

Methodology Article

Environmental Assessment of Heavy Metals Contamination and Radionuclides Exposure in Automotive, Industrial, and Residential Areas in Gboko, Nigeria

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Abstract

This study assessed heavy metal contamination and radionuclide exposure in automobile, industrial, and residential areas in Gboko, Nigeria. The concentration of heavy Metals in the soil of these areas was assessed to determine the presence and activity levels of radionuclides. The evaluation showed the potential health risks associated with exposure to these contaminants and suggested possible remediation and policy recommendations. The study used Atomic Absorption Spectrometry, and soil samples were air dried, while the equipment used to evaluate heavy metals was the Lovibond Tintometer model MD 600. The study used a model equation to analyze the data. Findings revealed that Heavy metal exposure varied across land-use areas, with lead (Pb) levels highest in residential zones (HQ: 0.171) and cadmium (Cd) posing the greatest concern overall, especially in residential areas where the HQ approached 0.380. Chromium (Cr) exposure was most significant in industrial zones, though all hazard quotients remained below hazardous thresholds, while elevated zinc (Zn) levels in automotive workshops stayed within safe limits; radiation levels from Ra-226, Th-232, and K-40 were minimal, with the highest dose in Industrial 1 due to Ra-226 (0.5 Bq/kg) resulting in a TED of 0.2420 mSv/y and ELCR of 0.0847. Nonetheless, all measured values were well below international safety limits, indicating that current heavy metal and radionuclide contamination does not pose significant health risks in the study areas. Proactive environmental monitoring, especially in high-activity zones, is recommended to reduce pollution and safeguard public health.

Keywords

Soil Contamination, Environmental Pollution, Internal Hazard Index, Radiological Hazard, Phytotoxic Effects, Reactive Oxygen Species

1. Introduction

It has been observed in recent times that the role the environment plays in a nation's development process cannot be relegated to the background. Apart from being the physical surroundings for natural habitats, the environment provides

the basis for human exploits for agricultural, industrial, commercial, technological, and tourism development of a society [5]. For this and several other reasons, environmental issues now occupy a centre stage in academic discourse and

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other public for at both the national and international levels. Recorded evidence has also shown that the environment represents a wide range of external circumstances, conditions, and the things that affect the existence and development of an individual, organism, group, and/or society [16]. Heavy metal exposure has been linked to various adverse health effects, including neurological disorders, organ damage, and cancer [1]. The increasing industrialization and urbanization in areas such as Gboko pose potential threats to groundwater quality, necessitating a thorough assessment of arsenic and heavy metal concentrations in these areas [2].

In Nigeria for instance, environmental issues did not gain official prominence until the 1988 Koko toxic waste dumping saga, which also brought to the fore the exigent need to establish the Nigeria Federal Environmental Protection Agency (FEPA), Federal Ministry of Environment and other relevant agencies, ostensibly to tackle environmentally related issues in the country. These include issues such as environmental pollution, sanitation, depletion of the ozone layer, desertification, flooding, erosion, poverty, bush burning, deforestation, and soil conservation [17]. All these mentioned above are pointers to the fact that issues of environment and environmental pollution, which form the basis of this paper, have taken centre stage in the nation's (Nigeria's) development process. Environmentally minded scholars [3, 4, 14] have associated environmental pollution with human activities and, albeit, persistent human interaction with the environment. Research has also shown that as the population of a country grows/increases with attendant pressure on the environment, especially in the wake of improved technologies, environmental abuse and pollution is nevertheless heightened with corresponding effects on lives of people and other living organisms, [6, 14].

The toxic mechanism of heavy metals functions in similar pathways, usually via reactive oxygen species (ROS) generation, enzyme inactivation, and suppression of the antioxidant defense. However, some of them cause toxicities in a particular pattern and bind selectively to specific macromolecules. Different toxic mechanisms of heavy metals increase our knowledge on their harmful effects on the body organs, leading to better management of animal and human poisonings [18]. Environmental and strategic impact assessment for heavy metals and radioactive elements outlines various possible negative effects to the environment that may result from the presence of heavy metals in food and underground water. This includes contamination of the water bodies (surface and ground water) as a result of heavy metals and general deprivation of fertile lands for agriculture [7]. Pollution of soil by high amounts of heavy metals affects the ecosystem and, in particular, its productivity. This poses a high risk to the animal and the health of the people living around where Anti-corrosion coatings and Battery acid are discriminately used. Exposure to elevated levels of heavy metals may lead to damage to the kidneys, brain, and even the developing fetuses [15]. Therefore, a good knowledge and understanding of the

levels of heavy metals, radioactivity and the spatial variation in the soil is very relevant and essential, the findings and recommendations from this study will give opportunities for further research on the environmental effect of mining and use of chemicals to the people living around Gboko, Automotive (Yandev), industrial (Mbayion) and Residential (Tyeku) any toxic effects that it might pose to soil, water and the crops grown on the soil. The findings of this study will provide adequate idea of the pollution levels of these sites and would add to the environmental database of the soil of this mechanic workshop, which will assist in the monitoring and comprehensive waste management plan, standard guidelines for establishment of mechanic villages, remediation strategies for heavy metal contaminated soil, code of practice, and continuous education for the mechanics.

Relevant Theories and Theoretical Framework

Fick's second law generally gives the diffusion equation describing the spread of contaminants in the environment

$$\frac{\partial c}{\partial x} = D \nabla^2 C \quad (1)$$

Where:

C (x, t) is the concentration of the contaminant at position x and time t. D is the diffusion coefficient, which represents how fast the contaminant spreads in the environment. ∇^2 is the Laplacian operator, which represents the spatial variation of the concentration (in multiple dimensions). In 1D, this equation simplifies to:

$$\frac{\partial c(x,t)}{\partial t} = D \frac{\partial^2 c(x,t)}{\partial x^2} \quad (2)$$

This equation assumes that the contaminant is diffusing through a medium (e.g., soil or water) and the diffusion is isotropic (the same in all directions). Boundary and initial conditions need to be specified to solve the equation for example, the Initial condition: the initial distribution of contaminants at t = 0. Boundary conditions: these could represent physical constraints like fixed concentrations at boundaries, no-flux conditions (representing the absence of contaminant flow across boundaries, for example, $\frac{\partial c}{\partial x} = 0$ at the boundaries for no flux in 1D

Radioactive Decay Law

The radioactive Decay law describes the process by which unstable atomic nuclei lose energy by emitting radiation in the form of particles or electromagnetic waves. It follows an exponential decay model, meaning the rate of decay is proportional to the number of unstable nuclei present at any given time [8].

The fundamental equation governing radioactive decay is:

$$N(t) = N_0 e^{-\lambda t} \quad (3)$$

Where N(t) is the number of undecayed nuclei at time t. N_0 is the initial number of radioactive nuclei at time t = 0, e is the

Euler's number (approximately 2.71828), t is the time, and the decay constant λ is related to the half-life ($t_{1/2}$) of the substance, which is the time it takes half of the radioactive nuclei to decay. The relationship between the decay constant and half-life is $\lambda = \frac{\ln(2)}{t_{1/2}}$

Bioaccumulation

Bioaccumulation is the gradual accumulation of substances, such as pesticides or other chemicals, in an organism. Bioaccumulation occurs when an organism absorbs a substance faster than it can be lost or eliminated by catabolism and excretion. Thus, the longer the biological half-life of a toxic substance, the greater the risk of chronic poisoning, even if environmental levels of the toxin are not very high. The modeled equation of toxicity of heavy metals in organisms relating mass and volume is given by:

$$C = \frac{M}{V} \quad (4)$$

Where C is the concentration of the metal, M is the mass of the metal, V is the volume of the medium (e.g., soil, water). The relationship helps us to express how the concentration in a specific organ or tissue is influenced by the mass of the metal and the volume of the compartment it occupies.

Toxicity Model

The toxicity of heavy metals typically increases with concentration. A simple model for might be based on a dose-response relationship where the effect of toxicity is a function of the heavy metal present in the organism. A common form of this dose-response relationship is the Hills equation or the sigmoidal function.

$$T(c) = \frac{T_{max}c^n}{EC_{50}^n + c^n} \quad (5)$$

Where, $T(c)$ is the toxicity or the effect of heavy metal at concentration c , T_{max} is the maximum possible toxic effect, EC_{50} is the concentration at which half of the maximum effect is observed (the effective concentration for 50% toxicity), n is the Hill efficient, which represent the steadiness of the curve. Linking toxicity with mass and volume, recall that $C = M/V$, we can substitute this into the toxicity equation.

$$T(m) = \frac{T_{max}(M/V)^n}{EC_{50}^n + (M/V)^n} \quad (6)$$

This equation relates the toxicity of the heavy metal to the M of the metal in the organism and the volume V of the compartment

Toxicity over time: If the concentration or mass of the heavy metal changes over time (due to uptake accumulation and elimination) we can model the mass of metal over time using a dynamic equation.

$$T(t) = \frac{T_{max}(\frac{M(t)}{V})^n}{EC_{50}^n + (\frac{M(t)}{V})^n} \quad (7)$$

Where $M(t)$ is the mass of the heavy metal in the organism at time t , which can be modeled using bioaccumulation equations like the one described earlier. The mass $M(t)$ changes over time due to the processes of uptake and elimination. General toxicity Equation is given as the relationship between bioaccumulation mass, volume and concentration could be written as

$$T_{(t)} = \frac{T_{max}(kuC_{ext}V/V)^n}{EC_{50}^n + (kuC_{ext}V/V)^n} \quad (8)$$

Where ku is the uptake rate constant C_{ext} is the external concentration of the heavy metal, and V is the volume of the organism or the compartment being. Threshold model (toxicity Vs concentration): for a simpler approach, sometimes a threshold concentration ($C_{threshold}$) is used, where Toxicity only occurs if the concentration exceeds a certain value.

Diffusion Equation of contaminants in soil

Water and soil (or water-saturated porous media) can be modeled using the Laplacian in the diffusion equations. The Laplacian operator accounts for the spatial variation of the concentration in multiple dimensions and is commonly used in partial differential equations. The diffusion in soil equation becomes

$$D_{eff} \times \nabla^2 C = 0 \quad (9)$$

Where, $D_{eff} = D_{water} \times \frac{\phi}{\tau}$ is the effective diffusion coefficient in the porous medium. C is the contaminant concentration in the water phase of the soil.

$$D_{eff} \frac{\partial^2 c}{\partial x^2} = 0 \quad (10)$$

The solution for the concentration profile is

$$C_{(x)} = C_{0e}^{-\frac{x}{L_{eff}}} \quad (11)$$

Where, L_{eff} is the characteristic diffusion length adjusted for the porosity and tortuosity of the soil. For a three-dimensional porous medium, the Laplacian operator becomes:

$$\nabla^2 C = \frac{\partial^2 c}{\partial x^2} + \frac{\partial^2 c}{\partial y^2} + \frac{\partial^2 c}{\partial z^2} \quad (12)$$

Radionuclides Detection

In practice, the detection of radionuclides involves not only the initial intensity but also the efficiency of the detector. The equation is modified to incorporate detection efficiency η

$$I_{detected} = \eta \times I \quad (13)$$

Where, $I_{detected}$ is the radiation intensity detected by sensor or instrument, η is the efficiency of the detector, which is the

fraction of emitted radiation that is actually detected. Activity of a radionuclide: the activity (A) of a radionuclide is related to the number of decays per unit time. For a radionuclide with activity A, the emitted radiation intensity is proportional to A, the equation is given as;

$$I \propto A \cdot e^{-\mu x} \quad (14)$$

Where A is the activity of the radionuclide (measured in Bq), $e^{-\mu x}$ represents the attenuation of radiation as it travels through a material.

2. Materials and Methods

This study was carried out in Gboko, Benue State of Nigeria, covering three major locations. There are, Mechanic site (Yandev), residential area (Tyeku) and industrial Dangote cement factory (Mbayion). Gboko, is a local government area in Benue State, North Central Nigeria. It is headquartered in the town of Gboko with a land mass of 2 264sq km. Having a population of 358,936 according to the 2006 census. It is the largest of the twenty-three local governments by population in Benue State. It lies between latitude $7^{\circ}19'30.00''$ N and longitude $9^{\circ}00'18.00''$ E. The vegetation type in Gboko is Guinea Savannah with annual rainfall between 150-180 mm and temperature of 26°C - 40°C [2].

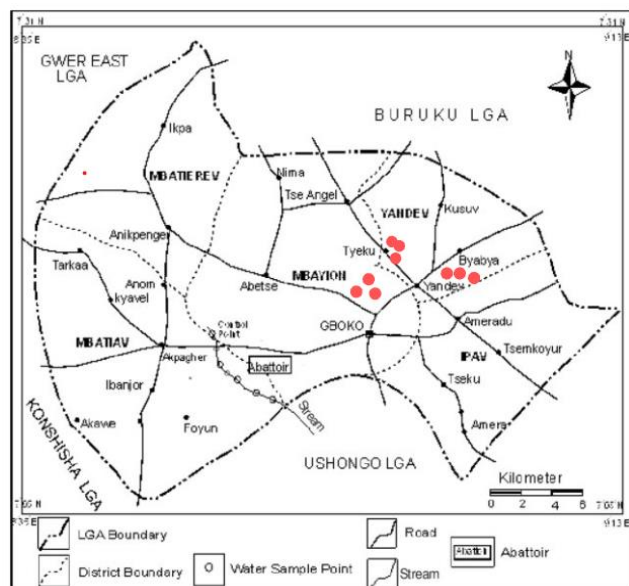


Figure 1. Map showing sample locations.

The method used is called Atomic Absorption Spectrum. The soil samples were air dried and then used to make a stainless-steel sieve after being smashed using a mortar and pestle. The equipment used to evaluate heavy metals is Lovibond Tintometer model MD 600. The sample was inserted into the well of the equipment after being cleaned and zeroed

using the meter zero key. The desired parameter to be determined was selected using the mode key. A 10 ml of the stock was measured into a vial. There are different reagents for different heavy metal tests, Hydrochloric Acid (HCl) in combination with Nitric Acid (HNO_3) was added into drops in the stock in 10 ml vial, the sample was removed and then Dithizone was added to the sample and shaken for one minute after which it was placed in the hollow space in the equipment, the sample containing the reagent was inserted and allow to be steady before readings were taken.

Soil Sample Preparation for NaI (Ti) Gamma Spectrometry Measurement

Each of the soil samples collected was dried and crushed to fine powder with the use of pulverizer. Packaging of the samples into radon-impermeable cylindrical plastic containers, which were selected based on the space allocation of the detector vessel, which measures 7.6 cm by 7.6 cm in dimension (geometry) was also carried out. To prevent radon-222 escaping, the packaging in each case was triple sealed with masking tape. The sealing process included smearing of the inner rim of each container lid with Vaseline jelly, filling the lid assembly gap with candle wax to block the gaps between lid and container, and tight-sealing lid-container with masking adhesive tape. Radon and its short-lived progenies were allowed to reach secular radioactive equilibrium by storing the samples for 30 days before gamma spectroscopy measurements.

Evaluation of Radioactivity of Samples-

The analysis was carried out using a 76 x76 mm NaI (TI) detector crystal optically coupled to a photomultiplier tube (PMT). The assembly has a preamplifier incorporated into it and a 1 kilovolt external source. The detector is enclosed in a 6 cm lead shield with cadmium and copper sheets. This arrangement is aimed at minimizing the effects of background and scattered radiation. The data acquisition software is Maestro by Canberra Nuclear Products. The samples were measured for a period of 29000 seconds, for each sample. The peak area of each energy level in the spectrum was used to compute for the activity concentrations in each sample by the use of the following equation:

$$C(\text{Bq} \cdot \text{kg}^{-1}) = \frac{C_n}{C_{fk}} \quad (15)$$

Where, C = activity concentration of the radionuclide in the sample given in $\text{Bq} \cdot \text{kg}^{-1}$, C_n = count rate (counts per second) and Count per second (cps) = $\frac{\text{Net Count}}{\text{Live Time}}$, C_{fk} = Calibration factor of the detecting system.

Calibration and Efficiency Determinations

Calibration of the system for energy and efficiency were done with two calibration point sources, Cs-137 and Co-60. These were done with the amplifier gain that gives 72% energy resolution for the 66.16 Kev of Cs-137 and counted for 30 minutes.

Standards

The standards used to check for the calibration are the K-40, RGU-1 for Ra-226 (Bi-214 peak) and RTG-1 for IAEA gamma Spectrometric reference materials RGK-1 for Th-232 (Ti-208).

Table 1. shows the coordinates of sampled collection location of Residential, Automotive and Industrial.

Sample Location	Latitude	Longitude	Sample location	Latitude	Longitude	Sample location	Latitude	Longitude
Residential			Industrial			Automotive		
Point 1	7 20'38"N	8 59'60E	Point 1	7 19'9.81N	9 1'23E	Point 1	7 45'58N	8 33'25E
Point 2	7 20'36"N	8 58'59E	Point 2	7 19'9.37N	9 1'23E	Point 2	7 45'57N	8 33'25E
Point 3	7 20'37"N	8 58'60E	Point 3	7 19'8.3N	9 1'24E	Point 3	7 46'56N	8 33'26E
Point 4	7 20'35"N	8 59'58E	Point 4	7 19'8.5N	9 1'23E	Point 4	7 45'58N	8 33'26E

3. Results

In the investigation, Lead, Cadmium, Chromium, Iron and Zinc were identified in the soil samples.

Table 2. Heavy metal distribution in three locations.

Sample Locations	Lead (Pb mg/kg)	Cadmium (Cd mg/kg)	Chromium (Cr mg/kg)	Iron (Fe mg/kg)	Zinc (Zn mg/kg)
Residential 1	0.07	0.003	0.02	0.2	0.6
2	0.05	0.02	0.07	0.3	0.8
3	0.06	0.02	0.02	0.4	0.7
4	0.09	0.04	0.06	0.5	0.5
Mean	0.06	0.04	0.03	0.4	0.7
Industrial 1	0.05	0.007	0.07	0.6	0.6
2	0.04	0.005	0.05	0.5	0.3
3	0.03	0.006	0.06	0.8	0.7
4	0.01	0.008	0.04	0.9	0.4
Mean	0.03	0.006	0.05	0.7	0.5
Automobile 1	0.01	0.005	0.03	0.5	0.2
2	0.02	0.007	0.05	0.2	0.5
3	0.02	0.004	0.07	0.5	0.8
4	0.04	0.005	0.04	0.6	0.7
Mean	0.02	0.005	0.04	0.5	0.6
WHO Limits (mg/kg)	0.01	0.003	0.05	0.3	3.0

Table 3. Health Risk Assessment of Heavy Metals.

CDI/HQ	Residential	Industrial	Automotive
CDI (Pb) mg/kg	0.00171	0.000857	0.000571
CDI (Cr) mg/kg	0.000857	0.00143	0.00114
CDI (Cd) mg/kg	0.00114	0.000174	0.000143
CDI (Fe)mg/kg	0.01143	0.020000	0.014286
CDI (Zn) mg/kg	0.02000	0.014286	0.017143
HQ (Pb)	0.171	0.0857	0.0571
HQ (Cr)	0.017	0.0290	0.0228
HQ (Cd)	0.380	0.0030	0.0477
HQ (Fe) mg/kg	0.029	0.0204	0.0244
HQ (Zn) mg/kg	0.097	0.0476	0.0571

CDI = Chronic Daily Intake, HQ = Hazard Quotient

Radionuclides present in soil

Table 4, presents the radiological assessment results of soil samples collected from three different environments: residential, automotive, and industrial. The measured parameters

include the activity concentrations of radionuclides ^{226}Ra , ^{232}Th , and ^{40}K in Becquerels per kilogram (Bq/kg), the Total Annual Effective Dose (TED) in millisieverts per year (mSv/y), and the Excess Lifetime Cancer Risk (ELCR).

Table 4. Radionuclide concentration in Residential, Industrial, and Automotive.

Sample location	Ra-226Bq/kg	Th-232Bq/kg	K-40Bq/kg	TED mSv/y	ELCR
Residential1	0.05	0.07	0.04	0.068	0.0238
2	0.03	0.02	0.09	0.0299	0.0105
3	0.02	0.01	0.07	0.0183	0.0064
4	0.04	0.012	0.07	0.0287	0.0100
Automotive 1	0.04	0.012	0.09	0.0295	0.0103
2	0.05	0.02	0.12	0.0403	0.0141
3	0.07	0.04	0.12	0.0619	0.0217
4	0.05	0.06	0.10	0.0643	0.0225
Industrial 1	0.50	0.011	0.13	0.2420	0.0847
2	0.04	0.034	0.12	0.0444	0.0155
3	0.07	0.04	0.14	0.0627	0.0219
4	0.06	0.015	0.15	0.0431	0.0151
Total activity (Bq/kg)	0.05	0.02	0.10	—	—

Health Risk Assessment

The risk of exposure to heavy metals and radionuclides can be assessed using dose-response relationships, for ingestion Exposure (via

contaminated water or food)

$$CDI = \frac{C \times IR \times ER \times Ed}{BW \times AT} \quad (16)$$

Where CDI= Chronic Daily Intake (mg/kg/day), C= concentration of contaminant (mg/2 or mg/kg), IR= intake rate (L/day for water or kg/day for food), EF= exposure frequency (days/year), BW= Body weight (kg), AT= Average time (day), SF= slope factor (mg/kg/day)²(-1). For inhalation exposure (via air)

$$\text{Risk} = \text{CIR} \times \text{SF} \quad (17)$$

Where, CIR= chronic Inhalation Rate (mg/day), SF= slope factor (mg/kg/day)²(-1).

For Dermal Exposure, Risk = Dermal exposure Dose x SF

$$\text{Dermal exposure Dose} = \frac{C \times SA \times ER \times Ed}{BW \times AT} \quad (18)$$

Where, C is concentration of contaminant (mg/kg), SA is skin surface area (cm²), EF is exposure frequency (days/year), ED is exposure duration (years), BW is body weight (kg), AT is averaging time (days)

4. Discussion

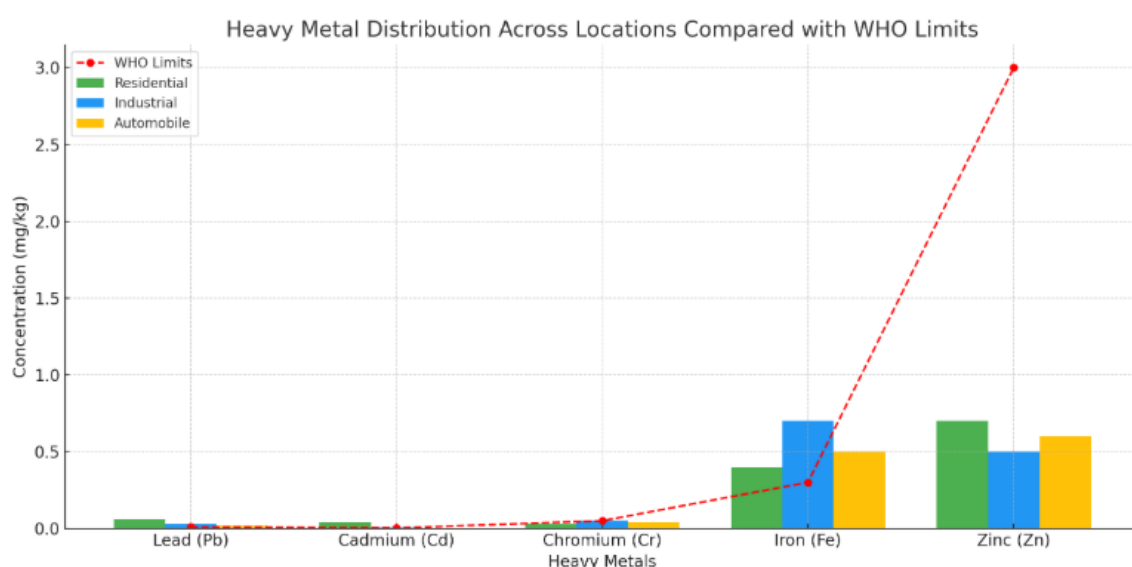


Figure 2. Shows a bar chart of the concentration of Heavy Metals distribution in milligrams per Kilogram (mg/kg) for different sample Sites.

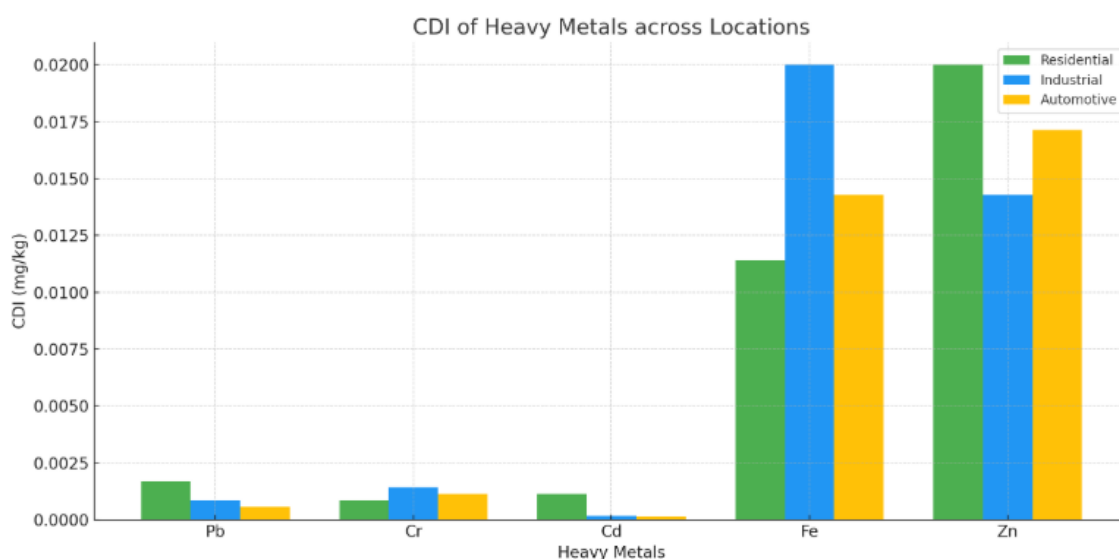


Figure 3. Shows a bar chart of the concentration of Chronic Daily Intake CDI (mg/kg/day) across different sample Locations.

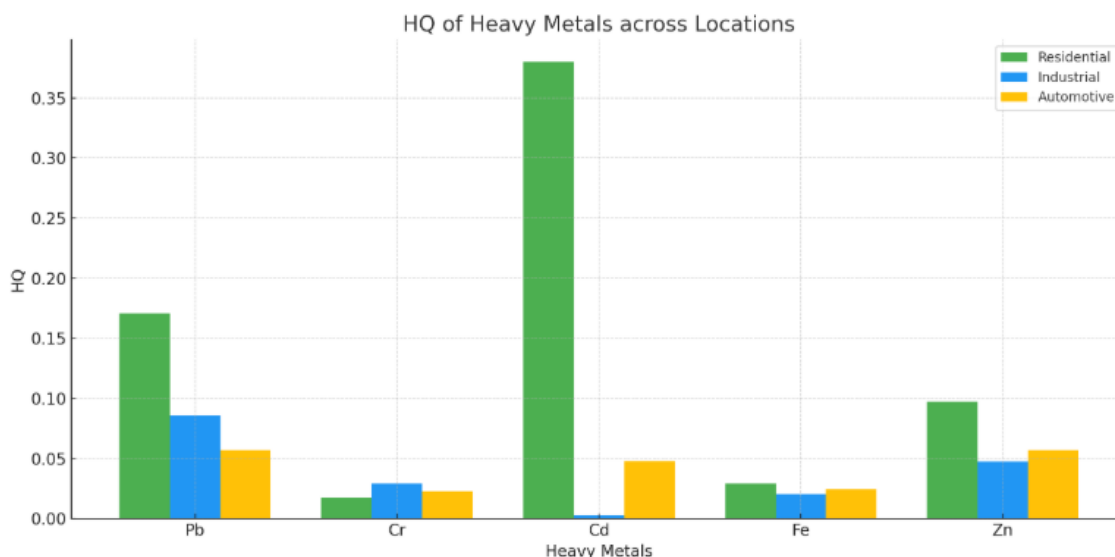


Figure 4. Present a bar chart visualizing the hazard quotient HQ for different sample Locations.

Lead (Pb)

The highest CDI for lead was found in residential areas (0.00171 mg/kg), followed by industrial (0.000857 mg/kg) and automotive zones (0.000571 mg/kg). Although all HQ values (residential: 0.171, industrial: 0.0857, automotive: 0.0571) were below the risk threshold ($HQ < 1$), prolonged exposure could still pose health risks. This finding is consistent with [12], which reported that even low-level Pb exposure may lead to dysfunction in the kidneys, liver, and central nervous system. The slightly elevated Pb levels in automotive and industrial areas could be attributed to vehicle emissions and battery disposal, as noted by [9] in their study on well water contamination.

Chromium (Cr)

Industrial areas exhibited the highest Cr intake (CDI: 0.00143 mg/kg), likely due to industrial effluents from electroplating and tannery activities. While HQ values remained below 1 (industrial: 0.029, automotive: 0.0228, residential: 0.017). [9] warn that chronic Cr (VI) exposure can cause nasal septum perforations, skin ulcerations, and respiratory cancer. The findings are comparable to those of [10], who reported Cr concentrations of 0.010-0.018 mg/kg in groundwater, reinforcing the need for long-term monitoring in industrial zones.

Cadmium (Cd)

Residential areas showed the highest Cd exposure (CDI: 0.00114 mg/kg, HQ: 0.380), nearing levels of concern. [11] highlighted that Cd bioaccumulates in the kidneys and liver,

leading to skeletal and respiratory disorders. Although automotive and industrial areas had lower Cd levels (HQ: 0.0477 and 0.003, respectively), the residential HQ suggests potential long-term risks, particularly since Cd has no known biological benefit and is classified as a human carcinogen. This is particularly concerning because chronic Cd exposure, even at sub-threshold HQ values, can cause irreversible organ damage over time, highlighting the urgent need for targeted remediation in residential zones.

Iron (Fe)

Industrial areas recorded the highest Fe intake (CDI: 0.02000 mg/kg), likely from corroded pipes or industrial discharges. While HQ values were below 1, [12] cautioned that excessive Fe consumption may lead to hemosiderosis, a liver condition caused by iron overload. The results contrast with [13], who reported lower Fe levels (0.004-0.0226 mg/kg) in groundwater, suggesting localized contamination in industrial zones.

Zinc (Zn)

Zinc levels were highest in industrial areas (CDI: 0.017143 mg/kg), but all HQ values were well below 1, indicating minimal risk. [15] noted that excessive Zn intake could cause stomach pain and vomiting, though current concentrations remain within safe limits.

Radiological Assessment of Soil Samples in Residential, Automotive, and Industrial Areas

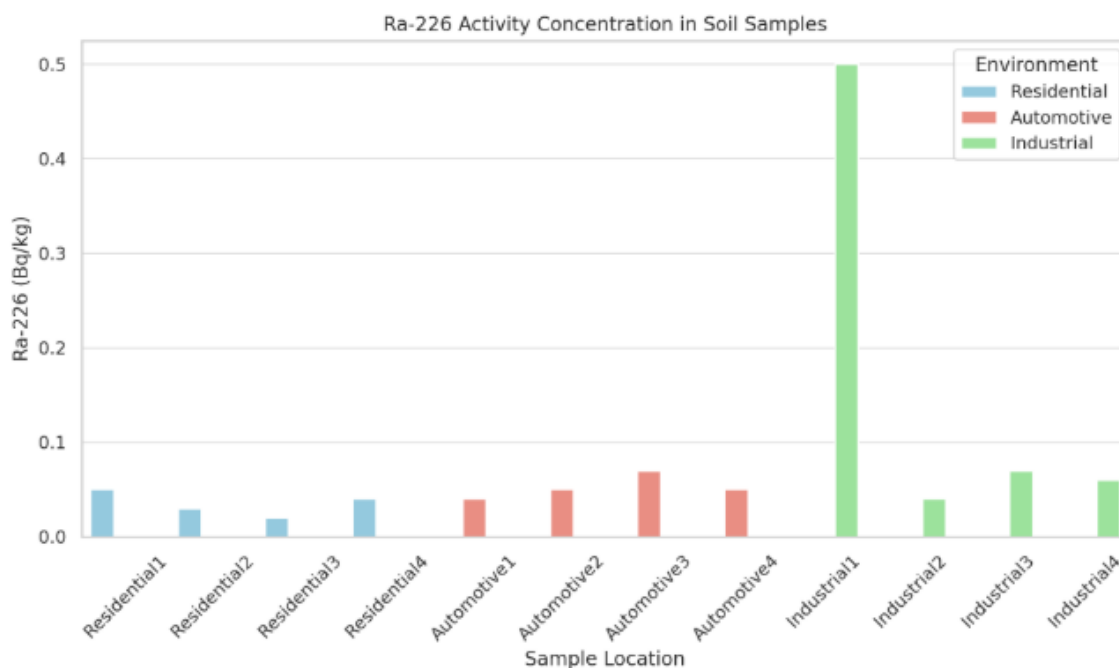


Figure 5. Shows a bar chart of Radium-226 Activity Concentration in (Bq/kg) across different sample Locations.

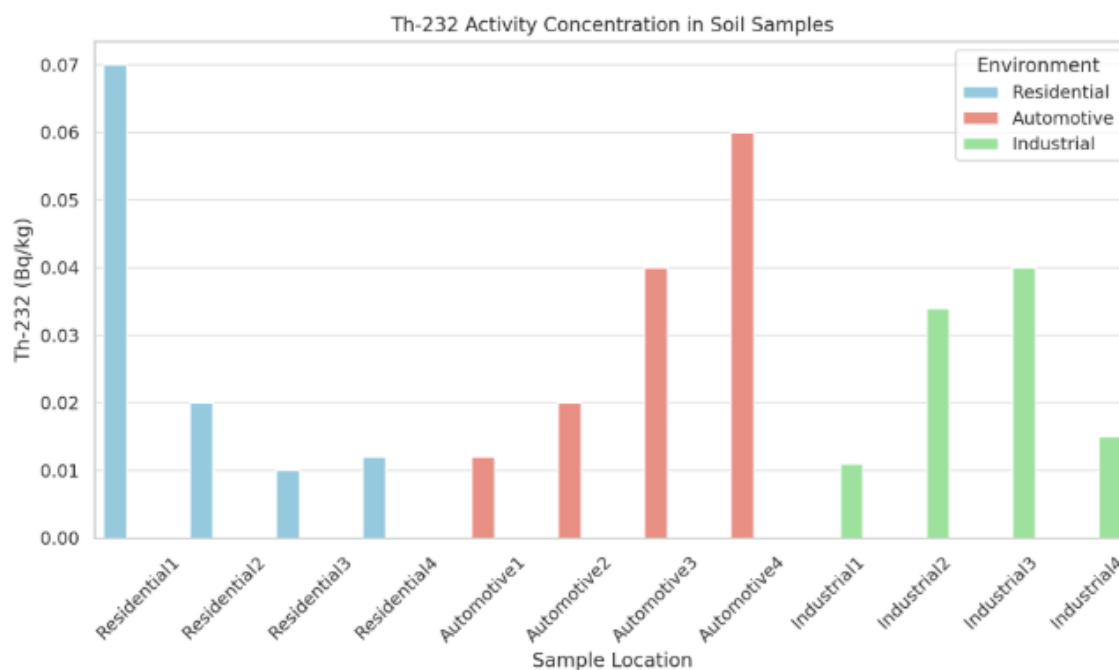


Figure 6. Shows a bar chart of Thorium-232 Activity Concentration in (Bq/kg) across different sample Locations.

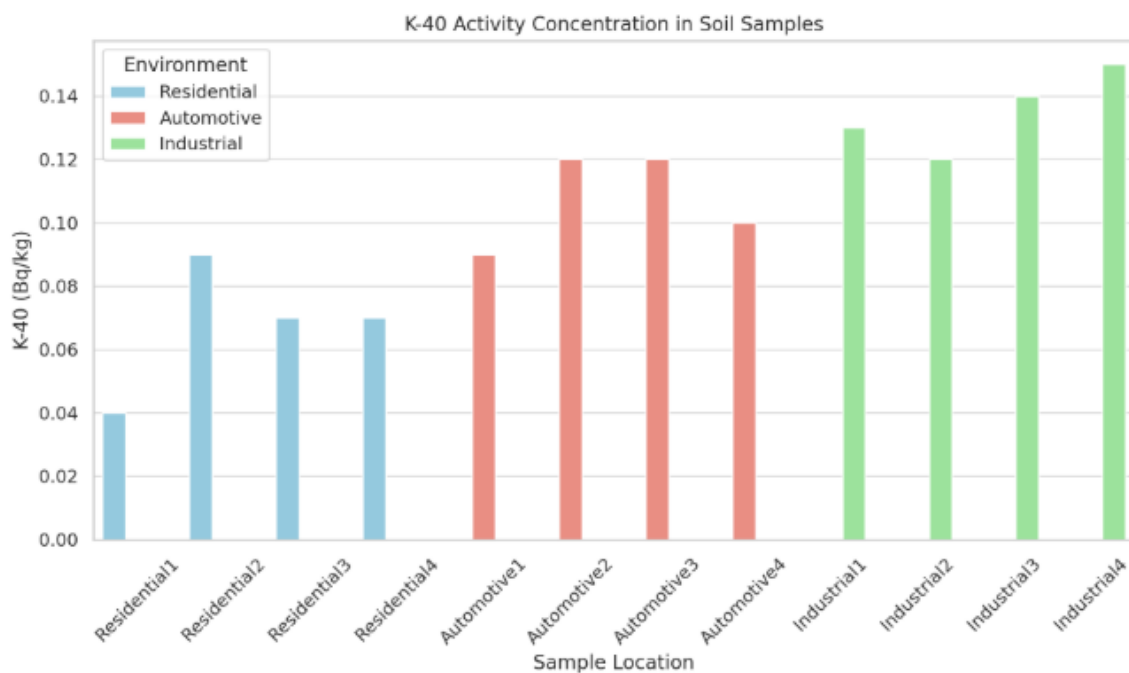


Figure 7. Shows a bar chart of Potassium-40 Activity Concentration in (Bq/kg) across different sample Locations.

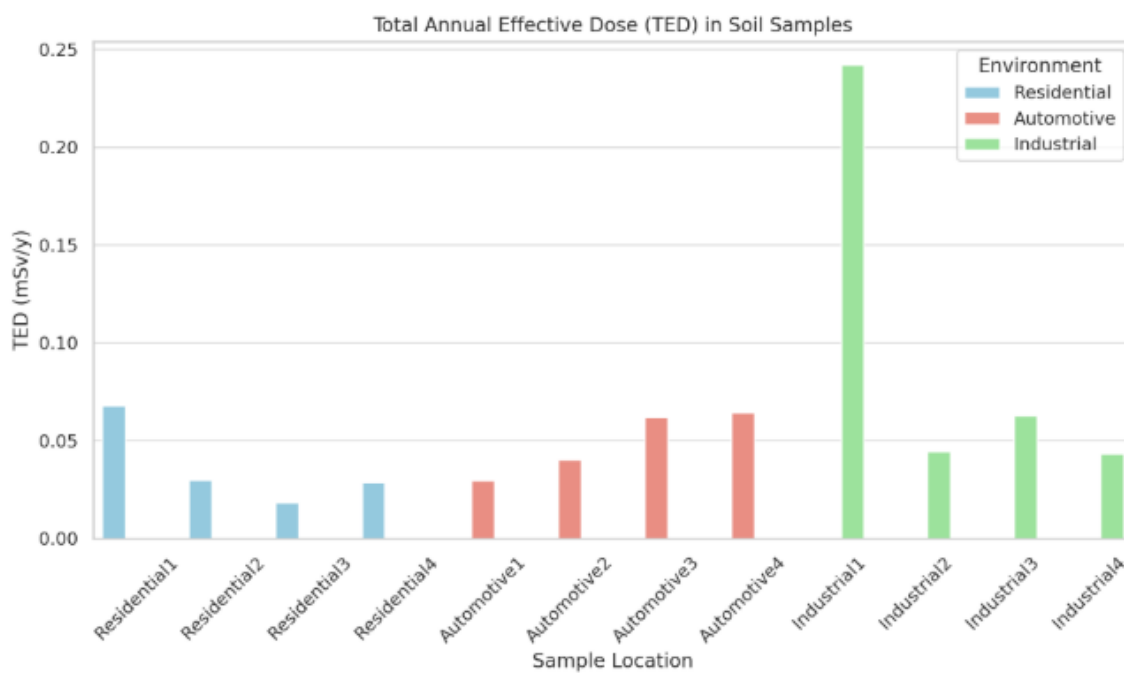


Figure 8. Shows a bar chart of the Total Annual Effective Dose TED in (mSv/y) across different sample Locations.

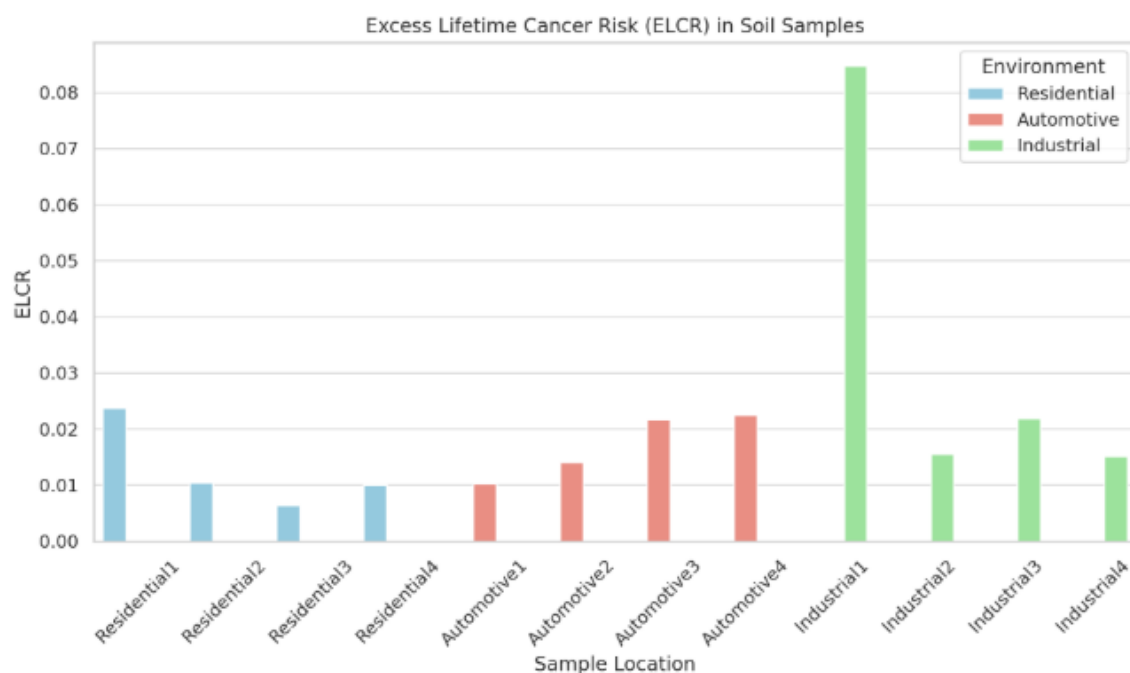


Figure 9. Shows a bar chart of the Excess Lifetime Cancer Risk ELCR across different sample Locations.

Residential Area

In the residential area, the lowest total activity concentration (sum of radionuclides) was observed in Sample 3 (0.03 Bq/kg), while the highest was in Sample 1 (0.16 Bq/kg). ^{40}K was the most dominant radionuclide in most samples, whereas ^{232}Th had the lowest concentration. The Total Annual Effective Dose (TED) ranged from 0.0183 mSv/y (Sample 3) to 0.068 mSv/y (Sample 1), well below the WHO recommended limit of 1 mSv/y for public exposure (UNSCEAR, 2000). Similarly, the Excess Lifetime Cancer Risk (ELCR) values (ranging from 0.0064 to 0.0238) were within the USEPA acceptable limit (1×10^{-4} to 1×10^{-3}). Although the radiological risk appears low, continuous monitoring is recommended to ensure long-term safety, especially in areas with slightly elevated readings.

Automotive Area

The automotive area exhibited higher radionuclide concentrations compared to the residential zone, with the highest total activity in Sample 4 (0.21 Bq/kg). Once again, ^{40}K was the most abundant radionuclide, likely due to natural geological composition. The TED values ranged from 0.0295 mSv/y (Sample 1) to 0.0643 mSv/y (Sample 4), remaining below the WHO limit. The ELCR values (between 0.0103 and 0.0225) were still within safe limits but slightly higher than those in residential areas. This suggests that vehicular emissions, road dust, and industrial byproducts may contribute to increased radionuclide levels, warranting periodic assessments to mitigate potential long-term exposure risks.

Industrial Area

The industrial area recorded the highest radionuclide concentrations, particularly in Sample 1 (^{226}Ra : 0.5 Bq/kg), leading to a significantly elevated TED (0.242 mSv/y) and

ELCR (0.0847). While these values remain below the 1 mSv/y threshold, the ELCR approaches the upper limit of the acceptable range, indicating a higher potential cancer risk over prolonged exposure. Ra-226 warrants deeper discussion due to its radiotoxicity and long half-life (~1600 years), which facilitates long-term environmental persistence and internal exposure risks via ingestion or inhalation. The presence of elevated ^{226}Ra may be linked to industrial waste, mining activities, or the use of phosphate-based materials. Sample 3 also showed notable levels of ^{40}K (0.14 Bq/kg), reinforcing the influence of industrial processes on soil radioactivity.

5. Conclusion

The findings indicate that while cadmium exposure in residential areas requires monitoring, overall heavy metal contamination remains below critical risk levels. Lead and chromium exposures were minimal, and zinc levels, though higher in automotive zones, were not hazardous. Regarding radionuclides, radiation exposure is negligible, with all TED and ELCR values complying with international safety standards. The slightly elevated Ra-226 in one industrial sample suggests localized contamination but does not indicate widespread risk. The study findings suggest several important measures should be taken to address soil contamination risks in Gboko. Zoning regulations need to be implemented to separate industrial and automotive activities from residential areas. The relocation of automotive workshops away from populated zones would significantly reduce residents' exposure to heavy metals like lead and cadmium. This spatial separation is particularly crucial given the elevated

cadmium levels found in residential soils. Such zoning interventions should align with NESREA (National Environmental Standards and Regulations Enforcement Agency) guidelines on environmental protection and pollution control, which emphasize the restriction of industrial activities near residential settlements to safeguard public health. Furthermore, a comprehensive monitoring program should be established by the Government to track contamination levels over time. The monitoring team should conduct regular soil testing focusing on residential areas with elevated cadmium concentrations and industrial sites showing higher radionuclide activity. This program should be designed in accordance with NESREA's National Environmental (Soil Quality) Regulations, which require periodic assessment of hazardous substances to ensure compliance with national soil quality standards.

Public education initiatives should be implemented to inform communities about safe soil practices and potential health risks associated with exposure to contaminated soils. Educational programs should be culturally appropriate and coordinated with local health and environmental agencies to maximize community engagement and behavioral change. In conclusion, aligning these recommendations with NESREA guidelines and Benue State environmental policies will enhance their effectiveness, ensuring sustainable soil management, protection of public health, and compliance with Nigeria's statutory environmental requirements.

Author Contributions

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Conflicts of Interest

The authors declare no conflicts of interest.

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