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Assessment of liquid radioactive waste characteristics and management practices in nuclear medicine facilities in Tanzania

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ABSTRACT

Residual liquids waste generated during nuclear medicine procedures may contain radioactive materials and toxic chemicals that pose potential risks to the environment and public health. This study assessed the physicochemical properties, radionuclide characteristics,, heavy metal concentrations and management practices of liquid radioactive waste generated at two major nuclear medicine facilities in Tanzania: Ocean Road Cancer Institute (ORCI) and Bugando Medical Centre (BMC). A cross-sectional study was conducted over eight days at ORCI and ten days at BMC. Approximately 735 mL of liquid waste was collected at each facility and combined into three composite samples per site. Radiation levels, physicochemical parameters, and heavy metal concentrations were measured using the APHA standard methods for the examination of water and wastewater. Heavy metal contamination was evaluated using the contamination factor, degree of contamination, pollution load index, heavy metal pollution index, and metal index. Results were compared against World Health Organization (WHO) guideline limits. Statistical differences between facilities were assessed using the Mann-Whitney U test, while radionuclide decay was modeled using exponential regression to estimate half-lives. The results indicated rapid radionuclide decay, with estimated half-lives of 0.62, 0.83, and 0.96 days for Tc-99m and Ga-68. Ambient radiation levels ranged from 0.15–0.75 µSv/h at ORCI and 0.38–0.85 µSv/h at BMC, with elevated readings observed in generator storage areas, hot laboratories, and gamma camera rooms also Gamma spectrometry revealed no detectable gamma-emitting radionuclides in the analyzed liquid radioactive waste samples. No significant differences in radiation levels were observed between the two facilities ($W = 11$, $p = 0.296$). ORCI effluents were acidic (pH 3.84 ± 0.67) with higher conductivity and TDS, while BMC effluents were near neutral (pH 7.09 ± 0.21) and exhibited higher salinity and turbidity. Concentrations of Cd, Ni, and Pb exceeded WHO limits at both sites, while Zn concentrations were significantly higher at BMC (5.98 ± 0.072 mg/L) compared to ORCI (0.87 ± 0.012 mg/L, $p < 0.001$). In conclusion, radiological risks associated with liquid waste from nuclear medicine facilities appear to be adequately controlled; however, chemical and heavy metal contamination remains a notable environmental concern. Radiological risks associated with liquid waste from routine monitoring, wastewater treatment practices, and strengthened regulatory oversight measures are recommended to mitigate these hazards.

Keywords: nuclear medicine, liquid radioactive waste, physicochemical parameters, heavy metals, environmental safety.

INTRODUCTION

Hospitals and healthcare facilities generate a wide variety of liquid wastes, including radioactive, chemical, and heavy metal contaminants, which can pose significant environmental and public health risks if not properly managed (Fatima et al., 2022; Sharma et al., 2025). In nuclear medicine departments, effluents often contain radiopharmaceutical residues, heavy metals from equipment, and chemicals used in diagnostic and therapeutic procedures (Al-Maqrashia et al., 2025). Improper disposal of such waste can lead to contamination of water bodies, infiltration into

soil and groundwater, accumulation of toxic metals in both aquatic and terrestrial ecosystems, and unintended exposure to ionizing radiation among healthcare workers and surrounding communities (Ma et al., 2023; Sakina et al., 2023).

Residual radioactive liquid waste refers to the small volumes of radiopharmaceutical solutions that remain in syringes, vials, tubing, generators, and other containers following routine nuclear medicine procedures (Cena and Hasi, 2024; Zolle et al., 2020). Although these containers are often considered empty after clinical use, they frequently retain measurable quantities of radioactive material due to dead-space volume, incomplete delivery, adsorption onto container surfaces (Kvaternik et al., 2020; Mushtaq et al., 2008), and preparation losses. Given that nuclear medicine departments conduct large numbers of procedures daily, these residual liquid waste though individually small in volume, can collectively represent a significant source of radioactive waste. Residual radioactive liquids are distinct from bulk radioactive wastewater because they often contain higher activity concentrations relative to volume and may include a complex mixture of radionuclides, salts, and trace metals derived from radiopharmaceutical formulations and generator systems (Sadeghi et al., 2013; Uğur et al., 2021; Velikyan, 2015). Their physicochemical properties influence radionuclide mobility, persistence, and interaction with wastewater treatment processes, while co-existing heavy metals introduce additional chemical toxicity concerns (Lieser and Mühlenweg, 1988; Sancho et al., 2021). As a result, residual radioactive liquids represent a combined radiological and chemical hazard that warrants separate consideration in waste characterization and management strategies (Keith-Roach, 2008; Mansaray and Kamara, 2025).

The presence of radioactivity in residual liquid waste has important implications for both radiation protection and environmental safety (Batista et al., 2016; Petropoulou, 2025). From an occupational perspective, residual radioactive liquids stored in work areas such as hot laboratories and radiopharmaceutical preparation rooms contribute to ambient radiation dose rates and may increase cumulative exposure to staff if not properly managed (Hugo et al., 2017; Hung et al., 2023; Santos et al., 2017). From an environmental standpoint, repeated disposal of residual liquids into decay tanks or wastewater systems can lead to the gradual release of radionuclides and associated chemical contaminants into the environment, particularly when decay, dilution, or treatment practices are insufficient (Batista et al., 2016; Martínez et al., 2018).

Radioactive isotopes commonly used in nuclear medicine, such as technetium-99 (Tc-99), gallium-68 (Ga-68), and technetium-99m (Tc-99m), can persist in the environment (Yunwen, 2025). Despite undergoing natural decay, their release in untreated or inadequately managed wastewater may lead to radiological hazards and bioaccumulation in the environment (Uğur et al., 2021). Similarly, metals such as cadmium, lead, nickel, and zinc contribute to long-term ecological toxicity (Ahmed Fatima et al., 2022).

Physicochemical parameters of residual radioactive liquids, including pH, salinity, total dissolved solids, electrical conductivity, and turbidity, also influence the mobility and toxicity of both chemical and radioactive contaminants (Al-Maqrashia et al., 2025). Variations in these parameters can affect the solubility of heavy metals and the decay behavior of radionuclides, thereby impacting the effectiveness of existing waste management strategies (Sakina et al., 2023). Monitoring both physicochemical and radiological characteristics of residual radioactive liquid is therefore critical to assess compliance with international safety standards, and to develop effective environmental protection measures (Hung et al., 2023).

Improper management of hospital and radioactive waste poses serious environmental and public-health hazards. Hospital effluents may contain toxic heavy metals, pharmaceuticals, disinfectants, pathogenic microorganisms, and radionuclides, which can contaminate surface water, groundwater, and soils when discharged without adequate treatment (Jordan and Eaton, 2024; Sharma et al., 2025). Heavy metals such as cadmium (Cd), lead (Pb), and nickel (Ni) are of particular concern because they are non-biodegradable, persistent in the environment, and capable of bioaccumulating in aquatic organisms, thereby posing long-term ecological and human health risks (EPA, 2026). Furthermore, radioactive waste generated from diagnostic and therapeutic procedures, even at low activity levels, may result in chronic radiation exposure and ecological imbalance if not properly managed (Ravichandran, 2017). These risks highlight the importance of effective hospital wastewater and radioactive waste management systems, particularly in developing countries where treatment infrastructure may be limited (World Health Organization, 2023).

Therefore, understanding the nature and implications of residual radioactive liquids is essential for accurate radioactive waste management (Cirstea et al., 2025). However, to the best of authors' knowledge, no comprehensive data currently exist on the radiological and physicochemical properties, nor on the heavy metal contamination, of residual radioactive liquids generated as waste in nuclear medicine procedures in Tanzania.

This study aims to fill that gap by systematically characterizing the residual radioactive liquids produced in nuclear medicine departments at the Ocean Road Cancer Institute (ORCI) and Bugando Medical Centre (BMC). Specifically, the objectives are to:

- Quantify the radiological characteristics of residual liquid waste, including the identification of radionuclides and measurement of their activity concentrations.
- Determine the physicochemical properties and heavy metal contaminants present in the residual liquid waste
- Assess the implications of these findings for occupational radiation protection, environmental safety, and compliance with international waste management standards.

MATERIALS AND METHODS

Study area

The study was conducted at two major nuclear medicine facilities in Tanzania (Figure 1): ORCI) in Dar es Salaam and BMC) in Mwanza. ORCI is a national referral center providing radiotherapy and nuclear medicine services, including the use of Tc 99, Ga 68, and other radiopharmaceuticals. BMC serves as a regional referral hospital whose nuclear medicine department primarily handles diagnostic procedures using Tc 99m. Both facilities operate liquid radioactive waste management systems, including decay tanks, and maintain controlled laboratory and clinical areas for nuclear medicine procedures. Effluents are discharged into municipal wastewater systems after compliance with internal radiation safety procedures. The climate in both locations is tropical, with minimal seasonal temperature variation.

Study design and sampling strategies

A cross-sectional study design was employed to assess radiological, physicochemical, and heavy metal characteristics of liquid radioactive waste. This study was conducted over three months (May to July, 2025). Liquid waste samples were collected over multiple days to capture temporal variability in radionuclide decay with sampling conducted over eight days at ORCI and ten days at BMC. Activity concentration were analyzed by HPGe Gamma Spectrometry. Sampling was carried out in hot laboratories where residual liquid wastes from used syringes and vials were temporarily stored prior to decay. In situ measurements of physicochemical parameters measured including Dissolved oxygen (DO), temperature,

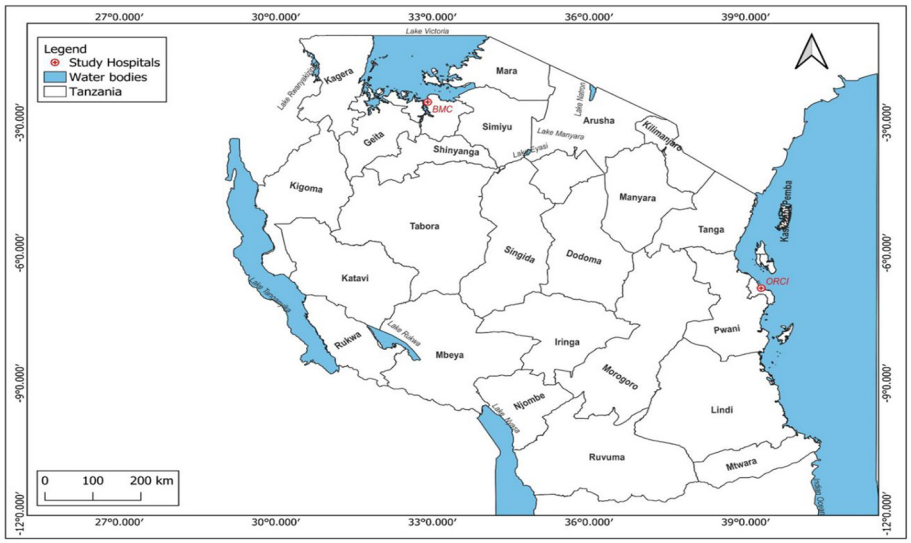

Figure 1. Geographic locations of the nuclear medicine facilities assessed in this study: Ocean Road Cancer Institute (ORCI) in Dar es Salaam and Bugando Medical Centre (BMC) in Mwanza, Tanzania

pH, electrical conductivity (EC), total dissolved solids (TDS), salinity, and sodium chloride, were performed using calibrated portable multiparameter meters (HI 2550 pH/ORPand EC/TDS/NaCl Meter). Turbidity was measured using a portable turbidity meter (2100Q, HACH COMPANY, S/N 18030C065464, expressed in NTU), while sulphate concentrations were determined using UV–VIS spectrophotometry (DR6000 UV VIS Spectrophotometer from HACH company with RFID technology). Chloride was analysed by the argentometric method, sodium by atomic absorption spectrophotometry, and total suspended solids (TSS) by the gravimetric method.

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Heavy metal zinc (Zn), cadmium (Cd), nickel (Ni), lead (Pb), copper (Cu), manganese (Mn), and chromium (Cr) were analyzed using atomic absorption spectroscopy (AAS) (Varian, Model: Spectra AA50; Serial No.: EL97103140), which had been calibrated on 19 June 2025 at the Geological Survey of Tanzania (GST). Ambient radiation dose rates were measured at six selected locations within each facility: offices, toilets, gamma camera rooms, cold kit storage, hot laboratories, and generator storage areas. Measurements were performed using calibrated survey meters Model: X5CPLUS, serial number S/N: 706619, with multiple readings taken at each site to account for temporal variations.

Sampling was performed by trained personnel using appropriate personal protective equipment, including laboratory coats, disposable gloves, and personal dosimeters. Radiation protection principles of time minimization, distance maximization, and shielding were strictly applied in accordance with IAEA recommendations (IAEA, 2019).

Collection and processing of radiological liquid wastes

A total of 80 residual syringes and 20 vials were collected at ORCI, together generated combined volume of approximately 360 mL. On the other hand, 75 residual syringes and 30 vials were collected at BMC, producing a total volume of approximately 375 mL. The residual liquid volume per syringe or vial ranged from 0.2 to 5 mL. Sampling included all syringes and vials available in the hot laboratories of the respective facilities during the study period to ensure representativeness. Due to the small volume of liquid waste in individual syringes and vials, composite sampling was adopted. At each facility, three composite samples were prepared by pooling aliquots from the collected syringes and vials. S1, S2, and S3 represented composite samples from ORCI while S4, S5, and S6 represented composite samples from BMC. Composite sampling ensured adequate sample volume for subsequent analyses and improved representativeness while minimizing analytical variability and cost. This approach is widely recommended for radioactive waste streams with limited individual sample volume (IAEA, 2019).

Radiation screening, physico-chemical examination and heavy metal analysis

Radiation dose rates were measured using a calibrated radiation survey meter (Model: X5CPLUS; Serial No.: 706619; calibration factor: 0.98; manufacturer: Thermo Scientific; last calibration: 24 February 2025) to confirm that exposure levels were within permissible handling limits. Samples were then sealed in appropriately shielded containers, clearly labeled, and transported in accordance with IAEA transport safety requirements to the Tanzania Atomic Energy Commission laboratory in Arusha for radionuclide activity concentrations using HPGe gamma spectrometry.

Physicochemical analysis was conducted at the University of Dodoma research laboratory, including determination of pH, temperature, EC, TDS, TSS, turbidity, salinity, DO, and major ions (Na^+, Cl^-, SO_4^{2-}), following standard methods for water and wastewater analysis (APHA, 2012).

Heavy-metal analysis (Zn, Cd, Ni, Cr, Pb, Cu, and Mn) performed at the Geological Survey of Tanzania (GST) using atomic absorption spectroscopy (AAS) in accordance with internationally accepted analytical protocols

Data processing and analysis

Data were checked for normality and homogeneity of variance. Descriptive statistics, including mean, standard error (SE), and ranges, were calculated. Comparisons between facilities for physicochemical and ambient radiation parameters were performed using the Mann-Whitney U test due to non-normal distributions. Temporal radionuclide decay was modeled using

exponential regression to determine half-lives and goodness-of-fit (R^2).

Heavy metal contamination was evaluated relative to World Health Organization (WHO) guideline limits. To assess heavy metal contamination in hospital wastewater, several indices were calculated using mean metal concentrations (mg/L) and international/national guideline values (WHO, 2017; Tanzania Bureau of Standards).

Contamination factor (CF): The CF for each metal was calculated as the ratio of the mean metal concentration (C_i) to its corresponding permissible concentration (C_i,standard):

$$CF_i = \frac{C_i}{C_i,standard} \quad (1)$$

CF values indicate the degree of contamination of individual metals, classified as low ($CF < 1$), moderate ($1 \leq CF < 3$), considerable ($3 \leq CF < 6$), or very high ($CF \geq 6$). Degree of contamination (Cd_i) of all metals at each facility was quantified by summing the individual CFs:

$$Cd_i = \sum_{i=1}^{n} CF_i \quad (2)$$

where: n – total number of metals analyzed.

Pollution load index (PLI) provides an integrated assessment of overall pollution and was calculated as the nth root of the product of all CFs: (El Hassani et al., 2024; Hossain et al., 2021).

$$PLI = (\prod_{i=1}^{n} CF_i)^{1/n} \quad (3)$$

where: $\prod$ represents the product of all *CFs* for the metals considered. *PLI* values below 1 indicate no pollution, while values above 1 indicate the presence of pollution. *PLI* equals to 1 indicate baseline pollution.

Heavy metal pollution index (HPI) was computed to evaluate the combined effect of multiple metals, assigning higher weight to metals relative to their guideline concentrations. It was calculated using the following formula:(Calmuc et al., 2021; El Hassani et al., 2024)

$$HPI = \frac{\sum_{i=1}^{n}\left[\frac{1}{C_i,standard}\left(\frac{C_i - C_i,ideal}{C_i,standard - C_i,ideal}\right)\times 100\right]}{\sum_{i=1}^{n}\frac{1}{Ci,standard}} \quad (4)$$

where: $C_i ideal$ – ideal concentration (usually 0 for toxic metals).

Metal index (MI) provides a cumulative measure of metal contamination and was calculated as the sum of all CFs (El Hassani et al., 2024):

$$MI = \sum_{i=1}^{n} CF_i \quad (5)$$

where: n is the total number of metals considered. *MI* values were interpreted as follows: $MI < 10$ indicates low pollution, $10 \leq MI < 20$ moderate pollution, $20 \leq MI < 30$ high pollution, and $MI \geq 30$ indicates a seriously affected environment.

Principal component analysis (PCA) was applied to physicochemical and heavy metal datasets to identify major contributors to variation between facilities. Statistical significance was set at $p < 0.05$. Analyses were conducted using R version 4.3.1.

Ethical clearance and compliance

This study received ethical approval from the National Health Research Ethics Review Committee (NatHREC) with an approval number NEW-2025-055 and permit to publish with Ref No. BD.242/437/01C/153. Formal authorization for sample collection was obtained from facility management and radiation safety officers at both ORCI and BMC. All sampling activities complied with national regulatory requirements enforced by the Tanzania Atomic Energy Commission (TAEC) and with relevant International Atomic Energy Agency (IAEA) guidance on radioactive waste management in medical applications.

RESULTS

General characteristics of the nuclear medicine facilities

Table 1 summarizes the key operational and structural characteristics of the two nuclear medicine facilities assessed using a structured facility checklist. ORCI provides both diagnostic and therapeutic nuclear medicine services and functions as a national oncology referral center, whereas BMC offers diagnostic services only and serves as a regional referral hospital. ORCI managed a higher patient workload, averaging 480 patients per month and 22 nuclear medicine procedures per day, compared with 220 patients per month and 12 procedures per day at BMC. Staffing levels were also higher at ORCI, with three nuclear medicine physicians, two medical physicists, one radiopharmacist, one radiation safety officer, and four dedicated radioactive waste management staff. In contrast, BMC had two nuclear

Table 1. General characteristics and operational profiles of the nuclear medicine facilities assessed using a structured facility checklist

Parameter	Indicator	Ocean Road Cancer Institute (ORCI)	Bugando Medical Centre (BMC)
Facility specialization	Type of nuclear medicine services	Diagnostic and therapeutic	Diagnostic only
	Oncology referral role	National cancer referral center	Regional referral hospital
Patient volume	Average patients per month	480	220
	Average nuclear medicine procedures per day	22	12
Staffing	Nuclear medicine physicians	3	2
	Medical physicists	2	1
	Radiopharmacists/radiochemists	1	1
	Radiation safety officer	1	1
	Dedicated radioactive waste management staff	4	3
Radioactive materials	Technetium-99 m	Available	Available
	Iodine-131	Available	Not available
	Gallium-68	Available	Not available
	Cobalt-60	Available	Not available
Waste management infrastructure	Delay-and-decay tanks	Present	Present
	Shielded liquid waste storage	Present	Present
Operational history	Year nuclear medicine services initiated	2003	2012
Regulatory oversight	Routine radiation monitoring	Implemented	Implemented
Budget allocation	Dedicated radioactive waste management budget	Available	Available

medicine physicians, one medical physicist, one radiopharmacist, one radiation safety officer, and three waste management staff.

Both facilities utilized technetium-99m for diagnostic procedures; however, ORCI additionally used iodine-131 and gallium-68, reflecting its therapeutic and advanced diagnostic capacity. Delay-and-decay tanks and shielded liquid waste storage facilities were present at both sites, indicating basic radioactive waste management infrastructure. Nuclear medicine services were initiated in 2003 at ORCI and in 2012 at BMC, Both facilities implemented routine radiation monitoring and maintained dedicated budgets for radioactive waste management.

Radiological characteristics of liquid waste

The temporal radiation levels of Tc-99 and Ga-68 in liquid waste at ORCI declined rapidly over the monitoring period (Table 2). Tc-99 activity decreased from 563.85 µSv/h on Day 1 to 0.24 µSv/h on Day 8, while Ga-68 decreased from 320.35 µSv/h to 0.32 µSv/h. Exponential decay models (Figure 2) fitted to log-transformed data confirmed significant decay for both radionuclides (Tc-99: $R^2 = 0.985$, $p < 0.001$; Ga-68: $R^2 = 0.873$, $p = 0.001$). Estimated half-lives were 0.62 days for Tc-99 and 0.83 days for Ga-68. Similarly, Tc-99m levels decreased from 550.15 µSv/h on Day 1 to 0.35 µSv/h on Day 10 at BMC, with an estimated half-life of 0.96 days ($R^2 = 0.919$, $p < 0.001$). The gamma spectrometry analysis showed no detectable gamma-emitting radionuclides in any of the analyzed liquid radioactive waste samples. The measured activities for all radionuclides were below the corresponding minimum detectable activity (MDA), indicating that the activity concentrations were too low to be quantified by the measurement system.

Ambient radiation levels

Ambient radiation dose rates measured at selected locations within the nuclear medicine facilities are summarized in Figure 3. At ORCI, ambient dose rates ranged from 0.15 µSv/h in office rooms to 0.75 µSv/h in generator storage areas. Similarly, at BMC, values ranged from 0.38 µSv/h in office rooms to 0.85 µSv/h

Table 2. Descriptive statistics of radiation dose rates (μSv/h) in liquid waste from ORCI and BMC, including exponential decay regression results, decay constants (λ), coefficient of determination (R^2), p-values, and estimated half-lives (days)

Parameter			Descriptive statistics of radiation dose rates (μSv/h)			Exponential decay regression results		
Facility	Radionuclide	Mean	Minimum	Maximum	Decay constant, λ (day^{-1})	R^2	p-value	Estimated half-life (days)
ORCI	Tc-99m	135.85	0.24	563.85	−1.127	0.985	<0.001	0.62
ORCI	Ga-68	88.43	0.32	320.35	−0.833	0.873	<0.001	0.83
BMC	Tc-99m	152.27	0.35	550.15	−0.722	0.919	<0.001	0.96

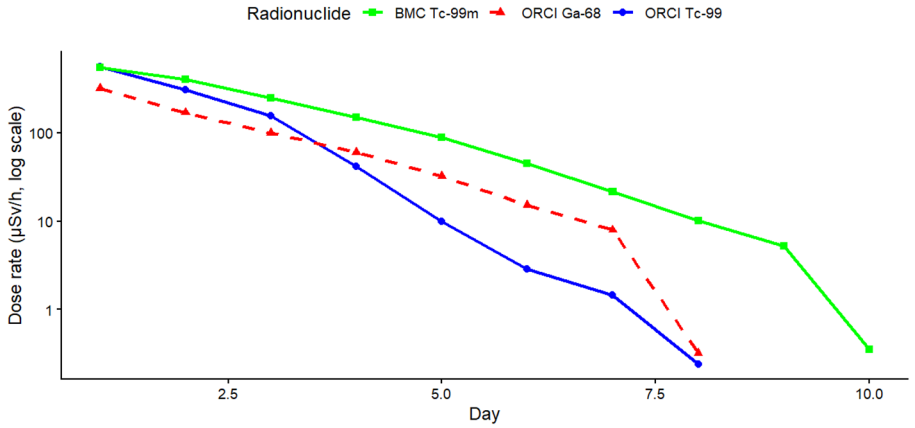

Figure 2. Exponential decay of radionuclides in liquid waste from nuclear medicine facilities. Data points represent measured radiation dose rates (μSv/h), and solid lines indicate fitted exponential decay curves used to estimate decay constants and half-lives

in generator storage areas. Across both facilities, higher radiation levels were consistently observed in operational and source-proximal areas, including generator storage, hot laboratories, cold kit storage, and gamma camera rooms, while lower levels were recorded in office spaces and toilets.

Comparatively, BMC exhibited slightly higher ambient radiation levels than ORCI at all monitored locations; however, the overall distribution of ambient dose rates did not differ significantly between the two facilities. This was confirmed by a Mann-Whitney U test (W = 11, p = 0.296), indicating no statistically significant difference in ambient radiation exposure levels across comparable areas of the two nuclear medicine departments.

All measured ambient dose rates at both facilities were within typical background-adjusted ranges reported for controlled nuclear medicine environments, suggesting effective implementation of radiation protection and shielding measures in routinely occupied areas.

Physicochemical characteristics of liquid waste

Physicochemical parameters (Table 3) showed no significant differences between the two facilities (P>0.05). However, ORCI effluents were acidic (pH 3.84 ± 0.39, range 3.17–4.50), with higher electrical conductivity (3983 ± 72.7 μS/cm, range 3850–4100) and TDS (1983 ± 43.9 mg/L, 1900–2050), and dissolved oxygen of 4.17 ± 0.17 mg/L (3.9–4.5). BMC effluents were near-neutral (pH 7.09 ± 0.12, 6.85–7.27), with higher salinity (0.38 ± 0.02%, 0.35–0.40), sulfate (0.18 ± 0.017 mg/L, 0.15–0.21), TSS (195 ± 2.9 mg/L, 190–200), and turbidity (5.53 ± 0.18 NTU, 5.2–5.8). Sodium and chloride concentrations were also higher at BMC (Na+: 20.22 ± 0.59 mg/L; Cl-: 2024 ± 3.5 mg/L) than ORCI (Na+: 16.58 ± 0.51 mg/L; Cl-: 1947 ± 31.8 mg/L). Temperature values were similar between facilities (ORCI: 23.3 ± 0.37 °C; BMC: 23.1 ± 0.18 °C). No statistically significant differences were observed for individual parameters s (p > 0.05).

Table 3. Physicochemical characteristics of liquid waste from ORCI and BMC

Parameter	ORCI (Mean ± SE, Range)	BMC (Mean ± SE, Range)
pH	3.84 ± 0.39 (3.17–4.50)	7.09 ± 0.12 (6.85–7.27)
Electrical Conductivity (µS/cm)	3983 ± 72.7 (3850–4100)	3757 ± 73.3 (3650–3900)
Total dissolved solids (mg/L)	1983 ± 43.9 (1900–2050)	1880 ± 52.5 (1800–1980)
Dissolved oxygen (mg/L)	4.17 ± 0.17 (3.9–4.5)	3.67 ± 0.09 (3.5–3.8)
Salinity (%)	0.12 ± 0.02 (0.10–0.15)	0.38 ± 0.02 (0.35–0.40)
Sulphate (mg/L)	0.07 ± 0.017 (0.04–0.10)	0.18 ± 0.017 (0.15–0.21)
Sodium (mg/L)	16.58 ± 0.51 (15.82–17.54)	20.22 ± 0.59 (19.87–21.84)
Chloride (mg/L)	1947 ± 31.8 (1890–2000)	2024 ± 3.5 (2018–2029)
Total suspended solids (mg/L)	179 ± 4.0 (172–186)	195 ± 2.9 (190–200)
Turbidity (NTU)	4.37 ± 0.23 (4.0–4.8)	5.53 ± 0.18 (5.2–5.8)
Temperature (°C)	23.3 ± 0.37 (22.6–23.8)	23.1 ± 0.18 (22.9–23.5)
Color	Colorless	Colorless

The Principal component analysis (PCA) of the physicochemical variables are shown in Figure 4 and indicate that the first two principal components explained 92.6% of the total variance. ORCI samples clustered in the region of lower EC, TDS, and salinity with slightly acidic pH and lower TSS, whereas BMC samples were associated with higher EC, TDS, and salinity, near-neutral pH, and moderate TSS.

Heavy metal concentrations and exceedance relative to WHO guidelines

The measured concentrations of selected heavy metals in liquid waste from ORCI and BMC are summarized in Table 4, while their exceedance relative to World Health Organization (WHO) guideline limits are summarized in Figure 5.

Mean zinc (Zn) concentrations were below the WHO/TBS limit at ORCI (0.87 mg/L) but exceeded it at BMC (5.98 mg/L). Cadmium (Cd) and lead (Pb) were markedly elevated at both facilities, with mean concentrations of 0.025 mg/L and 0.225 mg/L, respectively, surpassing WHO/TBS standards by approximately 8-fold and 22-fold. Nickel (Ni) also exceeded its guideline value (0.07 mg/L), whereas chromium (Cr), copper (Cu), and manganese (Mn) remained within acceptable limits. Contamination indices (CD, PLI, HPI, and MI) showed that BMC was more contaminated than ORCI. In both facilities, the Cd_i values were high (33.69–35.83), HPI exceeded 1000, and MI exceeded 33, signaling

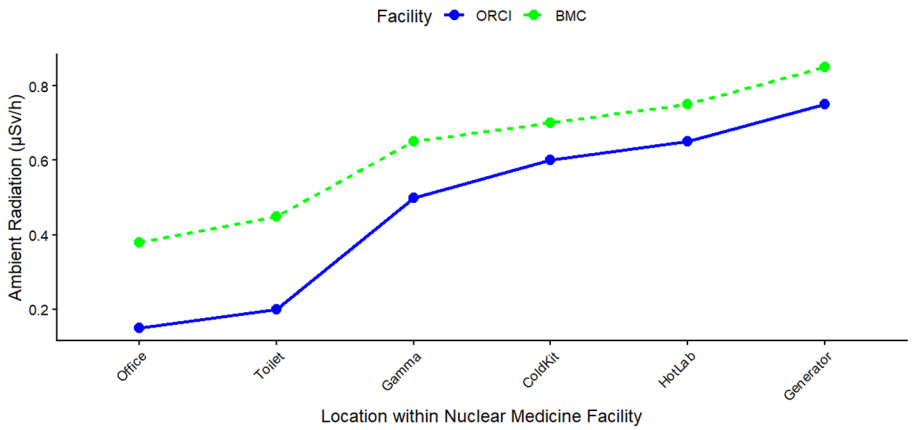

Figure 3. Ambient radiation dose rates (µSv/h) measured at selected locations within ORCI and BMC. Bars represent mean ± SE values across multiple readings. Higher dose rates were observed in operational areas such as generator storage, hot laboratories, and gamma camera rooms, while lower dose rates were recorded in office spaces and toilets

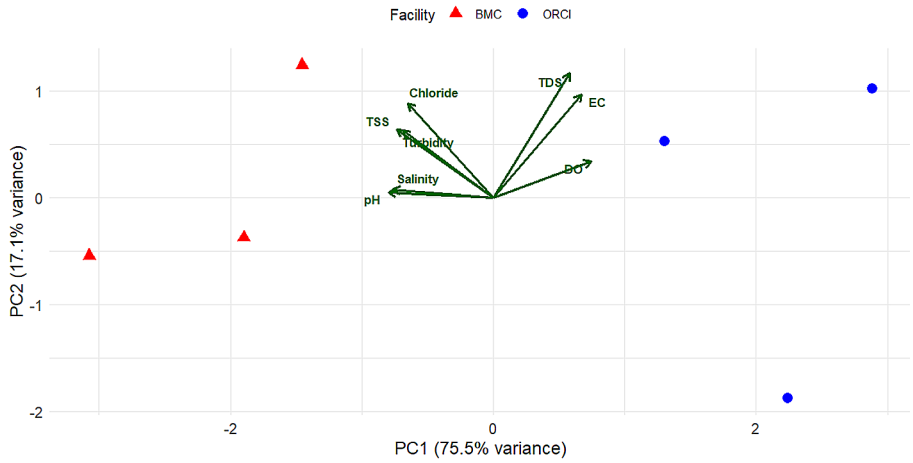

Figure 4. Principal component analysis (PCA) of physicochemical parameters in liquid waste from ORCI and BMC. PC1 and PC2 explain 92.6% of the total variance. ORCI samples cluster in regions of lower EC, TDS, and salinity with acidic pH, whereas BMC samples associate with higher EC, TDS, salinity, and moderate TSS

Table 4. Descriptive statistics of heavy metal concentrations (mg/L) in liquid waste from ORCI and BMC and their compliance with World Health Organization (WHO) guideline limits, including contamination factors (CF)

Parameter / Index	ORCI	BMC	WHO/TBS standard
Metals concentration (mg/L)	Mean± SD Conc. (Contamination factor, CF)		
Zn	0.87 ± 0.012 (0.29)	5.98 ± 0.072 (1.99)	3
Cd	0.022 ± 0.0029 (7.24)	0.025 ± 0.0029 (8.33)	0.003
Ni	0.17 ± 0.0058 (2.43)	0.185 ± 0.0087 (2.64)	0.07
Cr	0.002 ± 0 (0.10)	0.01 ± 0 (0.10)	0.05
Pb	0.22 ± 0.0087 (20.35)	0.26± 0.0087 (22.50)	0.01
Cu	0.06 ± 0.0058 (0.03)	0.50 ± 0.231 (0.25)	2
Mn	0.001 ± 0 (0.01)	0.006 ± 0 (0.01)	0.4
Degree of contamination (Cd_i)	33.69	35.83	—
Pollution load index (PLI)	0.47	0.85	—
Heavy metal pollution index (HPI)	1075.4	1076.2	—
Metal index (MI)	33.69	35.83	—

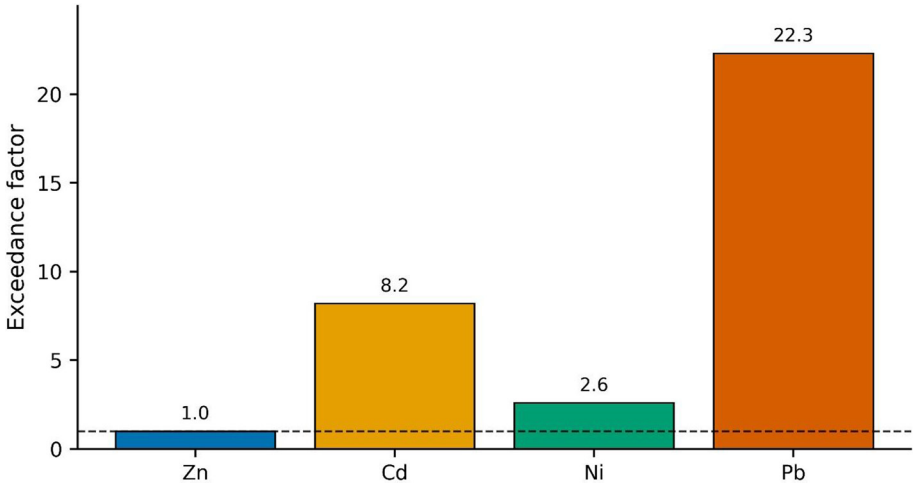

Figure 5. Exceedance of heavy metals in liquid waste from ORCI and BMC relative to World Health Organization (WHO) guideline limits. Metals exceeding WHO limits are indicated above the dashed line at 1.0, while metals below guideline limits fall below the line

critical pollution. Analysis of specific metal contamination indicated by contamination factors showed very high contamination for Cd and Pb, moderate contamination for Ni, and low to moderate contamination for other metals. Neither Tc-99m nor Ga-68 decay pathways produce Cd or Pb, their occurrence were due to radiogenic in origin. The observed concentrations are more reasonably attributed to non-radiological sources, including corrosion and gradual degradation of generator shielding (lead pots), metallic fittings, valve components, and possible cadmium-containing coatings.

The PCA of the composite heavy-metal concentrations measured in ORCI and BMC wastewater indicated that the first principal component (PC1) accounted for approximately 92% of the total variance, with all metals showing strong, nearly equal loadings. This demonstrates that PC1 represents the overall heavy-metal contamination gradient across the facilities. The ORCI samples (S1-S3) clustered at lower PC1 values, indicating lower cumulative metal contamination, while the BMC samples (S4-S6) clustered at higher PC1 values, reflecting greater overall contamination. The second principal component (PC2) explained only 6% of the variance and captured minor differences in the distribution of individual metals, such as Zn and Ni. Overall, the PCA confirms that total heavy-metal contamination clearly distinguishes the two facilities, with BMC exhibiting higher levels than ORCI (Figure 6).

DISCUSSION

The present study evaluated the radiological, physicochemical, and heavy-metal characteristics of residual liquid waste from nuclear medicine facilities. The objective was to assess temporal radiation levels and decay in residual radioactive liquids, ambient radiation levels within hospital premises, physicochemical parameters, and the presence of heavy metals, in order to determine compliance with international safety standards and potential environmental risks. To achieve these objectives, the study systematically monitored radiological dose rates over time, measured ambient radiation in different hospital areas, characterized the physicochemical properties of liquid effluents, and quantified heavy-metal concentrations. This comprehensive approach enabled an integrated assessment of both the safety and environmental impacts of residual radioactive liquid waste.

Temporal monitoring of radionuclides in liquid waste revealed rapid decay of Tc-99 and Ga-68 at ORCI, and Tc-99m at BMC, with estimated half-lives of 0.62, 0.83, and 0.96 days, respectively. These results indicate that radioactive effluents experienced predictable and effective decay prior to potential discharge, thereby minimizing radiological risk. he observed decay patterns are consistent with reports from nuclear medicine facilities elsewhere, underscoring the importance of decay tanks and storage protocols in ensuring safe radioactive waste management

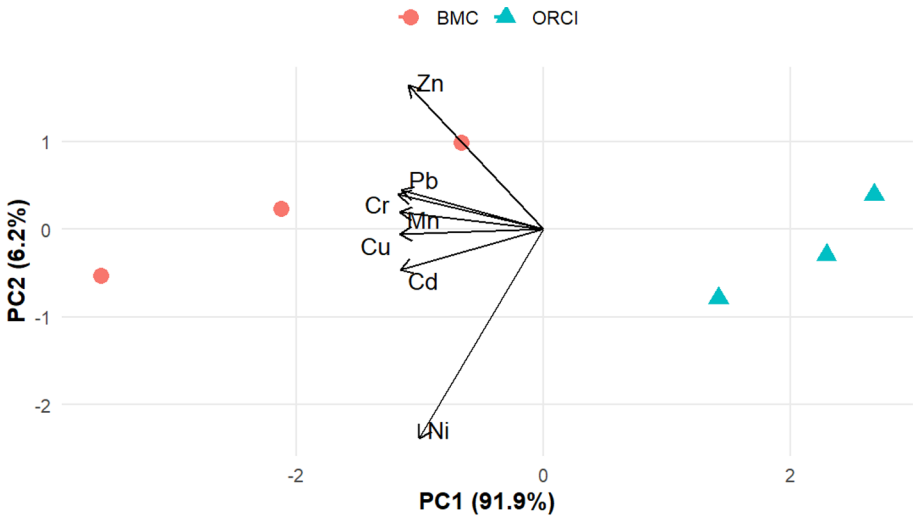

Figure 6. Principal component analysis (PCA) of heavy metal concentrations in liquid waste from ORCI and BMC. PC1 and PC2 explain 86.8% of the total variance. ORCI samples cluster in the lower-metal region, while BMC samples cluster in the higher-metal region, highlighting cadmium (Cd), nickel (Ni), and lead (Pb) as the dominant contributors to heavy metal pollution

(Yunwen, 2025). Similar studies have emphasized that timely storage and controlled decay are essential for limiting radiation exposure to both personnel and the environment (Al-Maqrashia et al., 2025; Hung et al., 2023).

Ambient radiation measurements showed higher dose rates in operational areas, including generator storage, hot laboratories, and gamma camera rooms, compared to office spaces and toilets. This distribution confirms that proximity to radiation sources is a primary determinant of exposure. Despite these differences, measured ambient radiation were within the recommended background-adjusted ranges for controlled nuclear medicine environments, reflecting adequate shielding and adherence to radiation protection standards (Hung et al., 2023). Comparable studies in oncology and nuclear medicine departments have similarly documented elevated radiation in source-proximal areas and background-level exposures in offices, reinforcing the need for spatial monitoring to ensure occupational safety (Ma et al., 2023; Yunwen, 2025). The absence of detectable gamma-emitting radionuclides in the analyzed liquid radioactive waste samples indicates that the activity concentrations were below the minimum detectable activity (MDA) of the HPGe gamma spectrometry system. This does not necessarily imply the complete absence of radionuclides but rather that their concentrations, if present, were too low to be distinguished from the background radiation. The non-detectable activity levels may be attributed to the decay of short-lived medical radionuclides, effective decay-in-storage practices, and dilution before analysis, suggesting that the waste posed a negligible radiological risk at the time of measurement (Ramebäck & Vidmar, 2020; Tomarchio et al., 2023).

Physicochemical analysis of liquid waste identified distinct facility-specific profiles. ORCI effluents were acidic, the acidic pH observed at ORCI may be attributed to the use of Ga-68 generator eluents, which are typically hydrochloric acid (HCl)-based, as well as other chemical reagents and cleaning agents used in radiopharmaceutical preparation and therapeutic procedures. The presence of dissolved ionic species further contributes to increased electrical conductivity and acidity. This acidic environment enhances the solubility and mobility of heavy metals, thereby increasing their concentrations in the liquid waste and characterized by higher electrical conductivity and total dissolved solids, whereas BMC effluents exhibited approximately neutral pH, higher salinity, and greater turbidity. Principal component analysis indicated that differences in ionic content, acidity, and particulate matter largely explained these variations. However, statistical analysis showed no significant differences for individual physicochemical parameters, suggesting that the overall wastewater quality was generally comparable across the two facilities. These findings are consistent with previous studies, which showed that hospital wastewater composition is influenced by specific operations based in hospital facility, including cleaning chemicals, radiopharmaceuticals, and other routine activities (Ahmed Fatima et al., 2022; Sabai and Balengayabo, 2023).

Heavy-metal analysis indicated that cadmium, nickel, and lead consistently exceeded World Health Organization guideline values in liquid waste from both facilities. Neither Tc-99m nor Ga-68 decay pathways produce heavy metals such as cadmium (Cd), nickel (Ni), or lead (Pb). Therefore, the elevated concentrations observed in this study are attributed to non-radiological sources, including corrosion and degradation of metallic infrastructure such as pipes, valves, and fittings, as well as leaching from lead shielding materials used in Tc-99m generator systems. Additionally, trace metal impurities may originate from Ga-68 generator eluents and associated radiopharmaceutical preparation processes, while zinc contamination was primarily elevated at BMC. The significantly higher zinc (Zn) concentrations observed at BMC may be associated with increased leaching from galvanized or zinc-coated materials, potentially enhanced by higher salinity and chloride levels, which are known to promote metal dissolution in aqueous systems. Lead showed the highest relative exceedance, suggesting that it was the dominant contributor to cumulative metal pollution. These results align with previous studies that identified hospital effluents as significant sources of heavy-metal contamination, with potential risks to aquatic ecosystems and human health (Ma et al., 2023; Sakina et al., 2023). Heavy metal contamination in hospital effluents is frequently linked to the use of metallic equipment, radiopharmaceutical preparation, and laboratory reagents. Effective pre-treatment measures prior to disposal are therefore essential.

The combined analysis of radiological, physicochemical, and heavy metal parameters

emphasizes that while radiological risks in liquid waste are effectively mitigated through decay practices and shielding, chemical and metal contamination remains a persistent concern. This observation is consistent with findings by Sancho et al. (2021) and Sharma et al. (2025), which highlighted that untreated liquid radioactive wastewater can contribute to bioaccumulation of toxic metals in aquatic organisms, degrade water quality, and ultimately pose health risks to communities relying on downstream water sources. Routine monitoring, strict adherence to wastewater management protocols, and the implementation of advanced treatment technologies are therefore critical to minimizing environmental impacts.

This study provides the first comprehensive characterization of residual liquid waste generated from Tc-99m and Ga-68 nuclear medicine procedures in Tanzania. While the findings confirm that radiological risks are effectively controlled through decay mechanisms, the presence of elevated heavy metal concentrations highlights an important gap in current waste management practices. These results underscore the need for integrated approaches that address both radiological and chemical contaminants to ensure environmental protection and regulatory compliance.

CONCLUSIONS

This study has demonstrated that nuclear medicine facilities in Tanzania implement effective radiological safety measures, as evidenced by the rapid decay of radionuclides in liquid waste and controlled ambient radiation levels within hospital premises. However, physicochemical and heavy-metal analyses revealed potential environmental risks, particularly with cadmium, nickel, and lead consistently exceeding WHO guideline limits. These findings highlight the need for strengthened radioactive waste management strategies to prevent heavy-metal contamination of ecosystems and associated public health impacts Future research should include multi-center studies involving a larger number of nuclear medicine facilities to improve the generalizability of findings. Long-term monitoring of Tc-99m and Ga-68 waste streams is recommended to capture temporal and operational variations. Additional studies should investigate other contaminants such as pharmaceutical residues, organic solvents, and microbial pathogens. Furthermore, the efficiency of existing wastewater treatment systems should be evaluated, and advanced treatment technologies for removing heavy metals and neutralizing acidic effluents should be explored. Environmental and human health risk assessments are also necessary to better understand the broader implications of hospital effluent discharge. It is recommended that hospital liquid radioactive waste management systems be enhanced to incorporate both radiological and chemical treatment processes. In addition to decay-in-storage practices for Tc-99m and Ga-68, pre-treatment methods such as precipitation, adsorption, or ion exchange should be implemented to remove heavy metals prior to discharge. Furthermore, the use of corrosion-resistant materials in infrastructure, routine maintenance of radionuclide generators and shielding systems, and neutralization of acidic effluents should be prioritized. Continuous monitoring and staff training are essential to ensure safe and sustainable waste management practices.

The study provides a valuable baseline information for evaluating radioactive residual waste and identifying areas for environmental and public health interventions. However, several limitations should be acknowledged. First, the research was conducted in only two nuclear medicine facilities, which may limit the generalizability of the findings to other hospitals with different operational practices, waste management systems, or radiopharmaceutical usage. Second, the temporal monitoring of radionuclides focused on short-term decay over a few days, which may not capture the behavior of long-lived isotopes or seasonal variations in effluent composition. Third, while heavy metals and basic physicochemical parameters were assessed, other potential contaminants such as pharmaceutical residues, organic solvents, and microbial pathogens were not included. Finally, the study relied on point measurements and composite samples, may not fully reflect temporal or spatial variations within the facilities' operational activities. Despite these limitations, the findings provide an important foundation for future research and policy development aimed at strengthening radioactive waste management and minimizing environmental and public health risks

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