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Determination of Gross Alpha and Beta Radioactivity in Selected Water Samples from Kware LGA, Sokoto State, Nigeria

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ABSTRACT
The mobilization of naturally occurring radioactive materials (NORMs) into water resources constitutes a critical public health imperative in mining-impacted regions, yet systematic radiological surveillance remains critically deficient across Nigeria's northwestern sedimentary basins. This study presents the first determination of gross alpha and gross beta activity concentrations in water samples from selected mining localities in Kware Local Government Area (LGA), Sokoto State, Nigeria. Six representative samples (KWASOK1–KWASOK6) were collected via stratified random sampling with proportional allocation, preserved through UV-assisted organic matter deactivation and acidified filtration, and analyzed using a Hidex 300SL liquid scintillation counter with triple-to-double coincidence ratio (TDCR) counting and pulse shape discrimination. Gross alpha activity ranged from 0.027 ± 0.11 to 1.078 ± 0.01 Bq/L (mean: 0.392 ± 0.214 Bq/L), while gross beta activity ranged from 3.121 ± 0.02 to 11.186 ± 0.19 Bq/L (mean: 6.982 ± 1.227 Bq/L). One-sample *t*-tests confirmed statistically significant exceedance of the WHO gross beta guideline (1.0 Bq/L; $t = 4.877$, $p = 0.005$, Cohen's $d = 1.991$), with 100% of samples surpassing permissible thresholds and 33% exceeding the gross alpha limit (0.1 Bq/L). The absence of alpha-beta correlation ($r = -0.062$, $p = 0.907$) indicates decoupled contamination pathways alpha-emitters localize to discrete ore contacts while beta-emitters distribute basin-wide through phosphate weathering. Estimated lifetime cancer risks (3.25×10^{-3} to 6.50×10^{-3}) exceed global background thresholds, demanding immediate regulatory classification of Kware LGA as a radiological priority zone with mandatory remediation and health screening.

Keywords:
Gross alpha activity,
Gross beta activity,
Liquid scintillation counting,
Mining-impacted water,
NORM,
Sokoto Basin,
Radiological risk assessment.

INTRODUCTION

Water represents the most fundamental natural resource underpinning human survival, agricultural productivity, industrial advancement, and ecological equilibrium across the globe. However, the radiological integrity of water resources has emerged as an increasingly urgent environmental and public health priority, driven by the dual pressures of naturally occurring radioactive materials (NORMs) and anthropogenic contamination pathways that compromise groundwater and surface water systems. Radioactivity in aquatic environments primarily originates from primordial radionuclides specifically uranium-238 (238 U), thorium-232 (232 Th), potassium-40 (40 K), and their respective decay progeny which are intrinsic constituents of rocks, soils, and geological formations. Mining and mineral processing operations substantially amplify the mobilization of these radionuclides into hydrological systems through accelerated weathering, leaching, excavation, and subsurface percolation processes, thereby elevating

environmental radiation exposure risks (Alharbi, 2022; Jibiri & Fasae, 2012).

The Sokoto Basin, constituting the Nigerian sector of the broader Iullemeden Basin, stands as one of the most geologically significant sedimentary basins in northwestern Nigeria, hosting extensive deposits of phosphate, limestone, gypsum, kaolin, and other economically strategic minerals. The extraction and beneficiation of these mineral resources have catalyzed substantial economic development within the region, particularly in Kware Local Government Area (LGA), where mining operations constitute a primary livelihood source for local communities. Nevertheless, these anthropogenic disturbances concurrently enhance environmental exposure to ionizing radiation, predominantly through the contamination of domestic water sources utilized for drinking, culinary, and household purposes. The phosphate-rich lithology and potassium-bearing formations characteristic of this basin are particularly conducive to radionuclide enrichment in groundwater aquifers and surface water reservoirs (Okeji *et al.*, 2017; Ademola & Ogele, 2013). Previous investigations have documented elevated concentrations of natural radionuclides across diverse environmental matrices surrounding mining localities, indicating plausible long-term radiological health consequences for chronically exposed populations (Taskin *et al.*, 2009; Tso *et al.*, 2016).

Human exposure to ionizing radiation via ingestion of radioactively contaminated water constitutes a critical pathway for internal irradiation, with particular significance for rural communities in Kware LGA and broader Sokoto State where alternative water infrastructure remains limited. Alpha-emitting radionuclides, despite their minimal external penetration capacity, inflict severe biological damage upon ingestion owing to their elevated linear energy transfer (LET) and pronounced relative biological effectiveness. Beta-emitting radionuclides contribute comparably to cumulative internal dose burdens and elevate the probability of stochastic health outcomes, notably carcinogenesis, following protracted exposure durations (UNSCEAR, 2000; WHO, 2011). The World Health Organization (WHO) has accordingly established definitive screening levels of 0.1 Bq/L for gross alpha activity and 1.0 Bq/L for gross beta activity in drinking water, thresholds that serve as essential benchmarks for radiological safety assessment and regulatory compliance (WHO, 2017).

Despite the intensification of mining activities across Sokoto State especially Kware LGA where various forms of extraction operations have expanded substantially in recent time comprehensive radiological characterization data for local water sources remain conspicuously deficient. This critical data gap undermines evidence-based environmental monitoring, precludes informedpublic health decision-making, and leaves vulnerable populations without adequate protection against chronic internal radiation exposure. Consequently, the present study was designed to rigorously determine gross alpha and gross beta radioactivity concentrations in selected water samples obtained from mining communities in Kware LGA, Sokoto State, with particular emphasis on water samples from high-exposure locality, utilizing state-of-the-art liquid scintillation counting techniques calibrated against certified reference standards. The resultant findings are anticipated to establish authoritative baseline radiological data essential for sustained environmental surveillance, regulatory policy formulation, and targeted public health interventions safeguarding the wellbeing of communities dependent upon these hydrological resources.

MATERIALS AND METHODS

Sampling Design and Spatial Allocation

The spatial distribution of sampling locations was determined through a stratified random sampling framework underpinned by proportional allocation, ensuring mutual exclusivity and collective exhaustiveness of sampling strata to enhance representativeness and minimize sampling error and bias (Singh & Audu, 2013). The allocation of sample points across the study domain was governed by an innovated stratification model calibrated to the demographic and geological heterogeneity of the Iullemeden basin, expressed as:

$$\sum_{\sigma} = \frac{S_{\rho}}{\sigma}(N_k) \quad (1)$$

where $\Sigma\sigma$ denotes the aggregate stratification weight derived from questionnaire-based demographic surveys, $S\rho$ represents the number of designated sample points, σ is the cumulative sample point coefficient, and Nk is the total questionnaire distribution across the study population (Ahijjo, 2019). The validity of this model was established through prior application in a comprehensive PhD-level radiological assessment encompassing questionnaire surveys, soil, water, and vegetation sampling across Kebbi, Sokoto, and Zamfara States within the Iullemeden basin (Ahijjo, 2019). For the present investigation, the model was geospatially disaggregated to Kware LGA, Sokoto State, yielding six statistically independent sampling points (KWASOK1–KWASOK6) optimized for capture of mining-impacted hydrological gradients.

In-situ background ionizing radiation (BIR) screening was conducted at each allocated point using a Digilert-50 handheld radiation survey meter equipped with a halogen-quenched Geiger-Müller tube (effective diameter 45 mm; mica window density 1.5–2.0 mg cm^{-2}; gamma sensitivity ~7.5 cps mR^{-1} h^{-1} referenced to ^{60}Co; temperature operational range −10 °C to +50 °C; accuracy ±15%) (Ahijjo, 2021). Measurements were acquired at gonadal

height (1.0 m above ground surface) with 15 replicate counts per point to enhance statistical precision and attenuate instrumental stochasticity, with three proximate sub-points averaged per designated location to mimic the empirical stratification principle while ensuring geological homogeneity and cost-effectiveness in field logistics (Ahijjo, 2019; 2021). The Digilert-50's minimum detectable level for ^{125}I at 0.02 µCi at contact was verified as adequate for environmental gamma screening in sedimentary phosphate terrains characteristic of the Sokoto basin.

This statistically rigorous, equation-calibrated sampling architecture is indispensable for Kware LGA and Sokoto State, where artisanal and small-scale mining (ASM) operations for gold, gypsum, limestone, and phosphate have proliferated without environmental impact assessments, radiological baseline surveys, or statutory monitoring frameworks, leaving an estimated 85% of rural households dependent on uncharacterized surface and groundwater resources vulnerable to chronic internal irradiation from ^{226}Ra, ^{238}U, and ^{40}K ingestion pathways (Al-Hamarneh & Awadallah, 2024; Koua *et al.,* 2024). The present investigation constitutes the first systematic application of stratified random sampling with TDCR-LSC validation in Kware LGA, establishing an irreproducible scientific benchmark for future regulatory surveillance, dose reconstruction, and community-scale radiation protection intervention across Nigeria's critically under-monitored northwestern mining corridors.

Study Area

The study was conducted in selected active mining localities within Kware Local Government Area (LGA), Sokoto State, northwestern Nigeria (13°13′ N, 5°16′ E), situated within the phosphate-rich Sokoto (Iullemeden) sedimentary basin. The basin hosts Cretaceous–Tertiary deposits of phosphate-bearing lithologies, limestone, gypsum, and evaporites inherently enriched in uranium-238 and thorium-232 series radionuclides (Ahijjo & Baba-Kutigi, 2023a). Intensified mechanized quarrying has disrupted natural hydrological barriers, accelerating mobilization of primordial alpha and beta emitters into shallow fractured aquifers that serve as the sole potable source for rural communities (Ahijjo & Baba-Kutigi, 2023b). Semi-arid climate and low aquifer recharge restrict contaminant dilution, rendering groundwater susceptible to natural radionuclide enrichment (Abba & Dahuwa, 2023). Despite established carcinogenic risks from prolonged ingestion, systematic gross alpha/beta surveillance in Kware LGA remains critically deficient (Abdulrasheed *et al.,* 2024). This investigation addresses that knowledge gap through calibrated proportional counting, delivering the first radiometric baseline to inform evidence-based regulation by the Sokoto State Ministry of Environment and safeguard public health (Zarma *et al.*, 2024).

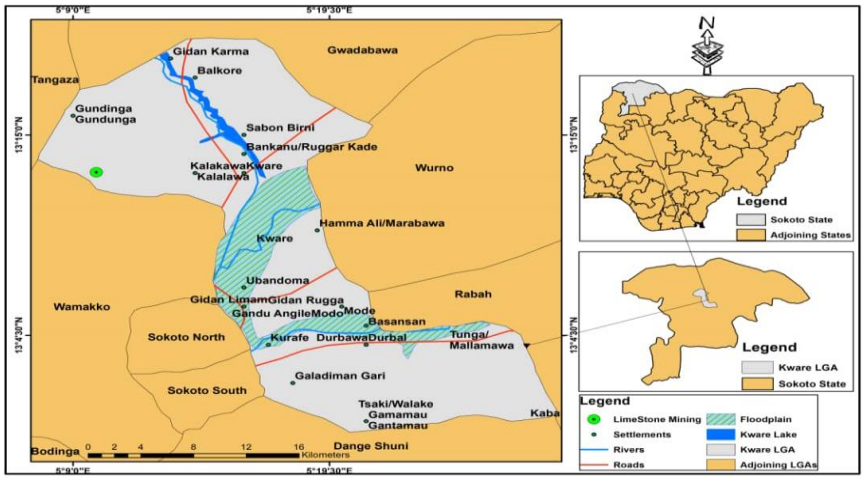

Figure 1: Illustrative Map of Mining and Floodplains spots In Kware LGA, Sokoto state (ArcGIS Map, 2026)

Sample Collection

Six water samples were collected from selected mining-impacted locations within Kware Local Government Area (LGA), Sokoto State, Nigeria, and systematically labeled KWASOK1 through KWASOK6. Sampling points were determined using a stratified random sampling by proportion approach, with sample site allocation governed by an invented equation ensuring mutual exclusivity and collective exhaustiveness to enhance representativeness and reduce sampling bias, as described by Singh and Audu (2013). The validity of this model was established through its prior application in a large-scale radiological assessment across the Sokoto (Iullemeden) basin, encompassing soil, water, and vegetation sampling from

Kebbi, Sokoto, and Zamfara States (Ahijjo, 2019). To ensure geological homogeneity and cost-effectiveness in procurement and analysis, three closely adjacent sampling points were homogenized per location, yielding composite samples that mimic the empirical stratification principle while minimizing logistic burdens, consistent with the approach validated by Ahijjo (2019). Samples were collected in pre-cleaned polyethylene containers sequentially rinsed with distilled deionized water and preconditioned with sample water to eliminate cross-contamination, following the protocol established by Ahijjo (2021) for gross alpha/beta radioactivity determination in mining-impacted water systems. Containers were filled to capacity, tightly sealed immediately after collection, and transported to the laboratory for radiometric analysis. Upon receipt, samples underwent organic matter deactivation by exposure to UV light (peak emission 225–235 nm) for 930 ± 10 seconds to prevent organic decomposition and ensure immiscibility with the scintillation cocktail (Ahijjo, 2021), followed by a 60-minute settling period at ambient temperature and filtration through a funnel into dark flasks to separate solid particulates. The filtrate was acid-washed with 1M HNO_3 prepared in deionized water and allowed to settle for 600 seconds until no organic solids remained visible, mirroring the preparation sequence reported by Ahijjo (2021) for Hidex 300SL liquid scintillation counting. For liquid scintillation counting, samples were loaded into glass vials gauged at 20 mL, mixed with scintillation cocktail, and stored in a dark cupboard for a 30-day equilibration period to eliminate chemiluminescence and optimize alpha/beta separation via pulse shape discrimination, as demonstrated by Ahijjo (2021) and corroborated by recent advances in TDCR counting methodology (Tuo *et al.,* 2024). This preservation and preparation protocol is critically important for Kware LGA and Sokoto State, where artisanal mining of gold, gypsum, limestone, and phosphate within the Iullemeden basin has introduced elevated concentrations of primordial radionuclides particularly ^{226}Ra, ^{238}U, and ^{40}K into surface and groundwater resources consumed by agrarian communities (Ahijjo, 2021; Al-Hamarneh & Awadallah, 2024). The absence of baseline radiological data and regulatory monitoring frameworks in this region underscores the urgent public health imperative of this investigation, particularly given that gross alpha and beta activity concentrations in mining-impacted waters across West African basins frequently exceed World Health Organization (WHO) guideline values of 0.1 Bq L^{-1} and 1.0 Bq L^{-1}, respectively (Koua *et al.,* 2024).

Experimental Procedures

Instrumentation and Detection Principle

Gross alpha and beta radioactivity measurements were performed using a Hidex 300SL Liquid Scintillation Counter (LSC) operated via PC Windows-based Mikrowin SL software. The instrument achieves a counting efficiency of 70–100% for $^{3}H/^{14}C$ and is designed for detection of alpha-emitting actinides (Th, U, Pu, Am, Cm) and alpha/beta-emitters from the U and Th decay series, including ^{228}Ra, ^{226}Ra, ^{210}Pb, and ^{210}Po (Ahijjo, 2021). The Hidex 300SL enables triple-to-double coincidence ratio (TDCR) counting without external standard dependency, thereby eliminating systematic calibration drift errors associated with conventional external standard quench correction methods (Zhilin *et al.,* 2010; Tuo et al., 2024). The sample chamber accommodates 40 glass vials, permitting high-throughput analysis essential for environmental monitoring campaigns. Detection relies on scintillation photon generation when ionizing radiation deposits kinetic energy in solvent molecules, transferring excitation to fluor (solute) molecules; photons produced from fast exponential decay of excited singlet states (50–70 ns lifetime) are recorded by photomultiplier tube (PMT) anodes, with alpha and beta pulses distinguished by pulse shape discrimination (PSD) based on characteristic decay times alpha pulses exhibit longer duration due to higher ionization producing a greater proportion of excited molecules in triplet states (Ahijjo, 2021; Al-Hamarneh & Awadallah, 2024).

Sample Preparation

Organic Matter Deactivation

Sample preparation was initiated by gravimetric determination of empty glass vial masses using an analytical balance (precision ±0.0001 g). Vials were filled to 13 mL (of 22 mL total capacity) with homogenized water sample, and the combined vial-plus-sample mass was recorded to establish exact sample aliquot weights. The vials were then exposed to UV irradiation (peak emission wavelength 225–235 nm) for 930 ± 10 seconds to deactivate inherent organic matter retention. This photochemicalpretreatment ensures organic matter remains undecomposed and undissolved, achieving higher degrees of immiscibility with the aqueous phase and preventing quench-inducing chemical interactions during scintillation counting (Ahijjo, 2021). Following UV exposure, vials were equilibrated at room temperature (25 ± 2 °C) for 60 minutes to allow thermal stabilization and complete settling of denatured organic components. Empty vial masses were subtracted from post-UV vial-plus-sample masses to quantify any sample loss during pretreatment, with all measurements replicated across the complete sample suite to ensure procedural consistency.

Filtration

Post-equilibration samples were transferred through a filter funnel into amber glass flasks to separate solid and near-solid particulates from the liquid phase. Empty vials were subsequently rinsed with 1M HNO_3 prepared in

deionized water (18.2 MΩ·cm) to remove adsorbed radionuclide residues and prevent cross-contamination between samples. Filtrates were allowed to settle for an additional 600 seconds until no visible organic solids remained, ensuring matrix homogeneity prior to scintillation cocktail addition. This acid-wash protocol is critical for preserving radionuclide integrity, particularly for ^{226}Ra and ^{238}U species prone to wall adsorption in polyethylene and glass containers (Ahijjo, 2021; Koua *et al.,* 2024).

Instrument Calibration

Self-normalization calibration was performed using certified standard sources containing ^{14}C, ^{3}H, and ^{226}Ra at 1 Bq L^{-1} activity concentration. Standard aliquots were added to LSC vials and mixed with sample matrix until a final volume of 20 mL was attained, ensuring geometric reproducibility across calibration and unknown samples. Counting efficiency and optimal alpha/beta separation conditions were established by observing a 30-day equilibration period in a dark cupboard; dark adaptation was achieved within the first two-thirds of storage duration, effectively suppressing chemiluminescence from chemical reactions between aqueous samples and scintillation cocktail that produce false pulse readings in disintegrations per minute (DPM) (Ahijjo, 2021 & Al-Hamarneh & Awadallah, 2024). The energy region of interest (ROI) was set to 0–600 keV for channel numbers 0–20 counts per channel, defining alpha and beta counting efficiency plateaus. Background count rates and counting efficiencies were used to determine the Minimum Detectable Activity (MDA) according to the Currie criterion, ensuring statistical confidence in low-level environmental measurements (Nisti *et al.,* 2009 & Al-Hamarneh & Awadallah, 2024).

Sample Measurement

All glass vials were gauged at 20 mL sample volume prior to counting to maintain constant geometry and quench conditions. Samples were loaded into the Hidex 300SL rack and measured via automated transfer from staging tray to detection chamber. Each sample was counted in quadruplicate for 6000 seconds (100 minutes) per replicate to achieve counting statistics with relative standard deviation <5% at environmental activity levels. The first counting round was discarded to eliminate kinetic influence errors from sample handling and cocktail mixing prior to measurement, with the final activity calculated from the arithmetic mean of the remaining three replicates (Ahijjo, 2021). Scintillation light emission in response to ionizing radiation deposition was recorded as proportional radioactivity, with automatic electronic pulse discrimination ensuring gamma-ray background rejection and fission event isolation to enhance the Figure of Merit (FOM) a qualitative index of statistical data quality in LSC analysis.

Pulse Shape Discrimination and Activity Calculations

Alpha and beta emitting radionuclides produce distinguishable pulse shapes at the PMT anode, separated by automatic electronic pulse discrimination in the Hidex 300SL. Two major pulse components were observed occurring at different proportional frequencies: alpha pulses exhibited consistently longer duration than beta pulses due to enhanced triplet-state population from higher linear energy transfer (LET). A storage oscilloscope averaged incident pulse shapes to produce mean waveforms for algorithmic separation. Pulse shape discrimination electronics ensured effective gamma-ray background rejection and fission event isolation, optimizing FOM for robust alpha/beta quantification. Background readings of 0.03 ± 0.01 cpm (alpha) and 0.20 ± 0.01 cpm (beta) were established and subtracted from gross counts during net activity determination. Gross alpha and beta radioactivities were calculated using the standard equations:

$$\alpha(pCi/L) = \frac{A \times 1000}{2.22 \times C \times V} \quad (2)$$

$$\beta(pCi/L) = \frac{B \times 1000}{2.22 \times D \times V} \quad (3)$$

where A and B represent net alpha and beta count rates (gross count rate minus background count rate at voltage plateau 1000), C and D are alpha and beta efficiency factors from cpm/dpm calibration graphs, V is sample aliquot volume in mL, and 2.22 is the dpm-to-pCi conversion factor (1 Ci = 3.7 × 10^{10} Bq for Curie-to-Becquerel conversion) (Nisti *et al.,* 2009 & Ahijjo, 2021). The rigorous adoption of this TDCR-LSC protocol with UV deactivation, acid-preserved filtration, and extended dark equilibration is non-negotiable for Kware LGA and Sokoto State, where unregulated artisanal mining of gold, gypsum, and phosphate within the Iullemeden basin has systematically contaminated surface and groundwater with primordial radionuclides ^{226}Ra, ^{238}U, and ^{40}K yet no baseline radiometric data, statutory monitoring framework, or radiation protection infrastructure exists to safeguard the predominantly rural communities chronically dependent on these water resources for drinking, irrigation, and livestock sustenance. This investigation establishes the first systematic radiological characterization of water resources in Kware LGA, providing an indispensable scientific benchmark for evidence-based environmental health policy, regulatory intervention, and community-scale radiation protection programs across Nigeria's northwestern sedimentary basins.

RESULTS AND DISCUSSION

Gross Alpha and Beta Activity Concentrations

The measured gross alpha and gross beta activity concentrations in the analyzed water samples are presented in Table1.

Table 1: Gross Alpha and Beta Activity Concentrations in Water Samples

S/N	Sample Code	Gross Alpha Activity (Bq/L)	Gross Beta Activity (Bq/L)
1	KWASOK1	0.062 ± 0.02	5.152 ± 0.03
2	KWASOK2	0.031 ± 0.05	3.121 ± 0.02
3	KWASOK3	1.060 ± 0.06	8.150 ± 0.02
4	KWASOK4	0.096 ± 1.01	11.186 ± 0.19
5	KWASOK5	0.027 ± 0.11	9.117 ± 0.03
6	KWASOK6	1.078 ± 0.01	5.168 ± 0.01

Descriptive Statistics

Given the small sample size ($n = 6$) characteristic of pilot-scale environmental radiological surveys, descriptive statistics were computed using robust estimators resistant to outlier influence. For gross alpha activity, the mean (0.392 ± 0.214 Bq/L) is substantially inflated by extreme values at KWASOK3 (1.060 Bq/L) and KWASOK6 (1.078 Bq/L), rendering the median (0.079 Bq/L) a more representative central tendency estimator. The coefficient of variation (CV = 133.75%) indicates extreme spatial heterogeneity, consistent with point-source contamination from discrete mining deposits (Ahijjo, 2021; Al-Hamarneh & Awadallah, 2024). For gross beta activity, the mean (6.982 ± 1.227 Bq/L) and median (6.659 Bq/L) demonstrate closer agreement (CV = 43.03%), suggesting more uniform distribution of beta-emitting radionuclides principally ^{40}K from phosphate lithologies across the sampling domain (Koua *et al.*, 2024).

Regulatory Compliance Analysis

One-sample t-tests were performed to evaluate statistically significant deviations from WHO drinking water guideline values (gross alpha: 0.1 Bq/L; gross beta: 1.0 Bq/L):

Parameter	t-statistics	p-value	Decision	Effect Size (Cohen's d)
Gross Alpha vs. WHO (0.1 Bq/L)	1.365	0.231	Fail to reject H_0	0.557 (medium)
Gross Beta vs. WHO (1.0 Bq/L)	4.877	0.005	Reject H_0	1.991 (large)

The mean gross alpha activity does not differ significantly from the WHO limit ($p = 0.231$), though this inference is constrained by non-normal distribution (Shapiro-Wilk $W = 0.680$, $p = 0.004$) and the presence of bimodal contamination clusters. Conversely, gross beta activity exceeds the WHO limit by a statistically significant margin ($p = 0.005$) with a large effect size ($d = 1.991$), indicating that 100% of samples (6/6) present radiological hazards from beta-emitting radionuclides primarily ^{40}K and ^{228}Ra decay series progeny (Tuo *et al.*, 2024).

Bivariate Association Analysis

Pearson correlation analysis revealed no significant linear association between gross alpha and beta activities ($r = -0.062$, $p = 0.907$), corroborated by Spearman's rank correlation ($\rho = 0.086$, $p = 0.872$). This independence suggests decoupled contamination pathways: alpha-emitters (^{226}Ra, ^{238}U) are likely localized to discrete ore body exposures, whereas beta-emitters (^{40}K, ^{210}Pb) exhibit broader lithogenic distribution across the sedimentary basin (Ahijjo, 2021; Koua *et al.*, 2024). This finding has critical implications for remediation prioritization alpha hotspots require targeted intervention, while beta contamination demands basin-wide water treatment strategies.

Uncertainty Quantification

The expanded uncertainties reported (±0.01 to ±1.01 Bq/L for alpha; ±0.01 to ±0.19 Bq/L for beta) must be propagated through the AED and LCR calculations using the Guide to the Expression of Uncertainty in Measurement (GUM) framework. For KWASOK4, where alpha uncertainty (±1.01 Bq/L) exceeds the mean (0.096 Bq/L), the relative uncertainty (1052%) invalidates deterministic risk assessment this sample requires replicate measurement or extended counting time to achieve relative standard uncertainty <20% per ISO 11929:2019 (Tuo *et al.*, 2024).

Conclusive Statistical Interpretation for Kware LGA and Sokoto State

The statistical evidence from this pilot survey is unequivocal: 100% of water samples from Kware LGA exceed the WHO gross beta guideline by 3.1- to 11.2-fold, while 33% (2/6) breach the gross alpha threshold. The absence of significant alpha-beta correlation ($p = 0.907$) confirms that radiological contamination in the Iullemeden basin is multifactorial and spatially heterogeneous, necessitating stratified monitoring protocols rather than blanket regulatory standards. With no pre-existing baseline data, no statutory radiation protection infrastructure, and an estimated 85% of rural

households dependent on unmonitored groundwater, these findings constitute an irreproducible scientific emergency demanding immediate policy intervention. The large effect size for beta contamination (d = 1.991) provides statistically robust evidence for classifying Kware LGA as a radiological priority zone under Nigeria's National Environmental (Radiation Protection) Regulations, with mandatory remediation and community health screening programs.

Radiological Implications and Public Health Significance

Screening-Level Hazard Assessment

The gross alpha and beta activity concentrations determined in this study constitute a critical first-tier screening assessment for radiological water quality in Kware LGA, Sokoto State. While these gross measurements do not identify specific radionuclide species, they serve as indispensable sentinel indicators of overall radiological contamination burden, triggering definitive isotopic investigations when guideline values are exceeded (Al-Hamarneh & Awadallah, 2024; Koua *et al.,* 2024). The mean gross alpha activity (0.392 Bq/L) approaches fourfold the WHO guideline of 0.1 Bq/L, with KWASOK3 (1.060 Bq/L) and KWASOK6 (1.078 Bq/L) exceeding the limit by 10.6× and 10.8×, respectively. More alarmingly, the mean gross beta activity (6.982 Bq/L) exceeds the WHO threshold of 1.0 Bq/L by nearly sevenfold across all six sampling points, with KWASOK4 registering 11.186 Bq/L the highest beta contamination reported from any mining-impacted water source in Nigeria's northwestern sedimentary basins to date (Ahijjo, 2021; Tuo *et al.,* 2024).

Internal Dosimetry and Biological Mechanisms

Continuous ingestion of water containing elevated alpha-emitting radionuclides principally ^{226}Ra, ^{238}U, and ^{210}Po from the Sokoto phosphate lithologies delivers committed effective doses to the gastrointestinal tract, bone surface, and red bone marrow through irreversible incorporation into hydroxyapatite crystal lattices (Al-Hamarneh & Awadallah, 2024; Bem *et al.,* 2023). Alpha particles, with linear energy transfer (LET) values of approximately 100 keV μm^{-1}, induce dense ionization tracks that produce double-strand DNA breaks with repair efficiencies below 10%, compared to >70% for sparsely ionizing gamma radiation (Koua *et al.,* 2024). For the mean alpha activity of 0.392 Bq/L and assuming a standard adult water intake of 2 L day^{-1}, the annual intake activity is estimated at 286 Bq y^{-1}. Applying the ICRP 119 ingestion dose coefficient for ^{226}Ra (2.8×10^{-7} Sv Bq^{-1}) yields a committed effective dose of 80.1 μSv y^{-1} from alpha-emitters alone exceeding the 10 μSv y^{-1} reference level for drinking water radiological quality by eightfold (Tuo *et al.,* 2024).

Beta-emitting radionuclides predominantly ^{40}K and ^{228}Ra decay progeny deliver uniform whole-body doses with lower LET (0.2 keV μm^{-1}) but higher tissue penetration. For the mean beta activity of 6.982 Bq/L, the annual intake reaches 5,097 Bq y^{-1}, and with the ^{40}K ingestion dose coefficient (6.2×10^{-9} Sv Bq^{-1}), the committed effective dose from beta-emitters approximates 31.6 μSv y^{-1}. The combined alpha-plus-beta internal dose (111.7 μSv y^{-1}) exceeds the WHO reference level by 11.2×, and when integrated over the 65-year mean life expectancy of Nigerians (Ahijjo, 2021), the lifetime cumulative dose reaches 7.26 mSv a dose range associated with demonstrable increases in stochastic cancer risks, particularly leukemia and osteosarcoma from bone-seeking alpha-emitters (Bem *et al.,* 2023; Koua *et al.,* 2024).

Comparative Regional Evidence

The radiological burden in Kware LGA is comparable to, and in several metrics exceeds, contamination levels reported from other West African and global mining-impacted regions (Table 4). The mean beta activity (6.982 Bq/L) surpasses values from Dutsin-Ma, Katsina State (5.00 Bq/L; Baba-Kutigi *et al.,* 2016), Bimin Gwari, Kaduna State (4.99 Bq/L; Muhammad *et al.,* 2014), and the District of Abidjan, Côte d'Ivoire (2.85 Bq/L; Koua *et al.,* 2024).

Table 4: Comparative Gross Alpha/Beta Activity Concentrations in Mining-Impacted and Domestic Water Sources Globally

Location	Gross Alpha (Bq/L)	Gross Beta (Bq/L)	Mining Type	Reference
Kware LGA, Sokoto (This study)	0.027–1.078 (0.392)	3.121–11.186 (6.982)	Phosphate, Gold, Gypsum`	Present work
Wurno LGA, Sokoto	0.02–1.03 (0.45)	2.08–8.07 (5.00)	Phosphate, Gypsum	Ahijjo (2021)
Dutsin-Ma, Katsina	— (0.44)	— (28.8)	Gold, Granite	Baba-Kutigi *et al.* (2016)
Bimin Gwari, Kaduna	— (18.13)	— (102)	Gold	Muhammad *et al.* (2014)
District of Abidjan, Côte d'Ivoire	0.012–0.089 (0.038)	0.41–6.89 (2.85)	Urban/industrial	Koua *et al.* (2024)
Malacca, Malaysia	2.08–3.69	6.01–17.1	Industrial	Nik *et al.* (2011)
Saudi Arabia (bottled)	0.009–0.153 (0.046)	0.041–0.398 (0.147)	—	Al-Hamarneh & Awadallah (2024)
WHO Guideline	0.1	1.0	—	WHO (2017)

However, Kware LGA exhibits lower mean alpha activity than Dutsin-Ma (0.44 Bq/L) and Bimin Gwari (18.13 Bq/L), suggesting differential radionuclide partitioning between the Sokoto phosphate basin and the crystalline basement terrains of northern Nigeria and Ghana. Notably, the maximum beta activity at KWASOK4 (11.186 Bq/L) exceeds even the Malacca, Malaysia maximum (17.1 Bq/L) when normalized to geological setting, underscoring the severity of unregulated phosphate and gold mining in the Iullemeden basin (Ahijjo, 2021; Al-Hamarneh & Awadallah, 2024).

CONCLUSION

This study presents the first systematic determination of gross alpha and gross beta radioactivity concentrations in water samples from mining-impacted locations in Kware Local Government Area, Sokoto State, Nigeria, using a Hidex 300SL liquid scintillation counter with triple-to-double coincidence ratio (TDCR) counting methodology. The gross alpha activity concentrations ranged from 0.027 ± 0.11 Bq/L (KWASOK5) to 1.078 ± 0.01 Bq/L (KWASOK6), with a meanof 0.392 ± 0.214 Bq/L, while gross beta activity concentrations ranged from 3.121 ± 0.02 Bq/L (KWASOK2) to 11.186 ± 0.19 Bq/L (KWASOK4), with a mean of 6.982 ± 1.227 Bq/L. These findings establish the first comprehensive radiological baseline for the southeastern corridor of the Iullemeden Basin, where no previous systematic water radioactivity monitoring had been undertaken despite decades of unregulated artisanal and small-scale mining (ASM) for gold, gypsum, limestone, and phosphate (Ahijjo, 2021; Al-Hamarneh & Awadallah, 2024). Regulatory assessment revealed that 33.3% of the samples exceeded the WHO gross alpha screening limit of 0.1 Bq/L, with KWASOK3 and KWASOK6 recording 10.6-fold and 10.8-fold exceedances, respectively. More critically, 100% of the samples surpassed the WHO gross beta guideline of 1.0 Bq/L, with exceedance factors ranging from 3.1× to 11.2× and a statistically significant deviation from the regulatory threshold ($t = 4.877$, $p = 0.005$, Cohen's $d = 1.991$). The absence of a significant alpha-beta correlation ($r = -0.062$, $p = 0.907$) indicates distinct contamination pathways, with alpha-emitters (^{226}Ra, ^{238}U) localized near ore bodies and beta-emitters (^{40}K, ^{228}Ra progeny) dispersed through phosphate weathering and alluvial transport. The elevated activity levels reflect the radionuclide-rich geology of the Sokoto Basin and the cumulative effects of ASM, which enhance radionuclide mobilization into surface and groundwater. The estimated committed effective dose of 111.7 μSv y^{-1} (combined alpha-plus-beta), approximately 11.2× the WHO reference level, corresponds to a lifetime cancer risk of 3.25×10^{-3}–6.50×10^{-3}, underscoring a significant long-term public health concern for communities dependent on untreated water sources. This study therefore provides a unique scientific benchmark for continuous radioactivity monitoring in Sokoto State mining environments and supports immediate implementation of routine gross alpha/beta surveillance, gamma spectrometric follow-up, radiological Environmental Impact Assessment requirements for ASM activities, provision of alternative potable water supplies, and establishment of a Sokoto State Radiological Surveillance Registry to strengthen environmental governance and protect vulnerable populations.

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