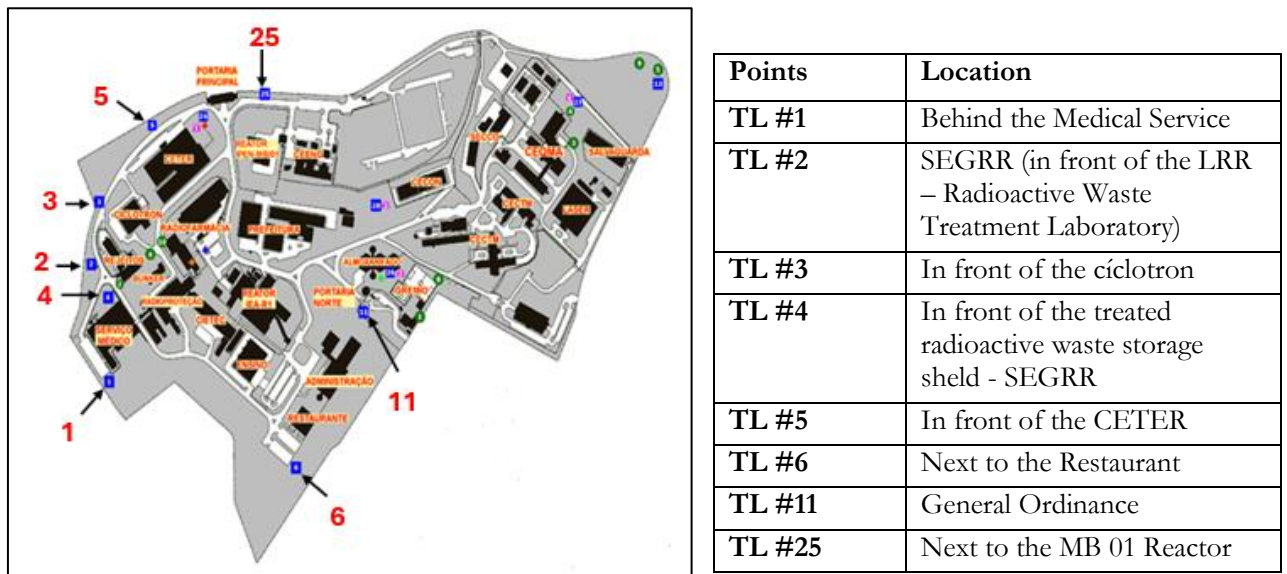
followed by a 100 °C temperature in an oven for 2 hours to stabilize the glow curve and reduce low-temperature peaks. The thermal treatment of the CaSO₄:Dy pellets was performed in a muffle furnace at a temperature of 340 °C for 1h.

2.3. Field deployment

After the preparation, the detectors were placed in dosimeter holders to be installed on the supports in the field.

The ERMP map at IPEN includes 13 environmental monitoring points. From these thirteen points, eight points (approximately 60%) were selected for field research monitoring [11], as shown in Figure 2.

Figure 2 – Geographical description of the field study points around the perimeter of the IPEN facilities



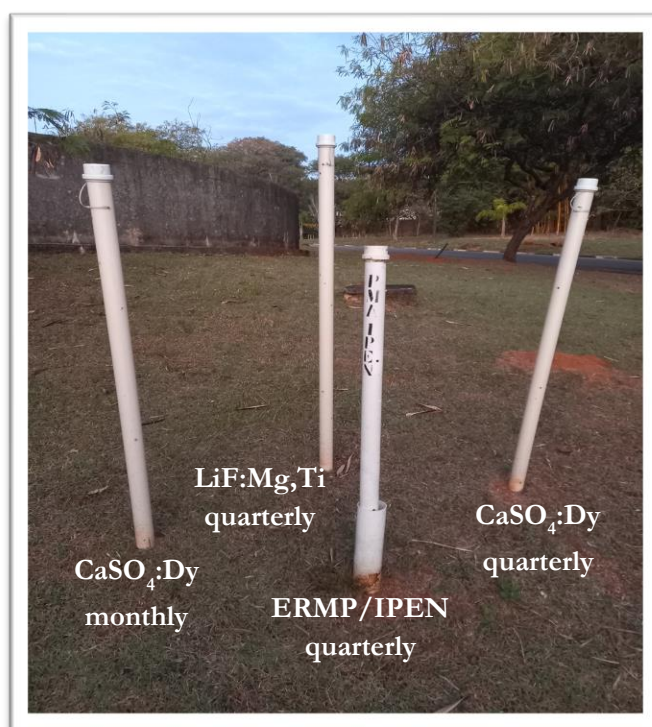
Source: Environmental Radiological Monitoring Program (ERMP) Evaluation Report from IPEN [5].

To collect the environmental monitoring data in the field, 24 (twenty-four) supports were installed, with 3 (three) supports for each of the 8 (eight) selected points. These supports were made from 5 cm diameter PVC pipes, and 1.30 meters in height. To allow air circulation inside the pipes, small holes of 0.5 mm in diameter were made along the entire length of the pipes.

The installation of the PVC pipes was carried out considering a distance of 15 cm from the pipe already installed by the Environmental Radiometry Sector/IPEN. For each point, three PVC pipes were installed, considering the monitoring of two TL $\text{CaSO}_4\text{:Dy}$ detector points for monthly and quarterly measurements, and one TL LiF:Mg,Ti detector point for quarterly measurements.

Figure 3 shows the supports for the dosimeter holders used in the field research for the $\text{CaSO}_4\text{:Dy}$ and LiF:Mg,Ti detectors.

Figure 3 - Supports for $\text{CaSO}_4\text{:Dy}$ and LiF:Mg,Ti dosimeter holders used in the field experiment.



2.4. Dosimeter evaluation

After the monthly and quarterly field periods, the dosimeter holders in the field were replaced for new measurements. The dosimeters collected from the field were then measured under a nitrogen gas flow. The readings of the LiF:Mg,Ti detectors were performed using

the Harshaw reader, model 4500 (manual type) [17], and the readings of the $\text{CaSO}_4\text{:Dy}$ detectors were performed using the Harshaw reader, model 5500 (manual type) [18].

For all experiments, a control dosimeter was kept in the shielding during the field period and was only removed when replacing the material in the field. The control dosimeter served to account for background radiation and potential handling contributions during field exposure and transportation.

The field research began in the October-December 2023 quarter for the $\text{CaSO}_4\text{:Dy}$ TL detectors (monthly and quarterly) and LiF:Mg, Ti (quarterly), concluding in the October-December 2024 quarter, totaling 5 quarters (15 months) for both detectors, distributed over the following periods, as shown in Table 1:

Table 1: Monitoring period of detectors in field research

Detector	Period	Measurements
$\text{CaSO}_4\text{:Dy}$ TL monthly	October/2023 to December/2024	15 moths
$\text{CaSO}_4\text{:Dy}$ TL quarterly	October/2023 to December/2024	5 quarters
LiF:Mg, Ti TL quarterly	October/2023 to December/2024	5 quarters

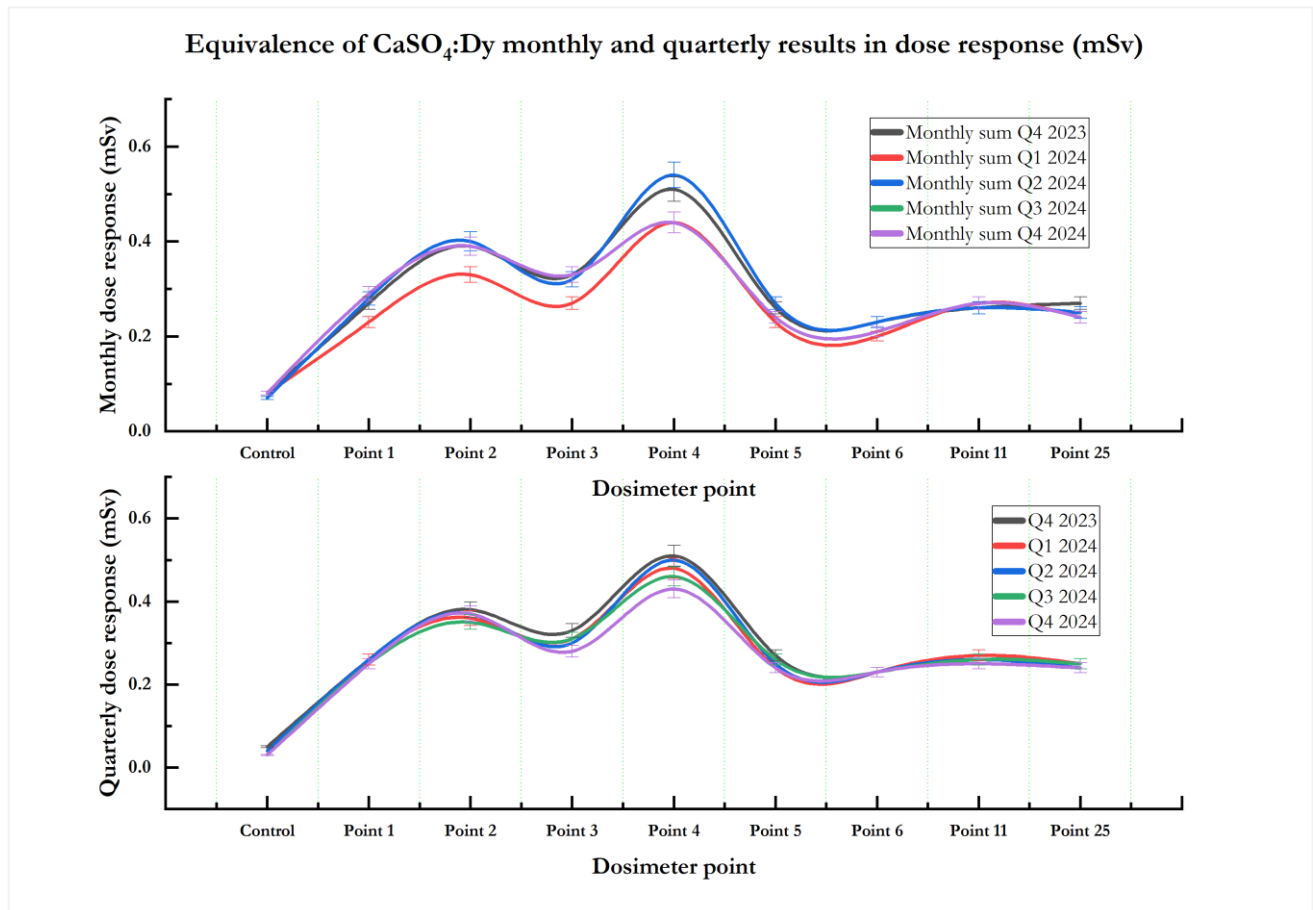
3. RESULTS AND DISCUSSIONS

3.1 Graphical presentation of data collected in the field research

The results present the monthly and quarterly dose responses, in mSv, for $\text{CaSO}_4\text{:Dy}$ and quarterly $\text{CaSO}_4\text{:Dy}$ and LiF:Mg, Ti detectors and $\text{CaSO}_4\text{:Dy}$ in the Field Research and in the IPEN's ERMP, collected at 8 (eight) points along the IPEN perimeter, during the period from October-December 2023 to October-December 2024, with material exchange and TL evaluation realized monthly and quarterly for the $\text{CaSO}_4\text{:Dy}$ detectors and quarterly for the LiF:Mg, Ti detectors.

Figure 4 shows the equivalence of the $\text{CaSO}_4\text{:Dy}$ monthly and quarterly results and the results of the quarterly $\text{CaSO}_4\text{:Dy}$ detector.

Figure 4 - Ambient dose equivalent values (mSv) with $\text{CaSO}_4\text{:Dy}$ detectors, collected monthly and quarterly results from October-December 2023 to October-December 2024.

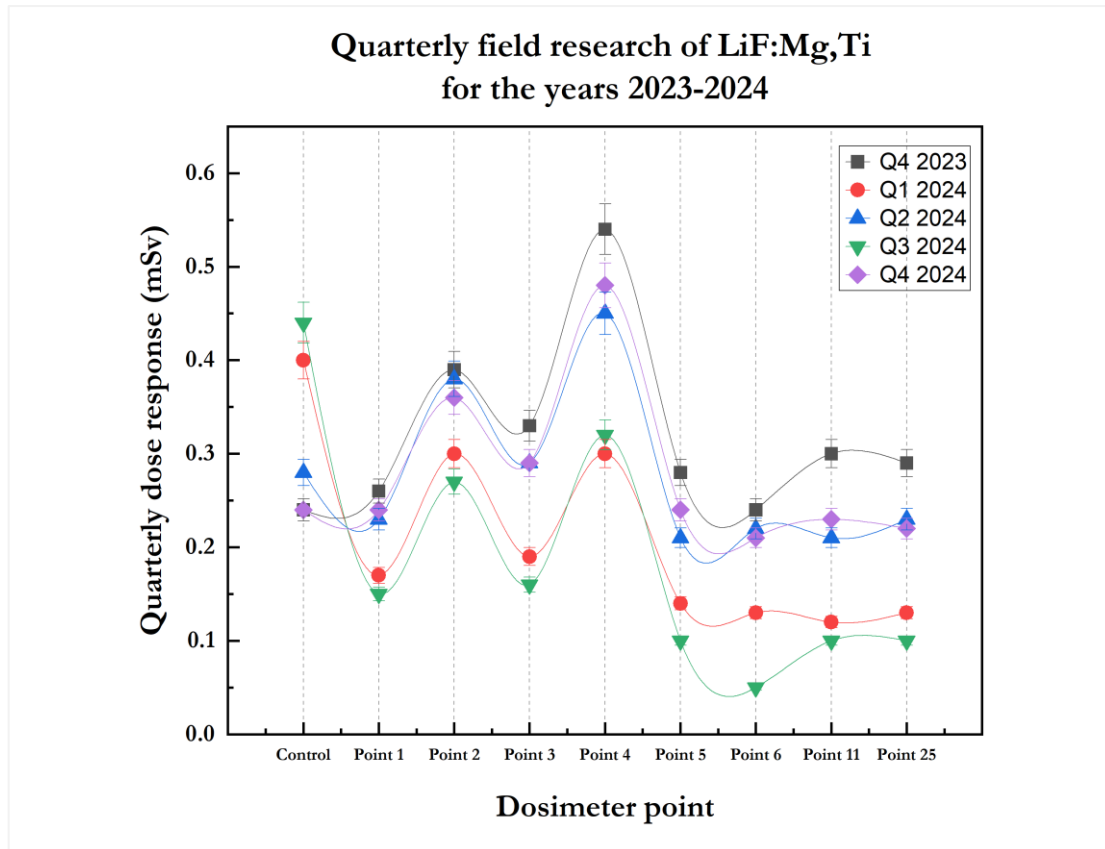


The results show that the monthly measurements of the $\text{CaSO}_4\text{:Dy}$ dosimeters are proportional to the results found in the quarterly $\text{CaSO}_4\text{:Dy}$ dosimeters.

The comparison between $\text{CaSO}_4\text{:Dy}$ monthly and quarterly measurements showed no statistically significant differences between the two aggregation methods. This addresses the proportionality question by confirming their statistical equivalence.

Figure 5 shows the results of the quarterly LiF:Mg,Ti detector.

Figure 5 – Ambient dose equivalent values (mSv) with LiF:Mg,Ti detectors, collected quarterly from October-December 2023 to October-December 2024.

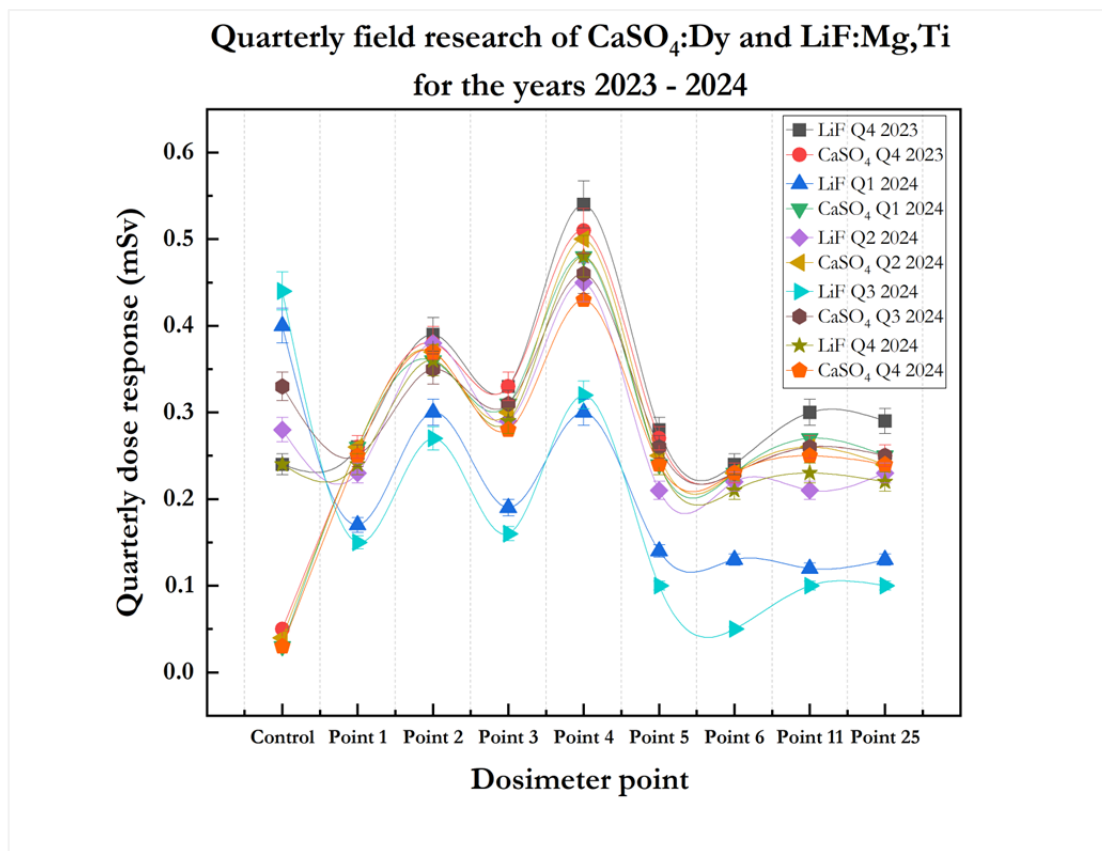


It can be observed that the dose values recorded in Q4/2023, Q2/2024, and Q4/2024 indicate equivalent results. Similarly, Q1/2024 and Q3/2024 also demonstrated comparable values; however, the measurements obtained during these periods were lower.

The field research compared $\text{CaSO}_4\text{:Dy}$ and LiF:Mg,Ti detectors under the same environmental conditions, with quarterly evaluations.

Figure 6 compares the quarterly monitoring results of the $\text{CaSO}_4\text{:Dy}$ and LiF:Mg,Ti detectors from October-December 2023 to October-December 2024.

Figure 6 – Ambient dose equivalent values (mSv) with the detectors $\text{CaSO}_4\text{:Dy}$ and LiF:Mg,Ti

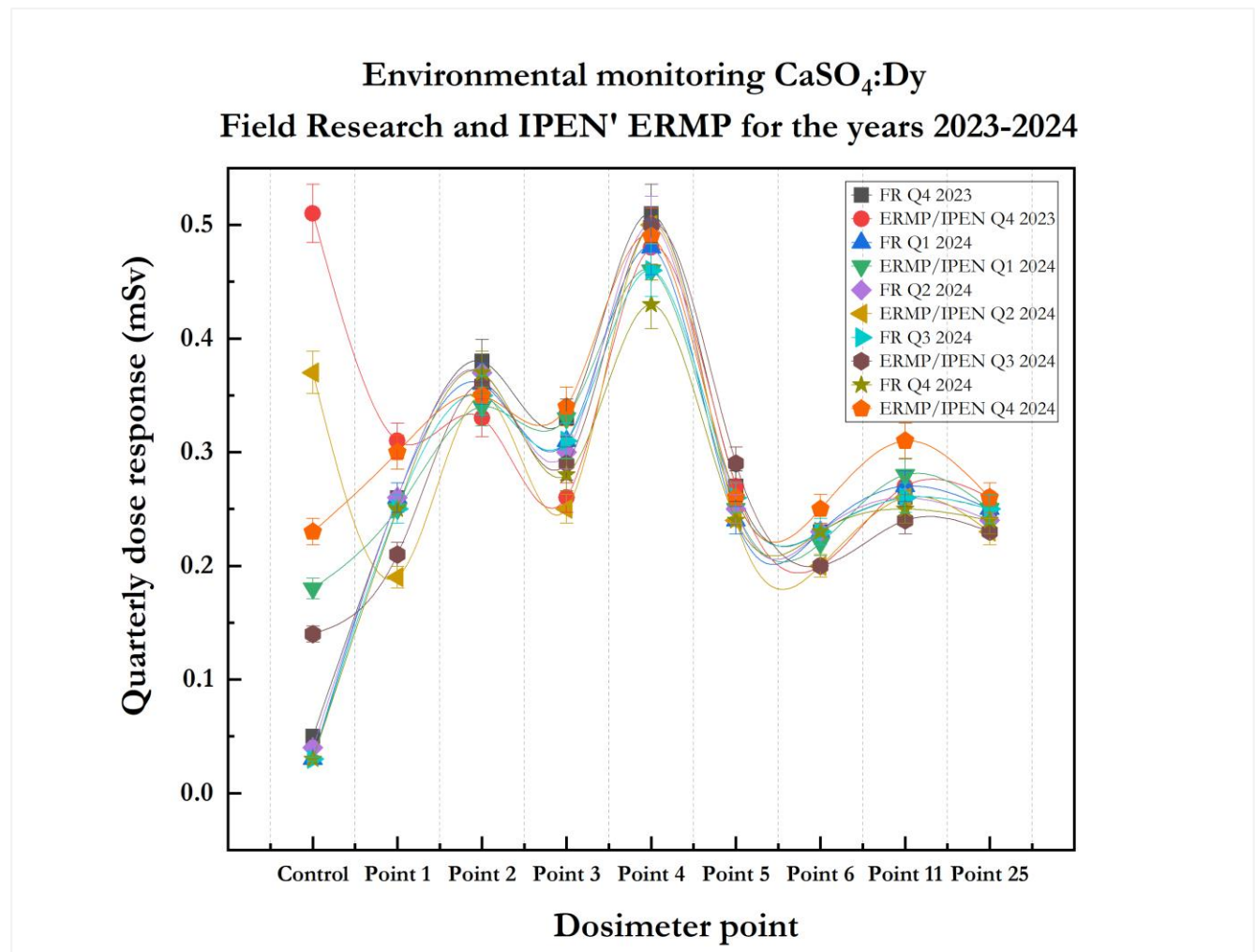


Point n° 4, located in front of the SEGRR (Storage Warehouse for Treated Radioactive Waste), is considered the point that presents the highest environmental dose for both tested detectors, a consequence of the storage of radioactive waste [19, 20, 21].

Two-way ANOVA methods indicated no statistically significant differences between the detectors for most quarters ($p > 0.05$), confirming that their responses can be considered equivalent within the limits of statistical uncertainty.

Figure 7 shows the Comparison between the monitoring results of the $\text{CaSO}_4\text{:Dy}$ detectors obtained in Field Research and in IPEN's ERMP.

Figure 7 – Ambient dose equivalent values (mSv) with data from the $\text{CaSO}_4\text{:Dy}$ dosimeters of the field research and the ERMP /IPEN, collected quarterly during the period from October 2023 to December 2024



The difference in values between the control dosimeter of the $\text{CaSO}_4\text{:Dy}$ detector from the field research and that of the ERMP of IPEN is due to logistical issues related to exchanging the dosimeter in the field and returning the control dosimeter to the appropriate shielding location. The control dosimeter of the field research remained in a shielded environment at all times, and its exchange schedule was managed exclusively by the researcher, ensuring consistency in handling and positioning. In contrast, the control dosimeter of IPEN's ERMP was under the responsibility of the Environmental Radiometry Sector, which follows its own operational schedule for dosimeter exchange and handling. Since this institutional

schedule is not under the researcher's control, minor differences in timing and logistics may occur between the two procedures, explaining the observed discrepancies.

3.2 Statistical analysis (significance): analysis of variance (ANOVA) methods and paired tests

The statistical analysis was conducted using the ANOVA method, as discussed by Choi et al. (2015), who highlighted its usefulness in evaluating uncertainties in experimental measurements [22]. The application of paired *t*-tests complemented the ANOVA method, allowing the detection of differences in specific periods (Choi et al., 2015) [22].

3.2.1 CaSO₄:Dy – Monthly and Quarterly measurements

ANOVA methods indicated no significant differences between methods ($p = 0.836$), across quarters ($p = 0.914$), or in their interaction ($p = 0.965$). However, paired *t*-tests revealed significant differences only in the 1st ($p = 0.0029$) and 2nd quarters of 2024 ($p = 0.0092$); no differences were found in the 4th quarter of 2023, 3rd and 4th quarters of 2024 ($p > 0.05$).

3.2.2 Detector comparison: CaSO₄:Dy and LiF:Mg,Ti

ANOVA methods revealed significant differences were observed between detectors ($p = 0.011$), across quarters ($p = 0.026$), and in their interaction ($p = 0.036$). Paired *t*-tests confirmed significant differences in the 4th quarter 2023 ($p = 0.021$), 1st ($p < 0.001$) and 3rd quarters 2024 ($p < 0.001$). While no significant differences were observed in the 2nd ($p = 0.491$) and 4th quarters 2024 ($p = 0.775$).

3.2.3 CaSO₄:Dy – Field Research (FR) and IPEN's ERMP

ANOVA indicated no overall differences between FR and ERMP ($p = 0.928$), across quarters ($p = 0.988$), or in their interaction ($p = 0.906$). Paired *t*-tests indicated significant differences only in the 2nd quarter of 2024 ($p = 0.031$) and the 4th quarter of 2024 ($p = 0.013$).

While no significant differences were observed in the 4th quarter 2023 ($p = 0.346$), 1st quarter 2024 ($p = 0.649$), and 3rd quarter 2024 ($p = 0.086$), all presenting $p > 0.05$.

3.3 Uncertainty Analysis

Measurement uncertainty analysis is fundamental for quantifying the reliability of a result. This study followed the principles of the Guide to the Expression of Uncertainty in Measurement (GUM) (JCGM 100:2008) [23] and complementary guidance provided by Farrance and Frenkel (2012) [24] and EURACHEM/CITAC (2012) [25], further supported by the IAEA recommendations on uncertainty evaluation in nuclear analytical measurements (IAEA TECDOC-1401, 2015) [26] and by the ISO 4037-1:2019 standard for radiological protection [27].

3.3.1 $\text{CaSO}_4\text{:Dy}$ for Monthly and Quarterly Sums

The calculations determine the uncertainties for the "monthly sum of the quarter" and "quarterly" measurements. For this analysis, we considered all 8 measurement points over 5 quarters, for a total of 40 measurements for each method.

Table 2 summarizes the mean readings, Type A and Type B uncertainties, combined uncertainty, and expanded uncertainty ($k = 2$).

Table 2 – Summary of analysis $\text{CaSO}_4\text{:Dy}$ for Monthly and Quarterly Sums

Method	Mean of Readings (mSv)	Type A Uncertainty (uA) (mSv)	Type B Uncertainty (uB) (mSv)	Combined Uncertainty (uc) (mSv)	Expanded Uncertainty (U) (mSv)
Sum	0.296	0.0139	0.0059	0.0151	0.0302
Quarterly	0.285	0.0139	0.0057	0.0150	0.0300

The analysis indicated that both methods have very similar uncertainties, of monthly sum (0.0302) and quarterly (0.0300), with the "Quarterly" method showing a slightly lower combined and expanded uncertainty.

3.3.2 CaSO₄:Dy and LiF:Mg,Ti

The calculations determine the uncertainties for the quarterly measurements. For the analysis, data from all points and quarters were used for both detectors. For each detector, $n = 40$ measurements (8 points $\times$ 5 quarters).

Table 3 summarizes the mean readings, Type A and Type B uncertainties, combined uncertainty, and expanded uncertainty ($k = 2$).

Table 3 – Summary of uncertainty analysis for CaSO₄:Dy and LiF:Mg,Ti detectors

Detector	Mean Reading (mSv)	Type A Uncertainty (uA) (mSv)	Type B Uncertainty (uB) (mSv)	Combined Uncertainty (uc) (mSv)	Expanded Uncertainty (U) (mSv)
LiF:Mg,Ti	0.263	0.0155	0.0053	0.0164	0.0328
CaSO ₄ :Dy	0.314	0.0136	0.0063	0.0150	0.0300

Source: Author

Expanded uncertainties were CaSO₄:Dy (0.0300) and LiF:Mg,Ti (0.0328), indicating slightly better consistency for CaSO₄:Dy.

Based on this analysis, the CaSO₄:Dy detector presented slightly lower combined and expanded uncertainties, suggesting marginally more consistent and reliable performance, considering the assumptions adopted for Type B uncertainty.

3.3.3 CaSO₄:Dy in Field Research (FR) and IPEN's ERMP

The calculations determined the uncertainties for the CaSO₄:Dy detector used in the Field Research (FR) and Environmental Radiological Monitoring Program (ERMP) of IPEN. For this analysis, all points and quarters were considered. For each set of measurements (FR and IPEN's ERMP), we have $n = 40$ measurements (8 points $\times$ 5 quarters).

Table 4 summarizes the mean readings, Type A and Type B uncertainties, combined uncertainty, and expanded uncertainty ($k = 2$).

Table 4 – Summary of uncertainty analysis for CaSO₄:Dy in Field Research (FR) and IPEN's PMRA

Measurements	Mean Reading (mSv)	Type A Uncertainty (uA) (mSv)	Type B Uncertainty (uB) (mSv)	Combined Uncertainty (uc) (mSv)	Expanded Uncertainty (U) (mSv)
PC	0.317	0.0148	0.0063	0.0161	0.0322
IPEN's ERMP	0.285	0.0109	0.0057	0.0123	0.0246

Based on this analysis, the IPEN's ERMP measurements (0.0246) presented lower combined and expanded uncertainties than those from Field Research (FR) measurements (0.0322).

The comparison between CaSO₄:Dy monthly and quarterly measurements showed no overall differences according to ANOVA, although paired t-tests revealed statistically significant discrepancies in the 1st and 2nd quarters of 2024. This indicates that while both aggregation methods are generally equivalent, specific periods may be influenced by additional sources of variability.

We observed that the numerical differences between points fell well within the combined expanded uncertainty of the measurements ($k = 2$), and thus, they cannot be interpreted as true variations.

The lower values in Q1 and Q3/2024 may be attributed to seasonal environmental factors such as rainfall and humidity variations, which can affect detector response

When comparing the two TLD detectors, CaSO₄:Dy and LiF:Mg,Ti, the two-factor ANOVA revealed significant differences both between detectors ($p = 0.011$) and across quarters ($p = 0.026$), with an interaction effect ($p = 0.036$) confirming that the detector response varied over time. Paired t-tests confirmed significant differences in the 4th quarter of 2023 and the 1st and 3rd quarters of 2024, whereas no differences were found in the 2nd and 4th quarters of 2024. Similarly, the comparison between CaSO₄:Dy results from the Field Study (PC) and IPEN's ERMP showed overall agreement, though paired tests detected

discrepancies in the 2nd and 4th quarters of 2024, likely reflecting environmental or operational factors.

The uncertainty analysis demonstrated that both detectors yielded low uncertainties suitable for environmental monitoring, but $\text{CaSO}_4\text{:Dy}$ exhibited slightly lower combined and expanded values compared to LiF:Mg,Ti . Although this improvement is marginal, it may become relevant in long-term monitoring programs, where consistency and reliability are critical. Taken together, these results confirm the robustness of the monitoring framework while emphasizing that detector selection remains essential to minimize variability and ensure accuracy under real field conditions.

4. CONCLUSIONS

The field research enabled a comprehensive evaluation of environmental monitoring around the IPEN perimeter using two thermoluminescent detectors: $\text{CaSO}_4\text{:Dy}$ and LiF:Mg,Ti . Although these detectors differ in sensitivity and response characteristics, both proved suitable for environmental dosimetry.

A rigorous analytical framework was applied, combining statistical tests (ANOVA and paired t-tests) with a comprehensive evaluation of uncertainties, including Type A, Type B, combined, and expanded uncertainties. This integrated approach provided dual validation: while ANOVA and paired comparisons confirmed equivalence in most cases and identified detector-specific differences in others, the uncertainty analysis demonstrated that all discrepancies remained within the expanded uncertainty limits ($k = 2$). Together, these methods ensured that the monitoring results are statistically and metrologically robust.

Overall, the findings demonstrated that both detectors provide consistent monitoring trends, although seasonal or operational factors can differentially influence their responses. $\text{CaSO}_4\text{:Dy}$ presented slightly lower combined and expanded uncertainties, suggesting

marginally greater stability under field conditions. Furthermore, the close agreement between the Field Research (FR) results and IPEN's ERMP using $\text{CaSO}_4:\text{Dy}$ reinforces the reliability of the monitoring framework.

Therefore, this study highlights the importance of integrating statistical and uncertainty analyses in environmental dosimetry. Such an approach strengthens confidence in the results, supports evidence-based conclusions, and emphasizes that optimizing detector selection is crucial for improving accuracy, minimizing variability, and enhancing the effectiveness of environmental radiation monitoring programs.

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CONFLICT OF INTEREST

All authors declare that they have no conflicts of interest.

REFERÊNCIAS

- [1] ICRP, INTERNATIONAL COMMISSION ON RADIATION PROTECTION. ICRP Publication 26. 1977 *Recommendations of the International Commission on Radiological Protection*. Annals of the ICRP, v. 1, n. 3, Pergamon Press, Oxford, 1977.
- [2] ICRP, INTERNATIONAL COMMISSION ON RADIATION PROTECTION. ICRP Publication 60, 1990 *Recommendations of the International Commission on Radiological Protection*, Bethesda, 1990.
- [3] ICRP, INTERNATIONAL COMMISSION ON RADIATION PROTECTION. ICRP Publication 103, *Recommendations of the International Commission on Radiological Protection*. ICRP Publication 103, Bethesda, 2011.
- [4] ICRP – INTERNATIONAL COMMISSION ON RADIOLOGICAL PROTECTION. *Compendium of Dose Coefficients based on ICRP Publication 60*. ICRP Publication 119. *Annals of the ICRP*, v. 41, suplemento, 2012.
- [5] ICRP – INTERNATIONAL COMMISSION ON RADIOLOGICAL PROTECTION. *Protection of the Environment under different Exposure Situations*. ICRP Publication 124. *Annals of the ICRP*, v. 43, n. 1, 2014.
- [6] ICRP – INTERNATIONAL COMMISSION ON RADIOLOGICAL PROTECTION. *Radiological Protection of People and the Environment in the Event of a Large Nuclear Accident (update of Publications 109 & 111)*. ICRP Publication 146. *Annals of the ICRP*, v. 49, n. 4, 2020.
- [7] IAEA - INTERNATIONAL ATOMIC ENERGY AGENCY (IAEA). *Radiation Protection of the Public and the Environment*. Safety Guide GSG-8. Vienna: IAEA, 2018.
- [8] IAEA - INTERNATIONAL ATOMIC ENERGY AGENCY (IAEA). *Regulatory Control of Radioactive Discharges to the Environment*. Safety Guide GSG-9. Vienna: IAEA, 2018.

- [9] IAEA - INTERNATIONAL ATOMIC ENERGY AGENCY (IAEA). *Prospective Radiological Environmental Impact Assessment for Facilities and Activities*. Safety Guide GSG-10. Vienna: IAEA, 2018.
- [10] CNEN, COMISSÃO NACIONAL DE ENERGIA NUCLEAR. NN 3.01: “Requisitos Básicos de Radioproteção e Segurança Radiológica de Fontes de Radiação”. Rio de Janeiro, 2024.
- [11] IPEN, INSTITUTO DE PESQUISAS ENERGÉTICAS E NUCLEARES, Laboratório de Radiometria Ambiental, Relatório de avaliação do Programa de Monitoração Radiológica Ambiental, São Paulo, 2021
- [12] ICRU, INTERNATIONAL COMMISSION ON RADIATION UNITS - ICRU Publication 85. *Fundamental Quantities and Units for Ionizing Radiation*. ICRU 85, Journal of the ICRU, 2011.
- [13] CAMPOS, L. L. Termoluminescência de materiais e sua aplicação em dosimetria da radiação. *Cerâmica* [online]. 1998, v. 44, n. 290, p. 244-251. disponível em: <<https://doi.org/10.1590/s0366-69131998000600007>>.
- [14] ALMEIDA FILHO, F. A.; CAMPOS, L. L., Dosimetry as a qualification and protection factor in the veterinary area - original text. *Revista Científica de Medicina Veterinária* - ISSN 1679-7353 Ano XVII – n. 34 – janeiro de 2020 – Periódico Semestral.
- [15] SILVA, A. M. B.; SOUZA, L. F.; ANTONIO, P. L.; JUNOT, D. O.; CALDAS, L. V. E.; SOUZA, D. N. Effects of manganese and terbium on the dosimetric properties of CaSO₄. *Radiation Physics and Chemistry*, v. 198, p. 110207, 2022.
- [16] IEC, INTERNATIONAL ELECTROTECHNICAL COMMISSION. *Radiation protection instrumentation dosimetry systems with integrating passive detectors for individual, workplace and environmental monitoring of photon and beta radiation*. Geneva: IEC; IEC 62387; 2020.
- [17] HARSHAW-BICRON. Model 4500 TLD Workstation Operator’s “Manual”, Publication N° 4500-0-0-0598-002, Saint-Gobain Industrial Ceramics, Ohio, USA, 1998.

- [18] HARSHAW-BICRON, Radiation Measurement Products, Operator's Manual, model 5500 automatic TLD Reader. Publication no. 5500-0-0-0399-001. Saint Gobain Industrial Ceramics Corporation, Ohio, USA, 1999.
- [19] KODAMA, Y.; MANZOLI, J.E.; RELA, P.R. TLD area monitoring on the small size industrial irradiator facility. International Nuclear Atlantic Conference (INAC), 2014.
- [20] MONTEIRO, I. H. T. S. *Determination of environmental and occupational gamma dose rates resulting from the presence of RDS-111 and the radioactive waste repository at IEN/CNEN*. 2005. Dissertation (Master's Degree) – Federal University of Rio de Janeiro, RJ, Brazil.
- [21] NUNES, M.G; CAMPOS, L.L. Study of CaSO₄:Dy and LiF:Mg,Ti detectors TL response to electron radiation using a SW Solid Water phantom. Radiation Measurements, v.43, p. 459-462, 2008.
- [22] CHOI, J. O.; NAM, G. H.; KIM, B. J. A thought on uncertainty evaluation using ANOVA. *Accreditation and Quality Assurance*, v. 20, p. 335-341, 2015. DOI: 10.1007/s00769-015-1172-x.
- [23] JCGM - JOINT COMMITTEE FOR GUIDES IN METROLOGY. *Evaluation of Measurement Data — Guide to the Expression of Uncertainty in Measurement (GUM)*. JCGM 100:2008. Sèvres: Joint Committee for Guides in Metrology, 2008. Disponível em: https://www.bipm.org/documents/20126/2071204/JCGM_100_2008_E.pdf.
- [24] FARRANCE, I.; FRENKEL, R. Uncertainty of Measurement: A Review of the Rules for GUM. *Journal of Research of the National Institute of Standards and Technology*, v. 117, p. 95-109, 2012. DOI: 10.6028/jres.117.004.
- [25] EURACHEM/CITAC. *Quantifying Uncertainty in Analytical Measurement (QUAM:2012.P1)*. 3. ed. Teddington: Eurachem, 2012. Disponível em: https://www.eurachem.org/images/stories/Guides/pdf/QUAM2012_P1.

- [26] IAEA - INTERNATIONAL ATOMIC ENERGY AGENCY. *Quantifying Uncertainty in Nuclear Analytical Measurements*. IAEA TECDOC-1401. Vienna: IAEA; 2015. Available from: https://www-pub.iaea.org/MTCD/Publications/PDF/te_1401_web.
- [27] INTERNATIONAL ORGANIZATION FOR STANDARDIZATION. *ISO 4037-1:2019. Radiological Protection — X and Gamma Reference Radiation for Calibrating Dosimeters and Doserate Meters. Part 1: Radiation characteristics and production methods*. Geneva: ISO, 2019.

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