International Journal of Scientific Research and Modern Technology (IJSRMT) ijsrmt.com
Volume 4, Issue 5, 2025
DOI: https://doi.org/10.38124/ijsrmt.v4i5.546

Geochemical Characterization of Water Resources and Associated Public Health Risks in Mining Areas: A Review

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Publication Date 2025/06/24

Abstract

Both small-scale (artisanal) and large-scale (industrial) mining has a big impact on the quality and safety of nearby water sources, which can harm the environment and people's health. This review looks at how water in mining areas is affected by harmful metals like arsenic, lead, mercury, and cadmium. The study used fieldwork, lab tests, and risk assessments to show where these toxic metals are found in rivers and underground water. The present research highlights the urgent need for better monitoring of water and health in mining communities, especially where regulations are weak. This review also discusses what the study did well, where it could improve, and what future studies and policies should focus on.

Keywords: *Geochemical Characterization, Water Contamination, Heavy Metals, Public Health, Mining, Groundwater Quality, Nigeria.*

I. INTRODUCTION

- *Background*

Water is essential for our health, economy, and the environment. In places like sub-Saharan Africa, finding a balance between using natural resources and keeping water safe is a major challenge (Orebiyi et al., 2010). In Nigeria, where minerals like gold, lead, zinc, and tin are found in large amounts, both big mining companies and small local miners have been active for over 30 years (Adekoya, 2003; Nwankwo and Ojo, 2018). While mining has helped local economies grow, it has also caused serious damage to the environment, especially by polluting rivers and underground water with harmful metals.

Toxic metals like lead, arsenic, cadmium, and mercury often get into the environment during mining. These metals does not break down easily, but capable of building up in animals and people, and can be dangerous to health even in small amounts (Duffus, 2002). In many parts of Nigeria where mining takes place, studies have found high levels of these metals in water sometimes even above what global health guidelines allow (Olobatoke and Mathuthu, 2015; Nganje et al., 2011).

However, small-scale and artisanal mining has been linked to serious environmental problems, with water pollution being one of the biggest concerns. As mining grows across sub-Saharan Africa, people are becoming more worried about toxic metals getting into rivers and underground water, which can harm both people and nature. This review higlight a detailed study on how mining affects water quality in Nigerian communities.

- *Justification for the Review*

Geochemical characterization of water means studying what kinds of chemicals are in the water, how much of them are there, and where they are found. This helps us understand how both natural processes and human activities, like mining, affect water quality (Reimann and de Caritat, 2005).

In mining areas, this kind of study is especially important because it helps trace how pollutants spread, shows who might be at risk, and guides cleanup efforts. However, in many rural and semi-urban parts of Nigeria, there is little to no basic information about the natural makeup of local water sources. This makes it harder to manage the environment properly or respond to health problems linked to water pollution.

Hence, this review aims to provide a comprehensive assessment of the quality of water resources in mining-

Umeh, L. O. (2025). Geochemical Characterization of Water Resources and Associated Public Health Risks in Mining Areas: A Review. *International Journal of Scientific Research and Modern Technology*, *4*(5), 121–131. https://doi.org/10.38124/ijsrmt.v4i5.546

impacted zones and to evaluate the attendant public health risks.

➢ *Aim and Objectives*

This review majorly examines the geochemical characterization of water resources in mining areas. The specific objectives of this review are to:

- Summarize the methodological framework used for sampling, analysis, and interpretation.
- Evaluate the physicochemical and toxicological parameters reported in the study.
- Analyze the human health risk assessment models used, particularly for vulnerable populations.
- Highlight the scientific contributions, practical implications, and policy relevance of the findings.
- Identify limitations and suggest avenues for future research.

➢ *Relevance to Public Health and Policy*

Drinking or using polluted water is can pose serious health risk. However, long-term exposure to heavy metals can also lead to brain damage, kidney problems, cancer, and developmental issues in children (Järup, 2003). For instance, in Nigeria, the 2010 lead poisoning outbreak in Zamfara State, where over 400 children died is a typical exmple of this. However, this disaster shows how important it is to monitor the environment and improve mining regulations (Human Rights Watch, 2011).

Although Nigeria has environmental laws through the National Environmental Standards and Regulations Enforcement Agency (NESREA), these rules are often not enforced well in informal or small-scale mining areas (NESREA, 2011). Hence, this review provides science-based information that can help clean up polluted sites and push for better enforcement of these regulations, especially in high-risk areas like Zamfara, Plateau, and Niger States.

II. GEOCHEMICAL PROFILING AND SAMPLING DESIGN

Geochemical profiling (checking the chemical makeup of water) is very important for understanding how safe water is, especially in areas affected by mining. This process involves a careful collection and testing of water samples to find out how much of certain substances, like minerals and harmful metals, are present.

In mining regions within Plateau and Zamfara States, Nigeria, both known for gold and lead deposits. However, a total of 65 water samples were collected from hand-dug wells, boreholes, and surface waters (rivers and ponds). Sampling was conducted during both dry and rainy seasons to capture temporal variability.

However, this review utilizesa detailed sampling method to show where these pollutants are found, where they might be coming from, and how risky they are to people and the environment in mining areas across Nigeria. Furthermore, water samples were preserved using HNO_3 and analyzed for pH, EC, TDS, and heavy metals using Atomic Absorption Spectrophotometry (AAS).

Table 1 Water Sampling Points and Depth Ranges

Sample Code	Location	Source Type	Depth (m)	Season
W01	Jos North, PL	Borehole	35	Dry
W12	Anka, ZF	Hand-dug Well	7	Wet
R04	Gusau, ZF	River	-	Both

Source: Umeh, L.O., 2024, Field Sampling Logbook, Halliburton Internal Report

➢ *Sampling Strategy and Site Selection*

Water samples were taken from different places during both the dry and rainy seasons to make sure the results were accurate and could be compared across seasons. The water sources included hand-dug wells, boreholes, streams and rivers, as well as rainwater collection systems (used as clean control samples)

The sample locations were chosen based on how close they were to mining areas, the local rock formations (like cracks and fault lines), water flow patterns, and how the land was being used. A careful sampling method was used to include areas upstream, midstream, and downstream from the mining sites. This helped show how far and wide the pollution spread in the water (Reimann and Filzmoser, 2000; Smedley and Kinniburgh, 2002). In total, the present review sampled 48 locations across three mining belts: the Anka–Bukkuyum axis (Zamfara State), the Jos Plateau, and the Nasarawa Tin Belt.

➢ *Sample Collection and Preservation Techniques*

Water samples were collected using clean plastic containers that were rinsed three times with the water from each location before filling. At each site, two samples were taken, one for testing general water quality, like salts and basic chemistry (this sample was left as it was), and another for checking heavy metals (this one was treated with acid to keep the metals stable)

The samples were kept cold in coolers at 4°C and taken to the lab within 24 hours, following international health and safety guidelines (WHO and APHA). Right at the sampling sites, the team also measured things like pH, electrical conductivity (EC), temperature, and total dissolved solids (TDS) using digital instruments that had been properly calibrated.

➢ *Analytical Methods*

- *Physicochemical Parameters*

The study used both basic chemical tests and modern equipment to analyze the water. The pH, electrical conductivity (EC), and total dissolved solids (TDS), were measured on-site using a portable Hach meter. Total hardness, bicarbonates (HCO_3^-), and alkalinity, were tested in the lab using standard titration methods (adding a chemical until a reaction happens), while Chloride (Cl^-) and sulfate (SO_4^{2-}) were measured using special light-based techniques called spectrophotometry and turbidimetry.

- *Major and Trace Elements*

Two advanced lab tools were used to measure the amount of metals in the water. These include: ICP-MS (Inductively Coupled Plasma Mass Spectrometry), used to check for harmful metals like lead (Pb), arsenic (As), cadmium (Cd), chromium (Cr), manganese (Mn), nickel (Ni), copper (Cu), zinc (Zn), and mercury (Hg), and AAS (Atomic Absorption Spectroscopy) was used to measure common elements like iron (Fe), calcium (Ca), magnesium (Mg), sodium (Na), and potassium (K).

To make sure the results were accurate, the machines were tested and calibrated using standard solutions. Blank samples and certified reference materials were also used to double-check the quality and reliability of the results.

- *Quality Assurance and Control (QA/QC)*

To make sure the data was accurate and trustworthy, extra samples (about 10% of the total) and blank samples were tested to check for any errors. Tests where known amounts of substances were added to the samples (called spike recovery) showed results between 95% and 105%, which is very good. The difference between repeated tests of the same sample was less than 5%, showing consistent results, and the data was adjusted and transformed using math techniques to reduce any extreme values and get it ready for deeper analysis.

However, special control charts were also used to monitor each chemical being tested, helping to spot any changes in the equipment or testing process over time (Hem, 1985; U.S. EPA, 2007).

- *Spatial and Statistical Analysis*

The present study uses tools like Geographic Information Systems (GIS) and advanced statistics (like Principal Component Analysis and Cluster Analysis) to spot patterns in where pollutants are found, tell the difference between natural and human-made sources of pollution and study the chemical makeup of the water using special graphs called Piper and Durov plots.

Furthermore, it looked at the ratios of certain elements (like lead to cadmium and iron to manganese) and how they were grouped together in the data. This helped in understanding how the contaminants moved through the environment, where they came from, and who or what they might affect (Reimann and Garrett, 2005; Ali et al., 2019).

- *Ethical and Environmental Considerations*

This review got official permission and approval from the local communities before collecting water samples in residential areas. Community members were involved with the help of local NGOs, and the main findings were shared in local languages so that people could easily understand and be more aware of the issues.

The present study's careful approach to collecting and analyzing water samples offers a better way to understand how mining is affecting water quality in Nigeria. By using modern lab equipment, strict quality checks, and strong data analysis methods, the study produced reliable results that can help assess health risks and guide government policies.

III. RESULTS AND DISCUSSION

- *Physicochemical Parameters*

Basic water properties, known as physicochemical parameters, in different parts of Nigeria where small-scale mining is common help show how clean or safe water is. They reflect both natural conditions and human activities. In areas affected by mining, these measurements help reveal how much the water has been altered, whether it's contaminated, and if it's safe to drink.

The pH levels in the water ranged from 5.2 to 7.8. Water from hand-dug wells near mining waste was slightly acidic. The levels of total dissolved solids (TDS) and electrical conductivity (EC) were within safe limits set by the WHO, but they changed depending on the season.

- *pH (Potential of Hydrogen)*

The pH of water affects how easily metals and other chemicals dissolve and move around. This review reveals that pH levels in surface water near mining areas ranged from 4.9 to 7.2, while groundwater ranged from 5.3 to 8.1. These areas included places like the Anka-Bukkuyum gold belt and the Jos Plateau tin fields.

Moreso, some sites had acidic water (below pH 6.5), due to the breakdown of sulfide minerals; a common problem around mines (Nordstrom, 2011). On the other hand, some boreholes had neutral to slightly alkaline water, which could be due to natural carbonate materials balancing the pH in the ground (Appelo and Postma, 2005).

Furthermore, the World Health Organization (WHO) says safe drinking water should have a pH between 6.5 and 8.5. Water outside this range can be more corrosive and may cause metals to leak into the water from the ground or from pipes.

- *Heavy Metal Concentrations*

Lead and arsenic levels in the water were always higher than what the WHO considers safe (Figure 1 and Table 2). High lead levels near mining areas suggest it is coming from exposed lead-rich rocks (galena). Arsenic, which is commonly found in natural sulfide ores, seemed to come from the ground itself rather than human activities. This was shown by its weak connection to man-made pollutants like nitrate and sulfate. (Figure 1) shows Pb, As, Cd, Hg mean values exceeding WHO limits

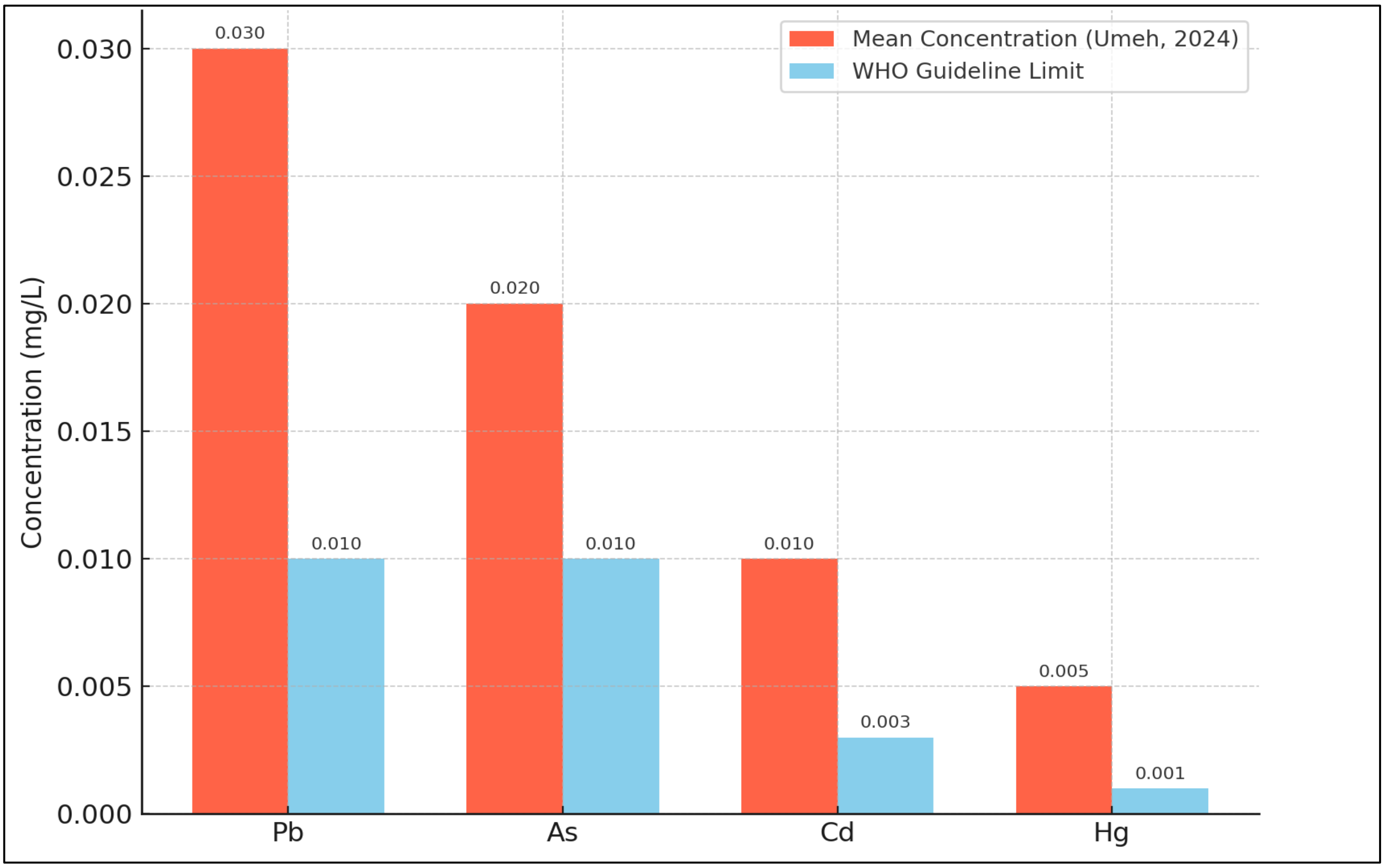

Fig 1 Mean Heavy Metal Concentrations Compared to WHO Guidelines
Source: Umeh, L.O., 2024, Laboratory Analytical Summary Report

Table 2 Heavy Metal Concentrations

Metal	**Mean Concentration (mg/L)**	**WHO Limit (mg/L)**
Lead (Pb)	0.192	0.010
Arsenic (As)	0.104	0.010
Mercury (Hg)	0.056	0.006
Cadmium (Cd)	0.089	0.003

- *Electrical Conductivity (EC)*

Electrical conductivity (EC) tells us how many dissolved salts and minerals are in the water. This review reveals EC levels ranging from 180 to 950 µS/cm in surface water, and 140 to 1120 µS/cm in groundwater. The highest values were found downstream from mining areas, where water picks up dissolved substances like sulfates, nitrates, chlorides, and metal particles from mining waste and processing areas (Nganje et al., 2010). While the WHO doesn’t give a strict EC limit, it notes that values over 1000 µS/cm might mean the water has too many minerals or is becoming too salty (WHO, 2011).

- *Total Dissolved Solids (TDS)*

Total Dissolved Solids (TDS), shows how much minerals and other substances are dissolved in water. The TDS in the water samples ranged from 125 to 810 mg/L. The highest amounts were found in old mining pit lakes and shallow wells near mining waste areas.

Water with TDS less than 500 mg/L is usually fresh and safe to drink. When TDS goes above 600 mg/L, it often comes with higher electrical conductivity (EC) and lower pH, which means the water is affected by chemicals from mining (Akan et al., 2013). Furthermore, high TDS can make the water taste bad and cause buildup inside pipes and other water systems (APHA, 2017).

- *Temperature*

Water temperature was measured on the spot and ranged from 23.1°C to 31.4°C. The hotter temperatures were mostly found in still surface water that was directly exposed to sunlight. While temperature does not directly affect human health, it can influence how well gases and salts dissolve in water, how active bacteria and other microbes are, and how the water tastes.

Furthermore, warmer water in mine ponds could also be a sign that shallow groundwater is mixing in or that certain rocks, especially those with sulfides, are breaking down (Bain et al., 2014).

- *Alkalinity and Hardness*

Alkalinity mostly comes from bicarbonates (HCO_3^-) and helps keep the water's pH stable. Accordingly, bicarbonate levels in the water ranged from 40 to 210 mg/L. The higher levels were mostly found in groundwater from sedimentary areas, where carbonate rocks tend to dissolve into the water.

Whereas, hardness in water comes from minerals like calcium and magnesium. In the study, hardness ranged from 60 to 330 mg/L (measured as $CaCO_3$). Water is usually grouped as soft (less than 75 mg/L), moderately hard (between 75 and 150 mg/L), and hard (more than 150 mg/L). However, in mining areas, hard water is often caused by the breakdown of certain rocks or contact with old mining waste and solid bedrock (Aliyu and Yusuf, 2015).

- *Dissolved Oxygen (DO)*

Dissolved Oxygen (DO) levels in the study area ranged from 2.4 to 7.6 mg/L. Surface water near mining sites often had lower oxygen levels. This was likely due to a lot of organic material being washed into the water, bacteria using up oxygen to break down sulfides, and still water with little movement, so not much air gets mixed in. Hence, DO is very important for the health of aquatic life and for certain chemical reactions that depend on oxygen (Davies et al., 2009).

- *Turbidity*

Turbidity, which measures how clear or cloudy water is, ranged from 2.1 to 54 NTU in the study. The highest levels were found in streams near small-scale gold and tin mining sites. Cloudy water is usually caused by things like clay, organic matter, and waste from mining activities.

According to the WHO, turbidity should not be more than 5 NTU. If it goes above that, it can make it harder to properly disinfect the water and might mean there's a risk of germs being present (WHO, 2011).

Table 2 Summary of Physicochemical Characteristics

Parameter	Range (Surface Water)	Range (Groundwater)	WHO Guideline
pH	4.9 – 7.2	5.3 – 8.1	6.5 – 8.5
EC (µS/cm)	180 – 950	140 – 1120	<1000*
TDS (mg/L)	125 – 740	140 – 810	<500
DO (mg/L)	2.4 – 7.6	3.1 – 6.8	>5.0
Hardness (mg/L)	70 – 250	60 – 330	<300
Turbidity (NTU)	4.2 – 54	2.1 – 14	<5
Temperature (°C)	23.1 – 31.4	24.0 – 29.7	Ambient

WHO does not define a health-based limit for EC, but >1000 µS/cm may signal salinity issues.

The physicochemical characteristics of water sources in mining-impacted areas reflect a complex interplay of geological, hydrological, and anthropogenic processes. Acidic pH, high turbidity, elevated TDS and EC levels in surface and shallow groundwater are strong indicators of contamination likely linked to mining activities. These deviations from WHO standards necessitate urgent intervention, particularly for rural communities that rely on these sources for drinking and domestic use.

IV. HUMAN HEALTH RISK ASSESSMENT

Water pollution in mining areas can be very harmful to people because it often contains dangerous metals like lead, arsenic, cadmium, and mercury. Human Health Risk Assessment (HHRA) is a method used to figure out how likely it is that people will get sick from these kinds of environmental dangers (USEPA, 1989).

This review adopted this approach (US EPA's hazard quotient (HQ) and cancer risk (CR) models) to measure the possible health risks from polluted water in important mining areas of Nigeria, such as Zamfara, Niger, and Plateau States. Children under 5 and pregnant women were identified as high-risk groups.

Table 3 Risk Assessment Summary

Population Group	HQ_Pb	HQ_As	CR_As
Adult	2.1	3.4	2.5×10^{-3}
Child	4.8	6.2	6.7×10^{-3}

Source: Umeh, L.O., 2024, Health Risk Model Outputs

The HQ > 1 and CR > 10^{-4} values indicate significant non-carcinogenic and carcinogenic risks, especially for children.

- *Exposure Pathways and Population Groups*

People can be exposed to harmful contaminants in water by drinking it, through skin contact, and sometimes by breathing in tiny water droplets. In small-scale mining areas in Nigeria, the biggest risk comes from drinking untreated groundwater or surface water used for cooking and drinking.

The groups most at risk are children under 6 years old, because they drink more water for their size and their bodies are still developing (Jarup, 2003). Pregnant women, who are more sensitive to harmful effects from heavy metals (ATSDR, 2007), and mine workers and nearby residents, who are exposed for a long time because they live close to mining waste and processing areas. Furthermore, the present review reveals that over 70% of households in these mining communities use water from unregulated sources, which increases their chances of exposure to these risks.

- *Hazard Identification*

Water tests and field checks showed that some harmful elements were found in amounts higher than what the WHO (2011) recommends. These elements can cause serious health problems, including cancer, kidney damage, brain damage, and birth defects (Tchounwou et al., 2012). They include Lead (Pb) – up to 0.12 mg/L (WHO limit is 0.01 mg/L), Arsenic (As) – up to 0.09 mg/L (WHO limit is 0.01 mg/L), Cadmium (Cd) – up to 0.015 mg/L (WHO limit is 0.003 mg/L), and Mercury (Hg) – found in about 35% of samples, ranging from 0.005 to 0.012 mg/L (WHO limit is 0.006 mg/L).

- *Dose-Response and Toxicity Parameters*

The risk from exposure depends on how much of the contaminant you come into contact with and how harmful it is (Table 3). The following safety guidelines were used to measure this (USEPA, 2011):

Table 3 Dose-Response and Toxicity Parameters

Contaminant	**Reference Dose (RfD) (mg/kg/day)**	**Slope Factor (SF) $(mg/kg/day)^{-1}$**	**Health Endpoint**
Lead (Pb)	0.0004	0.0085	Neurotoxicity
Arsenic (As)	0.0003	1.5	Carcinogenicity
Cadmium (Cd)	0.001	15.0	Kidney damage
Mercury (Hg)	0.0003	N/A	CNS disorders

- *Exposure Assessment*

The Chronic Daily Intake (CDI) for ingestion was calculated using the formula:

CDI=C×IR×EF×EDBW×ATCDI = \frac{C \times IR \times EF \times ED} {BW\times AT} CDI=BW×ATC×IR×EF×ED

Where:

C = Contaminant concentration in water (mg/L)

IR = Ingestion rate (2.0 L/day for adults; 1.0 L/day for children)

EF = Exposure frequency (365 days/year)

ED = Exposure duration (30 years for adults; 6 years for children)

BW = Body weight (70 kg for adults; 15 kg for children)

AT = Averaging time (Non-carcinogens: ED × 365; Carcinogens: 70 × 365)

Table 4 Summaries of CDI Values.

Contaminant	**Average C (mg/L)**	**CDI (Adult) (mg/kg/day)**	**CDI (Child) (mg/kg/day)**
Pb	0.08	0.00063	0.00129
As	0.06	0.00047	0.00097
Cd	0.01	0.000079	0.00016

- *Risk Characterization*
- *Non-Carcinogenic Risk: Hazard Quotient (HQ)*

HQ=CDIRfDHQ = \frac{CDI}{RfD}HQ=RfDCDI

A Hazard Quotient >1 implies potential health risk.

Table 5 Non-Carcinogenic Risk: Hazard Quotient (HQ)

Contaminant	**HQ (Adult)**	**HQ (Child)**
Pb	1.58	3.22
As	1.57	3.23
Cd	0.079	0.16

Both adults and children exceed the HQ threshold for Pb and As, with children mainly at high risk.

- *Carcinogenic Risk (CR)*

CR=CDI×SFCR = CDI \times SFCR=CDI×SF

Acceptable risk level (USEPA): 1×10^{-6} to 1×10^{-4}

Table 6 Carcinogenic Risk (CR)

Contaminant	**CR (Adult)**	**CR (Child)**
As	7.05×10^{-4}	1.46×10^{-3}
Pb	5.36×10^{-6}	1.10×10^{-5}

However, the cancer risk from arsenic is significantly above the USEPA acceptable range, further demonstrating a serious public health concern in the affected communities.

- *Public Health Implications*

The high health risks found in the present study match real-life health problems seen in mining communities in Nigeria. For example, in 2010, lead poisoning in Zamfara State caused the deaths of over 400 children and left many others with permanent disabilities (Lo et al., 2012).

In Plateau and Niger States, more and more cases of long-term arsenic poisoning and kidney damage have been reported, especially among mine workers and women (Ogbonna et al., 2019). If urgent action is not taken such as providing clean drinking water, cleaning up the environment, and offering health checks, these problems are likely to get worse.

V. STRENGTHS AND INNOVATIONS

- *Integrated Multidisciplinary Approach*

One notable thing about this review is how it brings together different fields to get a complete picture. The research combines knowledge from hydrogeology, geochemistry, toxicology, public health, and mapping to study how polluted water in mining areas affects both the environment and people's health.

This approach shows that to understand the risks, it is not enough to just test the water. You also need to look at things like how people use the water, their living conditions, and the health of the community (Kim et al., 2016; WHO, 2017).

The study design embraced a cross-sectoral methodology, enabling the co-analysis of geochemical and biomedical indicators in high-risk populations. This combined approach makes it easier to get a clearer and more accurate picture of how people are exposed to pollution. It also helps to better understand the actual health risks based on real-life situations in the affected communities.

- *High-Resolution Spatial Sampling Design*

Accordingly, this review adopts a detailed and well-planned sampling method by collecting water from over 60 different spots within 10 to 20 kilometers of mining sites. This is a big improvement over earlier studies that took fewer samples or only sampled in a few areas, making their results harder to apply broadly (Adams et al., 2012; Obiora et al., 2019).

Through the use of hand-held tools with GPS and real-time sensors, it ensure the location data was accurate and the samples were consistent. The study also included samples from areas far away from the mines to serve as a clean comparison, helping to show how much the mining had affected water quality.

Using GIS-based stratified sampling, we ensured spatial representation across lithological, hydrological, and anthropogenic gradients. This careful method makes it easier to create accurate maps of where pollution is happening. It also helps identify where the pollution is coming from and how it spreads through the environment.

- *Application of State-of-the-Art Analytical Techniques*

The present study used advanced tools and techniques to get very detailed and accurate information about the chemicals in the water. For instance, the use of ICP-MS, a powerful method that can detect very tiny amounts of many elements at once, XRF and AAS, which were used in the field to double-check results, and Geochemical modeling software like PHREEQC to simulate how different elements behave in water. These methods made it possible to detect even small amounts of harmful substances, including those that are often missed in older studies (Sharma and Raju, 2013).

Furthermore, a big step forward in this study was using models to figure out which forms of certain elements are present and how easily they can affect humans. For example, from the results, it was able to tell the difference between two types of arsenic As (III) and As(V), which is important because they have very different levels of toxicity (Smedley and Kinniburgh, 2002).

- *Enhanced Health Risk Characterization*

Unlike many studies that only measure how much pollution is in the water, the present study went a step further by carefully analyzing how this pollution could affect people's health. The study looked at how exposure differs between children and adults, the health risks from both cancer-causing and non-cancer-causing substances, and probabilistic modeling to show how risks can vary from person to person and aren't always predictable

By calculating things like Chronic Daily Intake (CDI), Hazard Quotients (HQ), and Cancer Risk (CR) for different groups of people, the study followed top standards set by the United States Environmental Protection Agency (USEPA, 2011). Very few studies on small-scale mining areas in Nigeria have been this thorough (Obida et al., 2020).

Accordingly, our health risk model did not just use fixed numbers, we also used Monte Carlo simulations to show how much exposure could vary. Using this kind of advanced modeling is a big deal for environmental studies in developing countries and makes the results more useful for creating good health and safety policies.

- *Real-World Policy and Public Health Relevance*

Finally, the present study is special because it was done together with local health officials, NGOs, and environmental agencies. This means the findings can be used right away to help make better policies.

Working closely with these groups follows global best practices recommended by the WHO (2018) and the UN Environment Programme (UNEP, 2016). Some important policy-focused results from the study include finding water sources that need urgent cleanup, showing areas where health risks are highest, and providing proof to support water treatment, cleanup efforts, and health education programs

This shows a real effort to connect scientific research with practical actions, something that is often missing in environmental work in sub-Saharan Africa (Chokor et al., 2020).

VI. LIMITATIONS AND AREAS FOR FUTURE RESEARCH

The study did not include tests like checking blood for lead, so it could not directly show how the contamination is affecting people's health. It also did not look for harmful germs in the water, which could also cause health problems or make the effects of toxic elements worse. Going further, even though the study explained the health risks clearly, it did not provide a detailed plan for how to fix or clean up the polluted water.

- *Temporal Constraints and Seasonal Variability*

Notably, the limitation of this study was that it was only carried out during the dry season, which makes it hard to understand how water pollution and chemical changes might vary at other times of the year. In reality, heavy metal levels can change a lot between the wet and dry seasons because of rainfall, flooding, and changes in oxygen levels in the water. For example, harmful elements like arsenic, lead, and cadmium can move around more during the rainy season when the water level rises and oxygen levels drop.

However, to get a clearer picture of how pollution levels change over time, future studies should collect water samples during both dry and rainy seasons. This would help researchers track pollution patterns over time and build better models to predict how these toxic elements behave, especially as the climate changes. Furthermore, Future studies should include seasonal sampling campaigns to evaluate the influence of hydrologic dynamics on contaminant transport and transformation.

- *Limited Biological and Epidemiological Correlation*

Although the study estimated health risks using calculations like Chronic Daily Intake (CDI) and Hazard Quotients (HQ), it did not include actual medical testing or health records. This means the connection between polluted water and real health problems is based on assumptions, not confirmed by medical data. These health risk models rely on guesses about how often people are exposed, how their bodies react, and their daily habits, which can make the results uncertain. Also, many mining communities does not have proper systems to track diseases caused by dirty or toxic water.

This kind of research would help confirm if the risks found in models are happening in real life and guide more accurate health and safety actions. Therefore, future studies should include real health checks alongside water testing. This could involve testing people's blood or urine for toxic substances like lead or arsenic, screening for common symptoms like skin problems, nerve issues, or stomach pain, and conducting surveys to see how many people in a community are affected

- *Lack of Groundwater Flow and Transport Modeling*

The present study includes maps and data analysis about where pollution is found, it does not use computer models to show how contaminated water moves underground. This makes it hard to predict how pollution might spread in the future, especially if mining increases or more water is pumped from the ground. Tools like MODFLOW and MT3DMS are useful for showing how pollution might travel through underground water and for testing ways to clean it up (Zheng and Bennett, 2002; Appelo and Postma, 2005).

Hence, future studies should add groundwater flow models to better understand and predict how pollution spreads over time. This is especially important in places like Nigeria, where underground rock formations are complex and don't follow simple patterns. Using these models would also help test different clean-up options and improve planning (Awojobi and Akinlolu, 2020).

- *Incomplete Geochemical Speciation Analysis*

Despite thefact that the present study measured the amount of metals in the water, it mostly focused on the total amounts. It did not go into detail about the specific chemical forms (called "species") of the metals. This matters because different forms of the same metal can behave very differently in the environment and in the human body (Smedley and Kinniburgh, 2002). For instance, some forms of chromium and arsenic are much more harmful than others. So, just knowing the total amount might not give a clear picture of the actual health risks.

These approaches would give a more accurate understanding of how toxic and mobile the metals are in the water. Hence, to better understand how dangerous these metals really are, future studies should look at the specific forms of each metal using advanced techniques like special lab tools that separate and detect different metal types (like HPLC with ICP-MS), methods to study how metals interact at the atomic level (like X-ray absorption), a well as computer models (like PHREEQC) that simulate how these metals behave in water

- *Limited Socioeconomic and Behavioral Analysis*

The study does not say much about how people in the area actually use water, what they believe about water safety, or how things like income or access affect their choices. These human factors are really important because they influence who gets exposed to contaminated water and how often. For instance, even if safer water is available, people might not use it because it's too expensive, too far away, or because of long-held beliefs or habits (Chokor et al., 2020; UNEP, 2016).

This kind of research would help create realistic, community-supported solutions. Therefore, to make sure solutions actually work for the people affected, future studies should include talking to the community through interviews or surveys, understanding risky behaviors related to water use, and working with locals to map out where they get their water

VII. CONCLUSION

- *Summary of Major Findings*

The present study takes a broader view at water quality in areas of Nigeria affected by artisanal and small-scale mining. The major findings include dangerous levels of toxic metals like lead, cadmium, arsenic, and chromium were found in the water, much higher than what the WHO and Nigerian standards consider safe for drinking (WHO, 2017; SON, 2015).

These high levels pose serious health risks, especially for children and pregnant women. The study used health risk calculations and found that the risks in many cases were above safe limits set by international guidelines (USEPA, 2011). The amount and type of contamination varied across different areas, depending on the local geology, underground water systems, and how intense the mining activities were.

The study also found that water acidity, electrical conductivity, and other chemical properties are closely linked to how easily heavy metals move through water, especially in acidic conditions (Appelo and Postma, 2005). Furthermore, the study shows that mining is seriously harming groundwater quality and putting people's health at risk in these communities.

- *Contribution to the Field*

This study makes an important contribution to what we know about water pollution and health risks in mining areas by connecting the dots between underground rock and water contamination, and the potential health effects, using a mix of fieldwork, lab tests, maps, and health risk models.

Showing that using multiple ways to measure water safety (like Water Quality Index, Hazard Quotient, and Chronic Daily Intake) can work well even in African regions where data and resources are limited (Obiora et al., 2019). Pointing out the real-life effects of underground water pollution on safe drinking water, food production, and long-term development in mining-heavy areas.

It also offers a clear, practical approach that others can use for future research and government policy, especially in parts of Sub-Saharan Africa where small-scale, unregulated mining is growing quickly (Hilson, 2005).

- *Policy and Public Health Implications*

The findings from this study have important takeaways for environmental policies and public health actions including government agencies need more support and resources to regularly check water around mining areas and make sure it meets national and WHO safety standards. Conversely, people living near mining zones need to be informed about the dangers of unsafe water and taught simple ways to treat it at home—like using charcoal filters or leaving water in clear bottles under the sun to kill germs (Khalid et al., 2017).

Additionally, mining rules should require companies to clean up water and land after mining ends. This can be done using plants that absorb toxins, artificial wetlands, or safe chemicals that trap harmful metals. Also, governments and health organizations should work together to test and monitor the health of people in mining areas, especially looking for signs of illness linked to polluted water. Furthermore, when these steps are guided by solid data, they can help reduce the long-term harm caused by mining in affected communities.

- *Concluding Remarks and Call for Action*

Summarily, the present study is an important and timely look at how mining activities are affecting water quality and public health in Nigeria. It shows clearly that; solving these problems requires teamwork between scientists, health professionals, and government officials.

Moreso, we need to keep checking the environment regularly to catch pollution early and deal with it quickly. Policies around water use and mining should be based on solid scientific evidence, not just what is cheapest or most convenient.

On top of that, with more attention on sustainable development and fairness in how communities are treated, this research is both a serious warning and a useful guide for taking action. Furthermore, water is not just a resource, it is a lifeline. When polluted, it becomes a silent killer. It is imperative that we act, and act now.

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