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Environmental Radiation Dose and Radiological Risk Assessment around a Cobalt-60 Gamma Irradiation Facility using Optically Stimulated Luminescence Dosimetry

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ABSTRACT

This study assessed environmental radiation dose and radiological risk around a cobalt-60 gamma irradiation facility in Abuja, Nigeria, using optically stimulated luminescence dosimeters (OSLDs) and survey-meter measurement. Twenty-five monitoring locations across five radiological areas/zones were monitored using OSLDs for 45 days. Accumulated OSLD doses were converted to annual effective doses (AEDs), while excess lifetime cancer risk (ELCR) and radiological hazard quotient (RHQ) were estimated. Ambient dose rates were als0 measured. One-way analysis of variance (ANOVA) compared AEDs among zones, while Pearson correlation examined the relationship between OSLD dose and survey-meter dose rate. Accumulated OSLD doses ranged from 0.080 to 0.210 mSv, averaging 0.124 ± 0.040 mSv. AEDs ranged from 0.649 to 1.703 mSv y^{-1}, with a mean of 1.006 ± 0.29 mSv y^{-1}. Survey-meter readings ranged from 0.129 to 0.230 µSv h^{-1}, averaging 0.162 ± 0.023 µSv h^{-1}. ELCR ranged from 0.930×10^{-3} to 2.444×10^{-3}, averaging $1.443 \pm 0.42 \times 10^{-3}$, while RHQ values ranged from 0.032 to 0.973, averaging 0.171 ± 0.281. ANOVA showed significant differences in AEDs among zones ($F(4, 20) = 3.99$, $p = 0.015$). Correlation between OSLD dose and survey-meter dose rate was weak, negative, and non-significant ($r = -0.213$, $p = 0.307$). Beyond routine monitoring, this study integrates passive dosimetry, direct measurements and risk indicators to characterise spatial environmental radiation and potential risks. The findings provide facility-specific baseline data, demonstrate the value of zone based monitoring and complementary dosimetric techniques, and offer a foundation for strengthening environmental surveillance and radiation protection planning at gamma irradiation facilities in Nigeria.

INTRODUCTION

Ionising radiation has become an important technological tool in industrial, medical, agricultural and food-related applications. Gamma irradiation is particularly useful because of the high penetrating power of gamma photons, which allows packaged and other materials to be treated without direct physical contact (Jildeh et al., 2021). Cobalt-60 remains one of the principal radionuclides used for gamma irradiation because of its suitable photon energies, high penetration capability and established use in industrial irradiation facilities (Mortuza et al., 2018; Jildeh et al., 2021). Gamma irradiation has been wifely applied in food preservation and safety, sterilization of medica and pharmaceutical products, and agricultural applications such as microbial control, pest management and shelf-life extension (Jildeh et al., 2021; Mshelia et al., 2023; Munir & Federighi, 2020). Despite these benefits, the operation of facilities containing high activity radioactive sources requires effective radiation protection programmes to minimise occupational and environmental radiation exposure.

The operation of facilities containing high activity radioactive sources presents distinctive radiation protection challenges because radiation fields may extend beyond the immediate source location, depending on source activity, shielding configuration, facility geometry and operational conditions (El-Quardi et al.,

2023; Majer et al., 2024). Although industrial irradiation facilities incorporate engineered safety provisions such as biological shielding, source storage arrangements, interlock systems, access controls and administrative measures, radiation protection cannot rely exclusively on facility design (Ahmed et al., 2022; Adriel et al., 2025). The effectiveness of these protective measures must be periodically evaluated through appropriate radiation monitoring to identify changes in radiation fields and possible weaknesses in shielding or operational safety arrangements. Consequently, environmental radiation monitoring constitutes an important component of the radiation protection programme of industrial gamma irradiation facilities (James et al., 2022; Majer et al., 2024).

Optically stimulated luminescence dosimetry (OSLD) provides an established passive technique for measuring accumulated ionising radiation exposure. OSL dosimeters store radiation-induced energy within their sensitive material and release part of this stored energy as luminescence when exposed to optical stimulation. The emitted light is subsequently measured to estimate the accumulated radiation dose. Their sensitivity, stability and relatively simple readout and ability to provide integrated dose measurements make them useful for radiation protection, environmental monitoring and other applications requiring passive dosimetric assessments (Yukihara et al., 2022; Yang et al., 2024). In particular aluminium oxide doped with carbon ($Al_2 O_3$:C) has demonstrated favourable dosimetric characteristics for environmental photon measurements.

Previous investigations have established the suitability of OSLDs for environmental radiation assessment. Timilsina and Gesell (2011) evaluated OSL dot dosimeters for environmental monitoring and reported good reproducibility and stability under laboratory and field conditions. Earlier investigations also demonstrated the suitability of $Al_2 O_3$:C for environmental photon-dose measurements and its application in residential environments and low-level environmental radiation monitoring (Bøtter-Jensen et al., 1999; Imatoukene et al., 2008; Klein et al., 2011). Similarly, Kobayashi et al., (2004) demonstrated the application of OSLDs deployed indoors and outdoors for estimating ambient environmental radiation doses over repeated three-month monitoring periods in Japan. Similar investigations have also been conducted in Nigeria. For instance, Ewuga et al., (2025) investigated the spatial distribution of natural gamma radiation dose rates in mining areas of Nasarawa state using in-situ measurements and geospatial mapping techniques. Their findings demonstrated the importance of spatial characterisation in identifying variations in environmental gamma radiation exposure and establishing location-specific radiological baselines. More recent investigations have continued to examine the dosimetric characteristics, sensitivity, stability, and performance of OSLDs, highlighting the importance of appropriate calibration and response characteristics for reliable dose measurements (Scott et al., 2024). Although these studies provide an important foundation for environmental OSL dosimetry, their findings do not fully address the specific radiation protection challenges associated with high activity industrial gamma irradiation facilities. Much of the earlier research concentrated on dosimeter performance, environmental background radiation and measurements in residential or general outdoors environments rather than the characterisation of radiation fields surrounding operational Co-60 irradiation installations. These environments differ considerably in terms of source activity, photon emission characteristics, shielding arrangements, source storage configurations and operational conditions. Furthermore, conventional environmental monitoring approaches maybe limited when they rely exclusively on either passive dosimetry or instantaneous dose rate measurements.

Although OSLD technology has been investigated in several countries, published literature involving OSLD in Nigeria have predominantly focused on medical dosimetry and related radiation protection applications rather than environmental monitoring around industrial gamma irradiation facilities (Ilupeju et al., 2022; Pada et al., 2025; Ilupeju et al., 2026). Consequently, facility-specific environmental radiation data for a Co-60 gamma irradiation facility in Nigeria remain limited. This represents an important gap because radiation exposure characteristics are influenced by local facility conditions, including radioactive source activity, shielding effectiveness, building configurations, operational practices and surrounding environment. A comprehensive assessment therefore connects measured environmental dose and ambient dose rates with appropriate radiological exposure and risks indicators to provide a better understanding of potential exposure conditions.

The present study therefore assessed environmental radiation dose and associated radiological risk around a panoramic, wet storage Co-60 gamma irradiation facility in Abuja, Nigeria, using optically stimulated luminescence dosimeters (OSLDs) to determine accumulated environmental radiation doses and a calibrated survey meter to measure the ambient dose rates at the different location to characterise the spatial distribution of radiation within the facility.

MATERIALS AND METHODS

Study Area, Design and Monitoring Locations

A facility-based environmental radiation monitoring study was conducted at the cobalt-60 gamma irradiation facility located in Sheda, Abuja, Nigeria. It is a category IV panoramic wet storage source. The study was

designed to characterize environmental radiation levels across different areas/zones of the facility and its surroundings. Twenty-five monitoring locations were selected to represent different area classifications and levels of accessibility. The locations included controlled areas, supervised areas, surveillance areas, general facility areas and locations outside the facility boundary (public areas). The controlled locations included the irradiation chamber, control room, E-room, water treatment plant, technical equipment room, CO_2 room, sample elevator room, PED and ceiling plug. Supervised locations included the production halls, workshop and product routes. The surveillance locations included the dosimetry laboratory, physico-chemical laboratory, Director's Office and conference room. General facility locations comprised the store/administration area, porters' lodge and generator house, while four external locations represented the north, south, east and west outside the facility boundary. The description, classification, locations, and OSLD identification codes are summarised in Table 1.

Table 1: Description and Classification of Environmental Radiation Monitoring Locations Within and Around the Cobalt-60 Gamma Irradiation Facility

Area Classification	Description	Location	Location Code	OSLD Bar Code
Controlled	Immediate vicinity of the Co-60 source; access restricted to authorized radiation workers during operation	Irradiation Chamber	IRC	EX00083683I
		Control Room	COR	EX00083693H
		E-Room	ERM	EX00093718D
		Water Treatment Plant	WTP	EX00093767A
		Technical Equipment Room	TER	EX00083870L
		CO_2 Room	CO2	EX00083657D
		Sample Elevator Room	SER	EX00083709C
		PED	PED	EX00083805I
		Ceiling Plug	CEP	EX000836599
Supervised	Adjacent to controlled areas; access permitted but monitored	Production Hall East	PHE	EX000836797
		Production Hall West	PHW	EX00083726G
		Workshop	WKP	EX00083721Q
		Product Entry Route	PNR	EX00083662M
		Product Exit Route	PXR	EX00083684G
Surveillance	Buffer zone between facility and public boundary	Dosimetry Laboratory	DOL	EX00083671N
		Physico-Chemical Lab	PCL	EX000837688
		Director's Office	DIO	EX00083675F
		Conference Room	CON	EX00083706I
General	Facility perimeter, accessible to non-radiation staff	Store Administration	STA	EX00083728C
		Porters Lodge	POL	EX00083710T
		Generator House	GEN	EX00083673J
Public	Areas beyond facility boundary accessible to the general public	North Outside	NOO	EX00083663K
		South Outside	SOO	EX000836789
		East Outside	EAO	EX00083800S
		West Outside	WEO	EX000836979

OSL Dosimetry

Environmental dose at each location was measured using nanodot Al_2O_3:C optically stimulated luminescence dosimeters (Landauer Inc.), placed at fixed positions for a continuous 45-day monitoring period. Each OSLD was assigned a unique identification/barcode corresponding to its monitoring location. The dosimeters were positioned at representative locations within each area to obtain integrated measurements of environmental radiation exposure. At the end of the monitoring period, the dosimeters were retrieved and read using a Landauer microStar reader operated in continuous-wave OSL (CW-OSL) mode, in which the dosimeter is illuminated with constant-intensity stimulation light while the resulting luminescence, proportional to absorbed dose, is recorded by a photomultiplier tube (Nanto & Okada, 2023; Choi et al., 2020). The Al_2O_3:C detector was selected for its high sensitivity, dose-response linearity over the range relevant to environmental monitoring, and negligible fading at room temperature, properties that make it well suited to long integration periods (Nanto & Okada, 2023). The accumulated radiation dose was recorded in millisieverts (mSv). The measured dose for each location was subsequently used to estimate the annual effective dose.

Survey-Meter Measurements

Instantaneous ambient radiation dose rates were measured at the same monitoring locations using a calibrated radiation survey meter. Measurements were recorded in μSvh^{-1}. Unlike the OSLD measurements, which represented cumulative exposure during monitoring period, survey-meter measurements represented the radiation dose rate at the specific time at which the measurement was performed**.**

Annual Effective Dose (AED)

The 45-day accumulated dose recorded by each OSLD (D_{45}, in mSv) was extrapolated to an annual effective dose (AED, in mSv/y) assuming a constant average exposure rate over the year, using the relation:

$$AED = (D_{45} / 45) \times 365 \quad (1)$$

The extrapolation of the 45-day accumulated OSLD measurements to annual effective dose was based on the assumption that the average radiation exposure rate at each monitoring location remained reasonably constant over the annual assessment period. This assumption was considered appropriate for estimating the annual exposure under relatively stable facility operational conditions, given the predictable radioactive decay characteristics of the sealed C0-60 source and the expectation of no substantial changes in shielding configuration or environmental exposure conditions during the assessment. The extrapolation represents an estimated annual dose rather than a directly measured annual exposure, and it recognises the potential influence of temporal variations in facility utilization, environmental background radiation and operational activities.

Excess Lifetime Cancer Risk (ELCR)

Excess lifetime cancer risk (ELCR) was estimated by multiplying the annual effective dose expressed in sieverts ($Sv\ y^{-1}$) by the assumed duration of working/exposure in years and the lifetime fatal cancer risk coefficient. A lifetime fatal cancer risk coefficient of $4.1 \times 10^{-2}\ Sv^{-1}$ was adopted in accordance with the risk coefficient used in the study. A working/exposure duration of 35 years was assumed for the calculation. The relationship was expressed as:

$$ELCR = AED\ (Sv) \times \text{duration of working life (years)} \times CR\ (Sv^{-1}) \quad (2)$$

The assumed occupational exposure duration of 35 years was adopted to represent a hypothetical long-term working lifetime for assessing the cumulative radiological risk associated with sustained occupational exposure. This assumption provides a standardised exposure period for estimating the potential lifetime implications of the annual radiation dose, under the condition that the estimated annual exposure remained reasonably representative throughout the assumed working period. Furthermore, the cancer risk coefficient of $4.1 \times 10^{-2}\ Sv^{-1}$ was adopted in accordance with the ICRP (2007) which recommends this nominal detriment-adjusted cancer risk for adult occupationally exposed workers aged 18-64 years. This coefficient was considered appropriate for the occupational component of this investigation.

Radiation Hazard Quotient (RHQ)

The radiation hazard quotient (RHQ) was adapted from the hazard quotient framework described by the National Research Council (NRC, 2007), in which an estimated exposure dose is compared with an appropriate reference dose. In this study, RHQ was calculated as the ratio of the annual effective dose (AED) to the applicable radiation dose reference value (RFD):

$$RHQ = \frac{AED}{RFD} \quad (3)$$

Where AED is the annual effective dose in mSv y^{-1} and RFD is the applicable reference dose for the area category. For occupationally exposed workers, 20 mSv y^{-1} was adopted as the occupational reference value, while 1 mSv y^{-1} was adopted for members of the public. The reference value was selected according to the area classification. An RHQ below unity indicates that the estimated annual dose is below the selected reference value. RHQ is interpreted as a comparative dose-to-reference ratio and should not be interpreted as a probability of adverse health effects (NRC 2007; 2009).

Statistical Analysis

Descriptive statistics (mean, standard deviation, minimum and maximum) were computed for accumulated dose, AED, survey-meter reading, ELCR and RHQ across the 25 monitoring locations. One-way analysis of variance (ANOVA) was performed to test whether mean AED differed significantly among the five radiological areas/zones (Controlled, Supervised, Surveillance, General and Public), with statistical significance set at $p < .05$. Where ANOVA indicated a statistically significant difference, pairwise comparisons were performed using Tukey's honestly significant difference (HSD) post hoc test. Pearson's correlation coefficient was computed between accumulated OSLD dose and the concurrent survey-meter reading to evaluate the association between cumulative and instantaneous dosimetry measurements. Statistical analyses were performed using IBM SPSS Statistics and Microsoft Excel.

RESULTS AND DISCUSSION

Environmental Radiation Dose Distribution

Environmental radiation measurements were obtained at 25 locations distributed across the controlled, supervised, surveillance, general facility and public areas. The spatial distribution of the Environmental

Radiation Dose and Radiological Risk indices across monitored locations is presented in Table 2. The result showed that the accumulated OSLD dose over the monitored period ranged from 0.080 to 0.210 mSv, with a mean of 0.124±0.040 mSv. The lowest accumulated dose was 0.080 mSv, recorded at locations STA and NOO. The highest dose was recorded at location DIO. This does not necessarily mean that location DIO represents a greater radiation hazard than the controlled irradiation area, rather it highlights the distinction between the radiation field magnitude at a particular time and integrated environmental exposure over an extended monitoring period. Further measurements involving detailed spatial dose mapping and repeated monitoring would be necessary to determine the specific cause. The results demonstrated relatively low environmental radiation levels across the 25 monitored locations, although measurable spatial differences existed within the facility. The observed spatial variation is consistent with the importance of dose mapping and spatial characterisation in gamma irradiation facilities. Previous investigations of cobalt-60 irradiation facilities have demonstrated that radiation dose distributions are strongly influenced by source geometry and shielding (Farah et al., 2006, Gual et al., 2019, Dridi et al., 2020). The four external monitoring points (NOO, SOO, EAO and WEO) recorded accumulated doses of between 0.080 and 0.120 mSv over the monitored period corresponding to an annual effective dose of approximately 0.649-0.973 $mSvy^{-1}$. These values suggest that the facility's shielding and source control arrangements were effective in limiting radiation fields at the monitored external locations during the study period.

The suitability of the OSLD for this type of monitoring is supported by previous studies such as Timilsina & Gesll (2011), where they independently evaluated OSL dosimeters for environmental monitoring and reported good reproducibility and stability under laboratory and field conditions and Kobayashi et al., (2004) also demonstrated that OSL dosimeters could be used to monitor environmental radiation over extended periods, including measurements conducted in indoor and outdoor environments.

Survey Meter Measurements

Survey-meter readings ranged from 0.129 to 0.230 μSvh^{-1}, with a mean of approximately 0.162±0.023 μSvh^{-1}. The highest instantaneous dose-rate measurement was recorded at the IRC (0.230 μSvh^{-1}). The lowest value was recorded at the DIO (0.129 μSvh^{-1}). The distribution demonstrates that the location with the highest instantaneous survey-meter reading was not the location with the highest cumulative OSLD dose. This difference provides an important basis for interpreting the correlation between the two measurement approaches. Figure 1 shows a comparison of the OSLD and Survey Meter Readings by Location.

Annual Effective Dose

The annual effective dose ranged from 0.649 to 1.703 $mSv\ y^{-1}$. The values associated with occupationally relevant monitoring locations were substantially below the occupational reference value of 20 $mSv\ y^{-1}$. The four external public monitoring locations recorded annual effective doses ranging from approximately 0.649 to 0.973 $mSv\ y^{-1}$, which remained below the 1 $mSv\ y^{-1}$ public dose limit. These results indicate that the measured doses at the monitored public locations were below the applicable public reference value during the monitoring period.

Excess Lifetime Cancer Risk

The calculated ELCR values ranged from approximately 0.930×10^{-3} to 2.444×10^{-3} with a mean of 1.443×10^{-3} ±0.42. The highest estimated value occurred at the location DIO, corresponding to the highest AED, while the lowest values were associated with locations having the lowest AEDs. These values indicate low estimated radiological risk.

Radiation Hazard Quotient

The calculated RHQ values ranged from 0.032 to 0.973, with a mean of 0.171 ± 0.281. All calculated RHQ values were below unity. Under the area-specific reference-dose assumptions adopted in this study; the results indicate that the estimated annual doses at the monitored locations were below their respective reference values. RHQ values should be interpreted as comparative dose-to-reference ratios rather than as direct probabilities of adverse health effects.

Comparative Analysis of Annual Effective Dose across Radiological Zones Using One-Way ANOVA

A one-way analysis of variance (ANOVA) was conducted to determine whether mean annual effective dose differed significantly among the five radiological zones: Controlled, Supervised, Surveillance, General and Public. The analysis revealed a statistically significant difference in mean annual effective dose across the zones, $F(4, 20) = 3.99$, $p = 0.015$, indicating that the mean dose was not equal across all five zones (Table 3). Subsequent post hoc analysis using Tukey's Honestly Significant Difference test identified statistically significant differences between the Surveillance and the Supervised zone, as well as between the Surveillance and Public zones (Table 4). These findings demonstrate spatial variability in the distribution of environmental radiation dose within and around the gamma irradiation facility. However, the observed differences should be interpreted alongside the applicable radiation protection reference levels, as

statistical significance does not necessarily indicate unacceptable exposure. The results nevertheless support the evaluation of radiation protection measures and environmental monitoring effectiveness.

Table 2: Environmental Radiation Dose and Radiological Risk Indices Across Monitored Locations

S/N	Location	Dose (D45) (mSv)	AED (mSvy^{-1})	Survey meter reading (uSvh^{-1})	ELCR (10^{-3})	RHQ
1	IRC	0.090	0.730	0.230	1.047	0.036
2	COR	0.180	1.460	0.167	2.095	0.073
3	ERM	0.160	1.298	0.199	1.862	0.065
4	WTP	0.090	0.730	0.167	1.047	0.036
5	TER	0.130	1.054	0.173	1.513	0.053
6	CO2	0.120	0.973	0.197	1.397	0.049
7	SER	0.100	0.811	0.158	1.164	0.041
8	PED	0.140	1.135	0.143	1.629	0.057
9	CEP	0.100	0.811	0.181	1.164	0.041
10	PHE	0.110	0.892	0.167	1.280	0.045
11	PHW	0.090	0.730	0.157	1.047	0.036
12	WKP	0.140	1.135	0.175	1.629	0.057
13	PNR	0.120	0.973	0.173	1.397	0.049
14	PXR	0.100	0.811	0.171	1.164	0.041
15	DOL	0.190	1.541	0.137	2.211	0.077
16	PCL	0.160	1.298	0.148	1.862	0.065
17	DIO	0.210	1.703	0.129	2.444	0.085
18	CON	0.140	1.135	0.156	1.629	0.057
19	STA	0.080	0.649	0.137	0.931	0.032
20	POL	0.160	1.298	0.143	1.862	0.065
21	GEN	0.100	0.811	0.139	1.164	0.041
22	NOO	0.080	0.649	0.154	0.931	0.649
23	SOO	0.090	0.730	0.137	1.047	0.730
24	EAO	0.100	0.811	0.154	1.164	0.811
25	WEO	0.120	0.973	0.154	1.397	0.973
Min		0.080	0.649	0.129	0.930	0.032
Max		0.210	1.703	0.230	2.440	0.973
mean±SD		0.124±0.04	1.006±0.29	0.162±0.023	1.443±0.42	0.171±0.281

Table 3: One-Way ANOVA Comparing Mean Annual Effective Dose Across Radiological Zones

Source of Variation	SS	Df	MS	F	P-value	F crit
Between Groups	0.015142	4	0.003786	3.99288	0.015357	2.866081
Within Groups	0.018962	20	0.000948			
Total	0.034104	24				

Note: Statistically significance was assessed at a = 0.03. a p-value below 0.05 indicates a statistically significant difference in mean annual effective dose among the radiological zones.

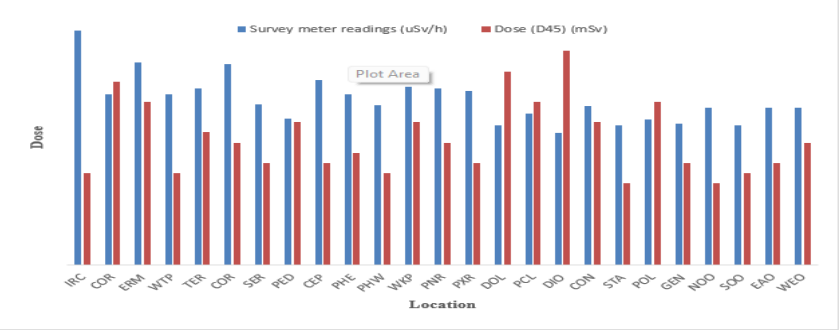


Figure 1: Comparison of OSLD and Survey Meter Readings Dose Across the Monitored Locations

Table 4: Tukey HSD Pairwise Comparisons of AED Across Radiological Zones

Comparison	Mean Diff.	q	p	Sig.
Controlled – Supervised	0.017	1.43	0.848	
Controlled – Surveillance	−0.052	3.95	0.075	
Controlled – General	0.010	0.69	0.988	
Controlled – Public	0.026	1.97	0.637	
Supervised – Surveillance	−0.069	4.72	0.024	*
Supervised – General	−0.007	0.46	0.997	
Supervised – Public	0.009	0.58	0.994	
Surveillance – General	0.062	3.71	0.104	
Surveillance – Public	0.078	5.03	0.015	*
General – Public	0.016	0.95	0.960	

Note. Sig. column marked with an asterisk (*) indicates $p < 0.05$

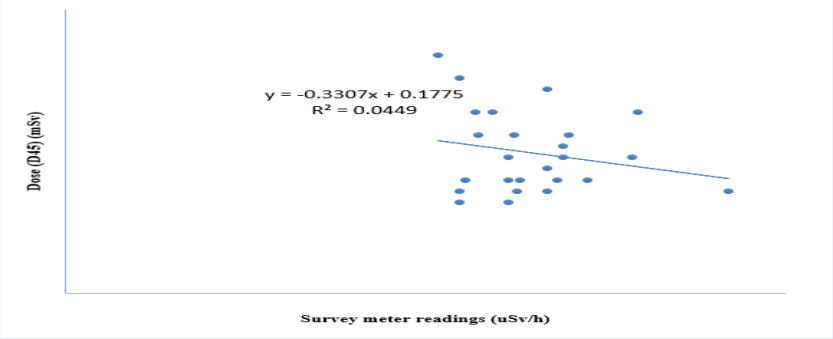


Figure 2: Relationship Between The OSLD Dose and Instantaneous Survey Meter Dose Rate

Correlation Between OSLD and Survey-Meter Measurements

Pearson correlation analysis demonstrated a weak, negative and statistically non-significant relationship between accumulated OSLD dose and instantaneous survey-meter dose rate ($r = -0.213$, $p = 0.307$). The result indicates that the two measurements did not show a statistically significant linear association during the monitoring period. The coefficient of determination was approximately $R^2 = 0.045$ as shown in Figure 2, indicating that only about 4.5% of the variability in the accumulated OSLD dose was linearly explained by the survey meter measurements. Therefore, instantaneous survey-meter measurements should not be regarded as reliable substitutes for integrated passive dosimetry when estimating cumulative environmental exposure

Table 5: Comparison of Environmental Radiation Monitoring Using OSL Dosimetry and Selected Gamma Irradiation Facility Dosimetry Studies

Study/ location	Radiation source/environment	Dosimeter/ measurement technique	Monitoring or measurement period	Reported dose	Main purpose
Present study- Abuja, Nigeria	Co-60 gamma irradiation facility and surrounding environment	OSLD+Calibrated survey meter	45 days	D_{45} 0.124 mSv mean dose. 0.162 μSvh^{-1} survey meter mean dose. 1.006 $mSvy^{-1}$ mean AED	Environmental radiation monitoring, spatial characterization and radiological risk assessment
Japan (Kobayashi et al., 2004)	Natural environmental radiation, indoor and outdoor	OSL dosimeters	Every 3 months, July 2001-june 2002	0.59 mSv annual average	Evaluation of OSLD for environmental radiation

	locations in Tokyo				monitoring
USA (Timilsina & Gesell, 2011)	Outdoor environmental radiation	OSL dosimeters: comparison with calibrated high-pressure ionisation ffchamber	Laboratory and field evaluation	OSLD dose capability reported from 0.05 mGy to 100 Gy: good reproducibility and stability	Independent performance evaluation of OSLD for environmental monitoring
Tunisia (Farah et al., 2006)	Co-60 semi-industrial gamma irradiation facility	Red/Amber Perspex and cellulose triacetate (CTA) dosimeters	Commissioning/irradiation experiments	Dose distributions, maximum/minimum absorbed doses, dose uniformity and isodose distributions were determined	Characterisation and commissioning of the irradiation facility
Bangladesh (Mortuza et al., 2018)	Co-60 gamma irradiation facility	Fricke and ceric cerous chemical dosimetry+MCNPX	Commissioning and dose mapping experiments	Dose mapping at tote-box and strategic wall positions: experimental measurement generally agreed with MCNPX results	Facility commissioning, dose mapping and Monte Carlo validation
Portugal (cavaco et al., 1991)	Industrial co-60 gamma irradiation facility	Red/Amber Perspex and CTA: Monte Carlo modelling	Commissioning and spatial dose measurement	Dose rate distributions and isodose curves: measurement compared with MCNP calculation	Facility commissioning and validation of radiation field characterisation

Comparison with published studies as shown in Table 5, shows that the present findings are consistent with the established application of OSL dosimetry for environmental radiation monitoring. From the table, international studies have demonstrated that OSL dosimeters provide stable, reproducible and sensitive measurements of low-level environmental radiation. The mean annual effective dose obtained in the present study was higher than the 0.59 mSv y^{-1} reported for natural environmental radiation in Japan; however, direct comparison should be interpreted cautiously because the present study was conducted within and around an operating Co-60 gamma irradiation facility, whereas the Japanese study primarily characterized natural environmental exposure. In contrast, much of the published literature concerning Co-60 irradiation facilities have concentrated on irradiation-cell characterization, product dose distribution, commissioning and Monte Carlo validation using Perspex, CTA or chemical dosimeters (Farah et al., 2006, Mortuza et al., 2018, Cavaco et al., 1991). The present study therefore complements the existing literature by applying passive OSL dosimetry specifically to integrated environmental monitoring across multiple facility area/zone classifications and external locations, while simultaneously incorporating calibrated survey-meter measurements and radiological risk indicators.

CONCLUSION

This study provides facility-specific evidence on environmental radiation levels around a ^{60}Co gamma irradiation facility in Abuja, Nigeria. By combining passive OSLD measurements with calibrated survey-meter measurements and radiological risk indicators, the study characterized both accumulated environmental dose and instantaneous dose rate at multiple monitoring locations. The findings indicate that environmental radiation levels at the monitored locations were relatively low during the study period. Occupationally

relevant annual effective doses were substantially below the occupational reference value, while the annual effective doses at the monitored public locations remained below the 1 mSv y^{-1} public dose limit. Statistically significant differences among zones indicate spatial variation in accumulated environmental dose. However, the weak and statistically non-significant correlation between OSLD dose and survey-meter dose rate suggest that the two measurements were significantly associated within the study data. This finding highlights the importance of interpreting passive dosimetry and instantaneous survey-meter measurements according to their respective measurements period.

Overall, the results are consistent with the effective radiation control during the study period. Periodic environmental monitoring, routine survey-meter measurements, instrument quality assurance, and continued evaluation of radiation protection measures are therefore recommended to identify changes in exposure conditions and sustain radiological protection of workers.

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