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Radiometric Analysis of Soil Sample from around Drinkable Ground Water Sources in Zamfara State, Nigeria

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Abstract: This study presents a comprehensive radiometric and toxicological assessment of soil samples collected around drinkable groundwater sources across all Local Government Areas of Zamfara State, Nigeria. Fifty-six samples (28 soil and 28 water) were collected using simple random sampling to evaluate concentrations of naturally occurring radionuclides (radon-222 in water) and heavy metals (Cr, Pb, Ni, Zn, and Cu) in soil. Soil samples were analyzed using X-ray fluorescence (XRF), while health risk assessments—both carcinogenic and non-carcinogenic—were conducted using U.S. EPA models. Results showed elevated concentrations of Pb (189.45 mg/kg), Ni (127.83 mg/kg), and Cu (209.56 mg/kg), all exceeding international guideline limits, while Cr (53.90 mg/kg) and Zn (99.04 mg/kg) remained within acceptable thresholds. Average Daily Intake (ADI) values indicated that ingestion is the dominant exposure pathway, particularly for children, with Pb, Cu, and Ni showing the highest intake levels. Hazard Quotient (HQ) and Hazard Index (HI) values across all exposure pathways were below 1, indicating no immediate non-carcinogenic risk; however, elevated metal concentrations suggest potential long-term health concerns. Carcinogenic risk values for metals such as Pb and Cr approached levels requiring public health attention. The findings highlight the impact of artisanal mining and environmental mismanagement on soil quality and underline the need for continuous monitoring, regulatory intervention, and community education. This study provides essential baseline data for policymakers, public health authorities, and environmental regulators concerned with contamination around drinking water sources in Zamfara State.
Keywords: Heavy metals, X-ray fluorescence spectrometer, hazard indices, and Annual dietary intake.

1 Introduction

Heavy metals such as lead (Pb), chromium (Cr), nickel (Ni), copper (Cu), and zinc (Zn) further exacerbate environmental contamination challenges due to their non-biodegradable nature and long biological half-lives [1, 2]. These metals accumulate in soils and subsequently enter crops, water bodies, and ultimately human and animal tissues. Numerous toxicological studies have linked chronic exposure to heavy metals with neurological impairments, renal dysfunction, immune suppression, and developmental abnormalities in children [3- 7]. Their presence in mining regions is often attributed to both natural mineralization and human activities such as ore processing, the use of improper smelting techniques, and environmental mismanagement [7- 13].

A notable region of concern is Zamfara State in northwestern Nigeria, where artisanal and small-scale gold mining (ASM) is widespread. The state gained global attention following the catastrophic 2010 lead poisoning outbreak, in which hundreds of children died due to extremely high lead exposure from gold ore processing activities [9]. This tragedy revealed critical gaps in environmental monitoring, regulatory enforcement, and community awareness regarding safe mining practices. Since then, researchers and policymakers have increasingly emphasized the need for sustained environmental surveillance, particularly focusing on soil and water contamination in communities heavily involved in mining [14- 17].

Several studies have attempted to quantify environmental contamination in Northern Nigeria. For example, Adebayo *et al*. [6] conducted a comprehensive evaluation of heavy metal distribution in agricultural soils around mining communities in Zamfara State. Their findings indicated elevated concentrations of lead, cadmium, and chromium—levels that exceeded both national and international safety limits. The study emphasized the direct link between

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mining intensity and soil contamination, noting the potential for these metals to infiltrate groundwater sources and food crops. Compared with the present study, Adebayo et al. focused solely on heavy metals without integrating radiological parameters such as radon concentration in water.

Similarly, Ononugbo *et al*. [7] assessed radon levels in groundwater sources across different regions of Nigeria and discovered that several samples exceeded WHO-recommended limits, posing potential long-term health risks. Their findings underscored the need for routine monitoring of naturally occurring radionuclides in drinking water, especially in geologically active regions or areas with mining activities. However, the study was limited to radiological assessments and did not include heavy metal analysis, highlighting the need for integrated environmental evaluations.

Despite the valuable insights provided by previous studies, there remains a significant research gap regarding heavy metals in soil across Zamfara State. The complex interplay between mining activities, natural geology, and environmental pathways requires a holistic approach to accurately characterize risks and inform mitigation strategies. Therefore, this study aims to provide a comprehensive radiological and toxicological assessment by simultaneously evaluating radon levels in groundwater and heavy metal concentrations in soil samples collected from different locations within Zamfara State. This integrated approach offers a more robust understanding of environmental contamination and supports evidence-based interventions for protecting public health and ensuring environmental sustainability.

2. Materials and Methods

2.1 Study Area

Zamfara State is located in the northwestern part of Nigeria, covering an area of approximately 39,762 square kilometers. It is characterized by diverse geological formations, including uranium-rich rocks. The state's terrain is characterized by savanna grasslands, low-lying plains, and river valleys. Geologically, the state is underlain by Precambrian rocks, including granites, gneisses, and schists, as well as sedimentary rocks like sandstones, shales, and limestones. The state is also known for its rich mineral deposits, including gold, lead, zinc, copper, and iron ore.

Agriculture is the mainstay of the state's economy, with crops such as cotton, groundnuts, millet, and sorghum being major cash crops. Livestock production is also a significant occupation in the state, with cattle, sheep, goats, and chickens being raised for meat and dairy products. Additionally, mining has become a significant occupation in Zamfara State, following the discovery of gold and other minerals. Trade and commerce are also important occupations in the state, with the state capital, Gusau, being a major commercial center.

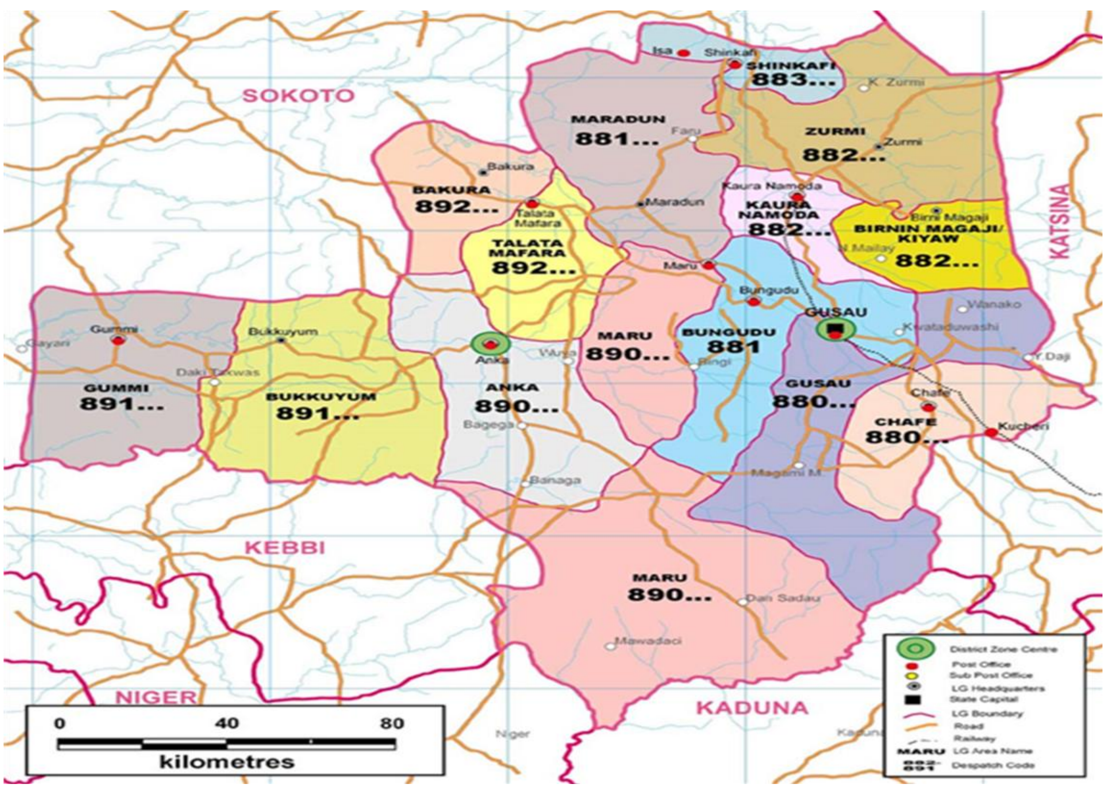

Fig. 3.1: Map of study area.

2.2 Population of the Study

The study encompasses all the local government areas of Zamfara State, Nigeria. Soil samples and Water samples from the well and rivers located in the study area. A total of fifty-six (56) samples (twenty-eight (28) each for soil and plant) were collected from the study area.

2.3 Sample and Sampling Technique

To obtain representative samples and ensure equal chances of selection, a simple random sampling technique was employed to collect two composite samples of soil from each local government area. Two water samples (one well and one river) were also collected from all the local government areas of Zamfara State, Nigeria. This technique was used to select a total of fifty-six (56) water samples for the sampling.

2.4 Method of Soil Sample Collection

Soil samples were collected using a shovel into a polyethylene bag with the opening well tightened to prevent contamination and labelled for identification. A shovel was used to collect soil samples to a depth of about 10 cm. Each composite soil sample collected weighed about 400 g of mass was separately collected and placed in a well-labeled polythene bag, and then was sealed to avoid cross-contamination of the samples during transportation to the laboratory.

2.5 Method of Soil Sample Preparation

All the soil samples were dried in the sun to remove moisture content. The samples were pounded and sieved with a 2 mm mesh to remove bigger particles such as stones, plant roots, coarse materials, and other debris, and obtained a homogenous, fine-texture powder that was smooth for a uniform matrix to the detector. Approximately 200 g of each texture was poured into a new polyethylene bag, tightly sealed with a rubber band, and correctly labelled for ease of identification according to the locations and sent for analysis.

2.6 Method of Soil Sample Analysis for Heavy Metals

The analysis of the soil samples for heavy metals was carried out using an X-ray Fluorescence spectrometer. X-ray fluorescence (XRF) spectrometry is a non-destructive and efficient method for determining heavy metal concentrations in soil. The technique works by bombarding a soil sample with high-energy X-rays or gamma rays, causing the atoms in the sample to emit secondary (fluorescent) X-rays. Each element in the soil produces unique energy emissions, which the XRF spectrometer detects to identify and quantify heavy metals such as lead (Pb), cadmium (Cd), and arsenic (As). Before analysis, soil samples are typically dried, ground, and sometimes pressed into pellets to ensure uniformity and reduce errors related to particle size or surface irregularities.

2.7 Method of Data Analysis

Health risk assessments were conducted using established dose conversion factors and risk models. Carcinogenic and non-carcinogenic risk assessment was performed for heavy metal concentrations in the soil sample. The analysis for radon-222 in water is in four (4) parts, which include calculation of concentration in Bq/l, Annual effective dose to stomach and lungs, Excess lifetime cancer risk, and Comparison of findings with standard and other researchers.

2.8 Hazard indices Determination of Heavy Metals Analysis

The potential exposure pathways for heavy metals in contaminated soils are calculated based on recommendations by several U.S Environmental Protection Agency. ADI (mg/kg-day) for the different pathways was calculated using the following exposure Equations (1) to (3) as prescribed by [18].

The ingestion of Heavy Metals through Soil (ADI_{ing}), Inhalation of Heavy Metals via Soil Particulates (ADI_{inh}), and Dermal Contact with Soil (ADI_{derm}) are given in equations (1), (2), and (3), respectively.

$$ADI_{ing} = \frac{CxIRxEFxEDxCF}{BWxAT} \quad 1$$

where ADI_{ing} is the average daily intake of heavy metals ingested from soil in mg/kg-day, and C is the concentration of heavy metal in mg/kg for soil. IR in mg/day is the ingestion rate, EF in days/year is the exposure frequency, ED is the exposure duration in years, BW is the body weight of the exposed individual in kg, and AT is the time period over which the dose is averaged in days. CF is the conversion factor in kg/mg.

$$ADI_{inh} = \frac{CxIR_{air}xEFxED}{BWxATxPEF} \quad 2$$

where ADI_{inh} is the average daily intake of heavy metals inhaled from soil in mg/kg-day, CS is the concentration of heavy metal in soil in mg/kg, IR_{air} is the inhalation rate in m^3/day, and PEF is the particulate emission factor in m3/kg. EF, ED, BW, and AT are as defined earlier in Equation (1).

$$ADI_{dems} = \frac{CxSAxFExAFxABSxEFxEDxCF}{BWxAT} \quad 3$$

Where ADI_{dems} is the exposure dose via dermal contact in mg/kg/day. CS is the concentration of heavy metal in soil in mg/kg, SA is the exposed skin area in cm^2, FE is the fraction of the dermal exposure ratio to soil, AF is the soil adherence factor in mg/cm^2, and ABS is the fraction of the applied dose absorbed across the skin. EF, ED, BW, CF, and AT are as defined earlier in Equation (3.3). Table 1 shows the exposure parameters used for the health risk assessment for the standard residential exposure scenario through different exposure pathways.

Table 1. Exposure parameter used for the health risk assessment through different exposure pathways for soil.

Parameter	Unit	Child	Adult
Body weight (BW)	Kg	15	70
Exposure Frequency (EF)	Days/ years	350	350
Exposure duration (ED)	Years	6	30
Ingestion rate (IR)	mg/day	200	100
Inhalation rate (IRair)	m^3/day	10	20
Skin surface area (SA)	cm2	2100	5800
Soil adherence factor (AF)	mg/ cm2	0.2	0.07
Dermal absorption factor (ABS)	None	0.1	0.1
Dermal exposure ratio (FE)	None	0.61	0.61
Particulate emission factor (PEF)	m3/ kg	$1.3x10^9$	$1.3x10^9$
Conversion factor (CF)	kg/ mg	10^{-6}	10^{-6}
Average time (AT) for carcinogens	Days	365x70	365x70
Average time (AT) for non-carcinogens	Days	365xED	365xED

2.8.1 Non- Non-Non-Carcinogenic Risk Assessment

Non-carcinogenic hazards are characterized by a term called hazard quotient (HQ). HQ is a unitless number that is expressed as the probability of an individual suffering an adverse effect. It is defined as the quotient of ADI or dose divided by the toxicity threshold value, which is referred to as the chronic reference dose (RfD) in mg/kg-day of a specific heavy metal, as shown in Equation (4);

$$HQ = \frac{ADI}{RFD} \quad 4$$

For n number of heavy metals, the non-carcinogenic effect on the population is a result of the summation of all the HQs due to individual heavy metals. This is considered to be another term called the Hazard Index (HI) as described by USEPA document [6, 16]. Equation (5) shows the mathematical representation of this parameter:

$$HI = \sum_{k=1}^{n} HQ_k = \sum_{k=1}^{n} \frac{ADI_k}{RfD_k} \quad 5$$

where HQ_k, ADI_k, and RfD_k are values of heavy metal k. If the HI value is less than one, the exposed population is unlikely to experience adverse health effects. If the HI value exceeds one, then there may be concern for potential non-carcinogenic effects [17, 19].

2.8.2 Carcinogenic Risk Assessment

For carcinogens, the risks are estimated as the incremental probability of an individual developing cancer over a lifetime as a result of exposure to the potential carcinogen. The equation for calculating the excess lifetime cancer risk is:

$$Risk_{pathway} = \sum_{k=1}^{n} ADI_k CSF_k \quad 6$$

where Risk is a unitless probability of an individual developing cancer over a lifetime. ADIk (mg/kg/day) and CSFk(mg/kg/day)-1are the average daily intake and the cancer slope factor, respectively, for the kth heavy metal, for n number of heavy metals. The slope factor converts the estimated daily intake of the heavy metal, averaged over a lifetime of exposure, directly to the incremental risk of an individual developing cancer [20]

The total excess lifetime cancer risk for an individual is finally calculated from the average contribution of the individual's heavy metals for all the pathways using the following equation:

$$Risk_{(total)} = Risk_{(ing)} + Risk_{(inh)} + Risk_{(dems)} \quad 7$$

where Risk(ing), Risk(inh), and Risk(dermal)are risk contributions through ingestion, inhalation, and dermal pathways.

Both non-carcinogenic and carcinogenic risk assessment of heavy metals are calculated using RfD and CSF values derived largely from the Department of Environmental Affairs (South Africa) and USEPA, as shown in Table 2.

3. Result and Discussion

The results of the mean heavy metal concentration in soil samples collected from the study area are presented in Figure 2. The level of Chromium (Cr), Lead (Pb), Nickel (Ni), Zinc (Zn), and Copper (Cu) in all the soil samples collected was measured. Figure 2 presents the heavy metal concentration in the soil samples.

Table 2. Reference doses (RfD) and Cancer Slope Factors (CSF) for the different heavy metals.

Heavy metal	Oral RfD	Dermal RfD	Inhalation RfD	Oral CSF	Dermal CSF	Inhalation CSF
As	$3.0x10^{-4}$	$3.0x10^{-4}$	$3.0x10^{-4}$	1.5	1.5	15
Pb	$3.6x10^{-3}$	NA	NA	$8.5x10^{-3}$	NA	4.2×10^{-2}
Cd	$5.0x10^{-4}$	$5.0x10^{-4}$	$5.7x10^{-5}$	NA	NA	6.3
Ni	$2.0x10^{-2}$	$5.6x10^{-3}$	NA	NA	NA	NA
Zn	$3.0x10^{-1}$	$7.5x10^{-2}$	NA	NA	NA	NA
Pb	$3.5x10^{-3}$	NA	NA	NA	NA	NA
Cu	$4x10^{-2}$	NA	NA	NA	NA	NA
Cr	$3x10^{-3}$	NA	NA	$5x10^{-1}$	NA	NA

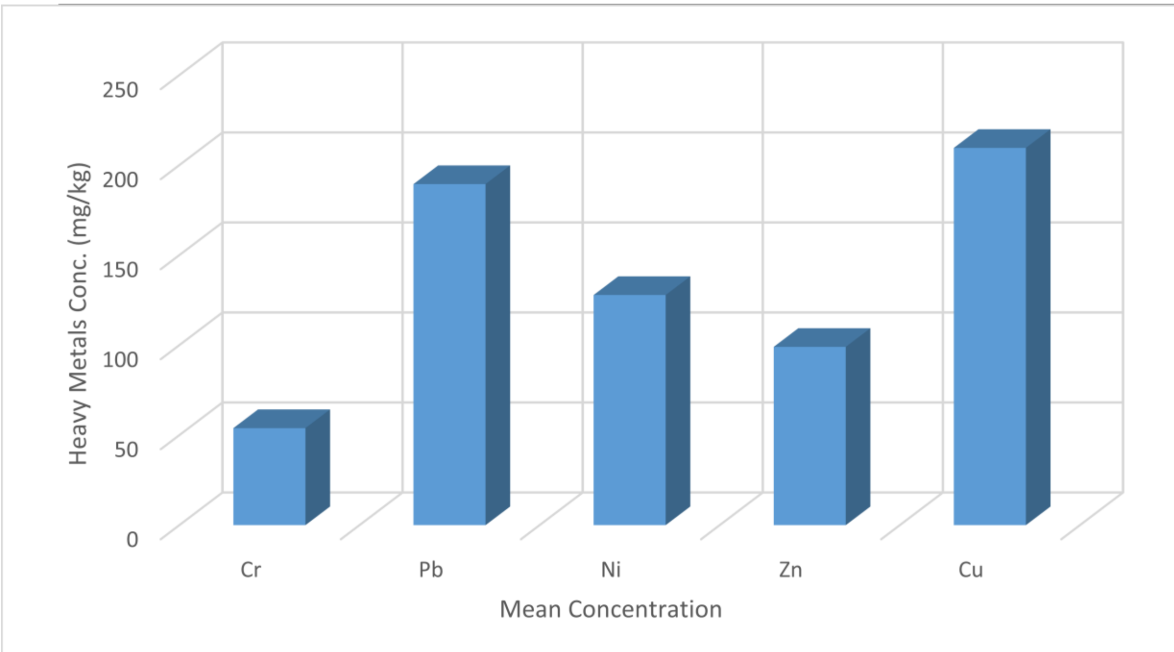

Fig. 2: Comparison of mean heavy metal concentration levels in soil samples collected from the study area

Figure 2 presents the mean heavy metal concentration in abandoned mining site soil samples collected from the study area. Soil samples collected from all Local Government Areas in Zamfara State, Nigeria, revealed elevated concentrations of several heavy metals. The mean concentrations of chromium (Cr), lead (Pb), nickel (Ni), zinc (Zn), and copper (Cu) were 53.90, 189.45, 127.83, 99.04, and 209.56 mg/kg, respectively. When compared with international soil quality standards from the Dutch, Canadian, and WHO/FAO guidelines, Pb, Ni, and Cu significantly exceeded acceptable limits, indicating potential environmental and health hazards. Only Cr and Zn remained within the recommended thresholds. The particularly high levels of Pb and Ni raise serious concerns due to their toxicity, bioaccumulation potential, and risk to human health, especially for children.

These elevated metal concentrations are likely linked to unregulated artisanal gold mining, which is prevalent in the region, along with possible contributions from improper waste disposal and agricultural runoff. The findings call for urgent remedial action, including environmental cleanup, stricter regulatory enforcement, public health monitoring, and community education on exposure risks. Without immediate intervention, the continued presence of these contaminants in soil could pose long-term risks to both ecological and human health in Zamfara State.

The calculated mean annual daily intake for ingestion, inhalation, and dermal contact is presented in Figure 3. The non-carcinogenic risk parameters, such as hazard quotient and hazard index, were calculated for all the pathways and are presented in Figure 4. The carcinogenic risk pathway was calculated, and the means are presented in Figure 3.

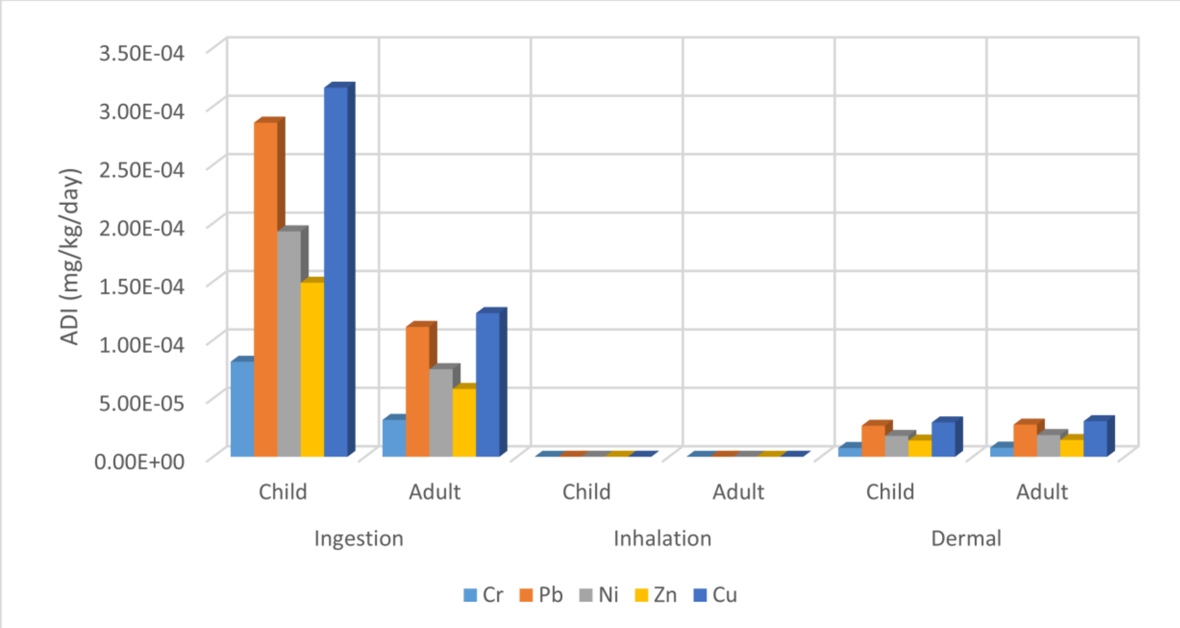

Fig. 3: Comparison of mean annual daily intake of soil samples collected from the study area.

Figure 4 presents the comparison of the mean annual daily intake of soil samples collected from the study area. The assessment of the mean annual daily intake (ADI) of heavy metals through ingestion, inhalation, and dermal contact in soil samples from Zamfara State, Nigeria, reveals that ingestion is the primary exposure route, especially for children. The ingestion ADIs (mg/kg/day) for children were notably high for copper (3.16×10^{-4}), lead (2.86×10^{-4}), and nickel (1.93×10^{-4}), while chromium (8.14×10^{-5}) and zinc (1.49×10^{-4}) were comparatively lower. Adults had significantly reduced ingestion values across all metals due to greater body mass and less frequent hand-to-mouth activity. These findings suggest that children are more vulnerable to soil contamination by heavy metals, with their intake of Pb and Cu nearing

or exceeding thresholds of concern established by regulatory bodies like the U.S. EPA [21]. For instance, the reference dose (RfD) for Pb ingestion is approximately 3.5×10^{-4} mg/kg/day, making the observed values in Zamfara highly concerning.

In contrast, inhalation exposures were minimal for both children and adults, with values in the range of 10^{-8} mg/kg/day. These low values, such as Cr (1.14×10^{-8}) and Pb (3.99×10^{-8}) for children, are consistent with findings from other studies in Nigeria and globally, where inhalation of soil particles contributes very little to total metal exposure unless industrial dust or mining operations significantly increase airborne particulates [19]. The dermal exposure pathway, however, was more significant than inhalation but still secondary to ingestion. Dermal ADIs for Pb (2.66×10^{-5}), Cu (2.94×10^{-5}), and Ni (1.79×10^{-5}) in children again reflect elevated risk potential, especially given their frequent skin contact with contaminated soil during outdoor play. Adults showed similar trends, although with slightly higher dermal absorption values due to increased surface area, but with a lower frequency of direct soil contact.

Comparative analysis with related studies confirms these trends. Khan *et al.* [20] and Usman and Ipinjolu [21] reported similarly high ingestion-based ADIs in northern and southwestern Nigeria, respectively, especially in areas impacted by mining. Li *et al.* [22] in China also found comparable values in industrially contaminated zones, reinforcing the conclusion that children in such environments are at risk of chronic exposure to toxic metals. The elevated levels of Pb and Cu in Zamfara soils likely stem from artisanal gold mining, poor waste management, and a lack of environmental controls. These findings highlight an urgent need for public health interventions such as soil remediation, stricter regulation of mining activities, and community education to mitigate long term health effects, particularly among children.

Figure 4 presents the mean hazard quotient and hazard quotient of heavy metals in soil samples collected from the study area. The Hazard Quotient (HQ) is a critical metric in assessing the non-carcinogenic health risk posed by exposure to toxic metals in soil. An HQ value >1 indicates a potential health risk, while a value <1 suggests the risk is negligible. In this study, all HQ values for Cr, Pb, Ni, Zn, and Cu across all exposure pathways (ingestion, inhalation, dermal) for both children and adults were below 1, indicating no immediate non-carcinogenic health risk. However, among the exposure routes, ingestion posed the highest potential for toxicity, particularly in children. The ingestion HQs for Pb (0.0817) and Cr (0.0271) were notably higher than for other metals, reflecting the elevated bioavailability and toxic potential of these elements in Zamfara's soil. Children again showed higher vulnerability due to behavioral factors and lower body weight compared to adults, as seen in previous studies [20, 22].

Inhalation exposure, on the other hand, contributed the least to the overall hazard quotient values. For instance, the HQs for Cr (3.79×10^{-6}) and Pb (1.14×10^{-5}) in children, and even lower values in adults, suggest negligible risk through this pathway. These values are consistent with other reports from mining-

impacted regions of Nigeria and elsewhere, where soil inhalation is not a dominant exposure route unless fine dust particles are frequently suspended in the air [19, 23]. However, continuous exposure in dry, dusty environments like Zamfara may still pose a latent concern if particulate generation increases, especially due to artisanal mining operations.

Dermal contact revealed moderate HQs for Pb (0.0076 in children, 0.0079 in adults) and Cr (0.0025 in children, 0.0026 in adults), indicating a minor but noteworthy route of exposure. While these values are still below the safety threshold of 1, they mirror trends seen in other mining regions, such as in the findings of Usman and Ipinjolu [21], where dermal absorption of heavy metals—particularly Pb and Ni—was found to contribute significantly to total risk, especially for populations with frequent skin contact with contaminated soil. The HQs for Zn and Cu were relatively lower in all pathways, reflecting their lower relative toxicity compared to Pb and Cr. Despite HQs being within safe limits, cumulative exposure over time and potential synergistic effects of multiple metals necessitate proactive environmental and public health interventions, particularly in child-dense communities.

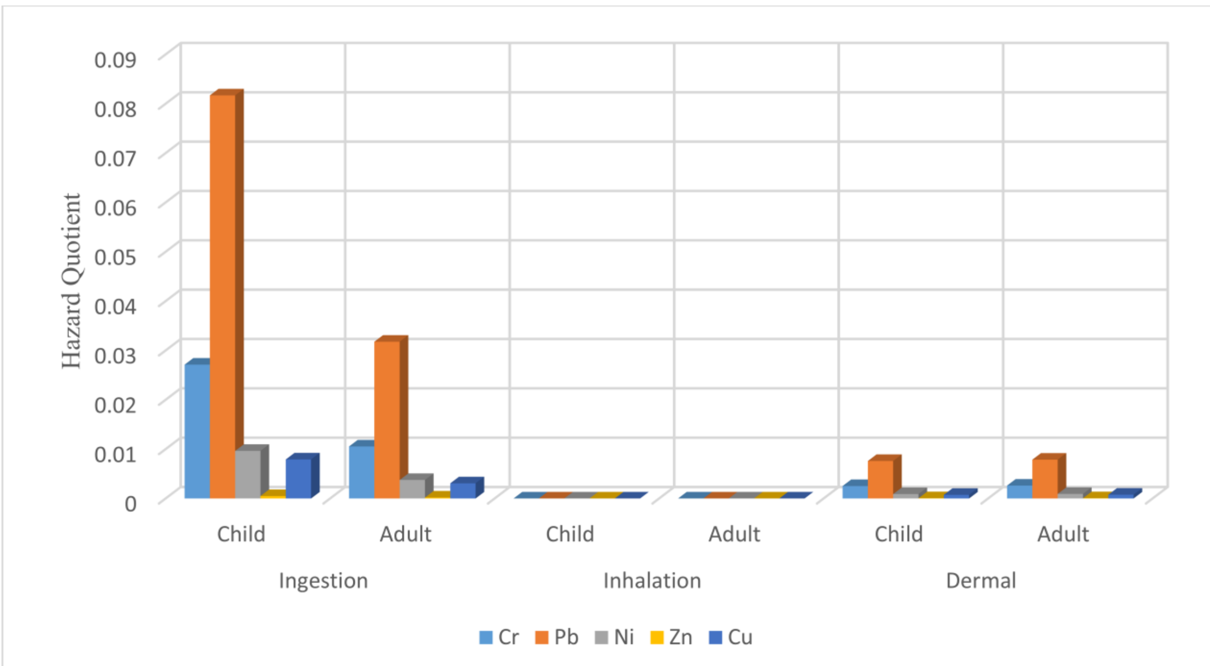

Fig.4: Comparison of mean hazard quotient and hazard quotient of heavy metals in soil samples collected from the study area.

Figure 5 presents the mean hazard index of heavy metals in soil samples collected from the study area. The mean Hazard Quotient (HQ) values for children and adults due to exposure to heavy metals in soil samples from Zamfara State, Nigeria, through ingestion, inhalation, and dermal contact offer insight into potential health risks. For children, the average HQ values across exposure routes were 0.810772 (ingestion), 0.000113 (inhalation), and 0.0754 (dermal contact). For adults, these values were0.315344, 4.85×10^{-5}, and 0.0781, respectively. These results suggest that ingestion is the dominant pathway for both age groups, especially for children, where the HQ approaches 1—the threshold for non-carcinogenic risk—indicating potential for adverse health effects if exposure persists over time. This aligns with findings by Khan *et al.* [20], who reported similarly elevated HQ values for ingestion in children in mining-impacted northern Nigeria.

Inhalation exposure, on the other hand, posed negligible risk to both children and adults, with HQ values in the range of 10^{-4} to 10^{-5}. These extremely low values are typical of exposure to soil-borne metals under non-industrial, non-dusty conditions. The low inhalation HQs are consistent with results from Kim *et al.* [19] in studies of urban and rural soils, where ingestion and dermal contact were far more significant than inhalation unless fine particulates were elevated in the atmosphere due to mining or construction activities. Thus, while inhalation is not an immediate concern in Zamfara based on the data, it should not be entirely disregarded in drier seasons when dust levels rise.

Regarding dermal exposure, the HQ values were moderate and relatively similar for children (0.0754) and adults (0.0781). Although still well below 1, these values suggest a non-negligible risk, especially when considered alongside ingestion exposure. These findings correspond with those of Usman and Ipinjolu [21], who highlighted dermal exposure as a significant pathway in communities with direct contact with contaminated soils, such as through farming, mining, or outdoor play. The comparable values for children and adults here may reflect similar exposure conditions across age groups. Overall, these results indicate that cumulative exposure, especially via ingestion and dermal contact, may pose a long-term health risk and call for targeted interventions such as soil remediation, health education, and improved environmental monitoring.

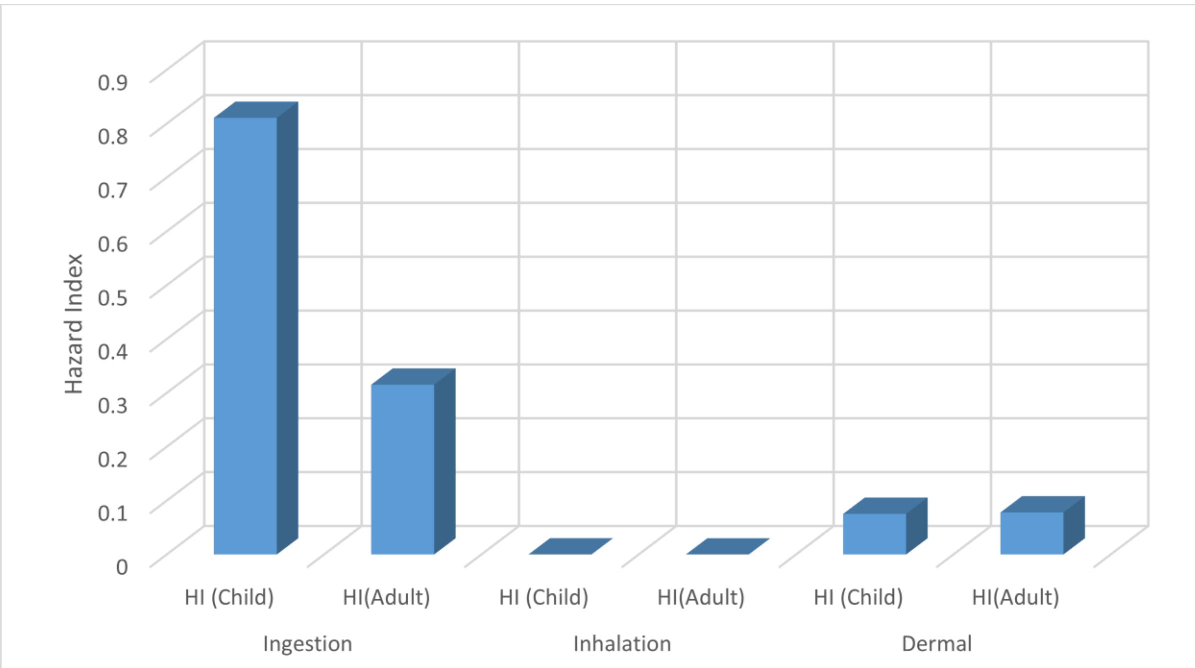

Fig. 5: Comparison of the mean hazard index of heavy metals in soil samples collected from the study area.

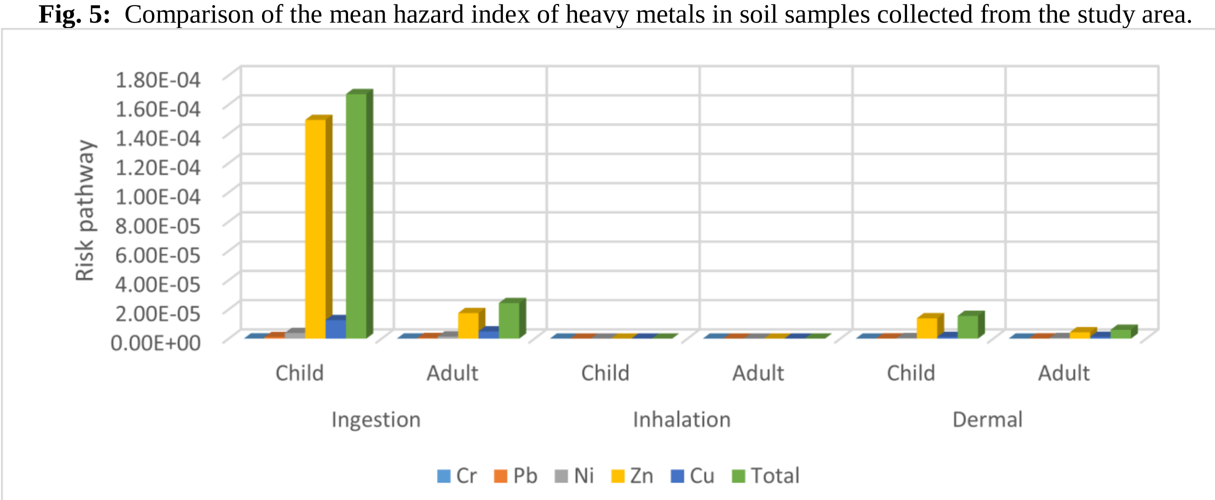

Fig. 6: Comparison of calculated risk pathway of heavy metal concentration in soil samples collected from the study area. etal concentration in soil samples collected from the study area.

Figure 6 presents the calculated risk pathway of heavy metal concentration in the soil sample collected from the study area. The carcinogenic risk assessment of heavy metals (Cr, Pb, Ni, Zn, and Cu) in soil samples from Zamfara State, Nigeria, through ingestion, inhalation, and dermal pathways reveals varying levels of potential cancer risk for both children and adults. The ingestion route posed the most significant carcinogenic risk, particularly for Ni (3.86×10^{-6} for children and 1.50×10^{-6} for adults), Cu (1.27×10^{-5} for children and 4.92×10^{-6} for adults), and Zn (1.49×10^{-4} for children and 1.74×10^{-5} for adults). These values exceed the USEPA acceptable risk range of 1.0×10^{-6} to 1.0×10^{-4} (USEPA, 1989), indicating a potential carcinogenic risk, especially in children who are more vulnerable due to higher exposure relative to body weight. This is consistent with the findings of Khan *et al*. [20] and Ajayi *et al*. [23], who reported elevated carcinogenic risks for Ni and Pb in soils near mining areas in Nigeria.

Inhalation exposure presented minimal carcinogenic risk across all metals and both age groups, with values well below the threshold of concern. For instance, the inhalation cancer risk for Ni was 5.39×10^{-10} for children and 2.31×10^{-10} for adults, and for Pb was 1.44×10^{-10} and 6.16×10^{-11}, respectively. These low values suggest that inhalation of soil particles is not a significant cancer risk factor in the study area under normal conditions. However, in dusty seasons or in proximity to artisanal mining operations, this pathway could contribute more substantially to overall risk, as noted by Kim *et al*. [19]. The highest inhalation risk was from Zn (2.09×10^{-8} in children), though still marginally within safe limits.

For dermal contact, notable carcinogenic risks were found particularly for Zn (1.39×10^{-5} for children) and Ni (3.59×10^{-7} for children), again exceeding or nearing the USEPA threshold in some cases. The risk values for Cu and Pb were slightly lower but still noteworthy. This trend mirrors findings by Usman and Ipinjolu [21], who highlighted the relevance of dermal exposure in mining communities, especially for children engaging in outdoor play or farming. Overall, while inhalation poses minimal risk, ingestion and dermal contact with contaminated soils in Zamfara pose moderate to high carcinogenic risks, particularly for children. These findings emphasize the need for risk mitigation strategies such as soil remediation, public health awareness, and protective measures in high-exposure zones.

Table 4.10: Comparison of heavy metal concentrations of the present study and other published studies.

Study Location	Cr (mg/kg)	Pb (mg/kg)	Ni (mg/kg)	Zn (mg/kg)	Cu (mg/kg)
Zamfara State (This Study)	53.90	189.45	127.83	99.04	209.56
Mkpuma Ekwoku (SE Nigeria)	12.66	109.55	2.34	210.00	8.24
Kogi State (NC, Nigeria)	-	4.45–47.7	3.81–93.1	5.02–81.4	0.33–16.9
Ishiagu (SE Nigeria)	21.67	-	15.00	162.64	11.18
Wukari (NE Nigeria)	-	89.6–247.0	-	26.8–163.0	7.1–61.2
Durumi Quarry, Mpape (Abuja)	-	4.56–22.53	-	0.26–5.20	-

The heavy metal concentrations in Zamfara State soils—Cr (53.90 mg/kg), Pb (189.45 mg/kg), Ni (127.83 mg/kg), Zn (99.04 mg/kg), and Cu (209.56 mg/kg)—are notably elevated compared to findings from various regions in Nigeria. These elevated levels are primarily attributed to intensive artisanal mining activities prevalent in Zamfara.

For instance, Chukwu and Oji [24] reported mean concentrations in agricultural soils near an abandoned lead-zinc mine in Mkpuma Ekwoku, Southeastern Nigeria, as follows: Pb (109.55 mg/kg), Zn (210 mg/kg), Ni (2.34 mg/kg), Cu (8.24 mg/kg), and Cr (12.66 mg/kg). While Zn levels were higher in their study, the concentrations of Pb, Ni, Cu, and Cr were significantly lower than those observed in Zamfara, highlighting the severe contamination in Zamfara's soils.

Similarly, in Kogi State, north-central Nigeria, Akinola *et al*. (2017) found soil concentrations ranging from Cu (0.33–16.9 mg/kg), Ni (3.81–93.1 mg/kg), Pb (4.45–47.7 mg/kg), to Zn (5.02–81.4 mg/kg). These values are substantially lower than those recorded in Zamfara, particularly for Pb and Cu, underscoring the heightened pollution levels in Zamfara's soils.

4. Conclusion

The study revealed that soils around drinkable groundwater sources in Zamfara State contain elevated concentrations of Pb, Ni, and Cu, exceeding international safety limits and indicating contamination largely linked to artisanal mining and poor environmental practices. Although Cr and Zn remained within acceptable levels and the calculated Hazard Quotient (HQ) and Hazard Index (HI) values were below 1—suggesting no immediate non-carcinogenic risk—the high metal concentrations and ingestion-based exposure, especially among children, highlight the potential for long-term adverse health effects. Carcinogenic risk estimates for Cr and Pb further indicate possible future cancer risks if exposure continues unchecked. Overall, these findings underscore the urgent need for regulatory enforcement, soil and water quality monitoring, environmental remediation, and increased community awareness to reduce heavy metal exposure and safeguard public health in Zamfara State.

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