Mitigating Aquatic Pollution from The Maiganga Coal Mine: Source Identification, Risk Assessment, And Community-Driven Management Strategies

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Abstract- Even though coal mining is a pivotal source of energy production, mining operations at the Maiganga coal mine site have resulted in significant environmental pressures, especially on surface water and agricultural systems. Also, potentially toxic elements (PTEs) introduced by acid mine drainage (AMD) and mine runoff have the ability to bioaccumulate and endanger both human health and the environment. This project developed community-informed mitigation measures for sustainable environmental management while evaluating the risks, causes, and amount of PTE contamination. During the dry and wet seasons of 2025, 132 environmental samples (soil, water, sediment, and food crops) were collected from six locations that represented the downstream, control, and mine-proximal zones, and Atomic Absorption Spectrophotometry (AAS) was used to evaluate and determine the metal concentrations. Results of the study showed that the average amounts of Pb (0.15 mg/L), Cd (0.03 mg/L), and As (0.04 mg/L) in surface water were higher than the WHO (2017) allowable limits, soil and sediment samples showed moderate to severe contamination, according to non-carcinogenic risk assessment, both adults and children had Hazard Index (HI) values greater than 1, with children's exposure to lead carrying the highest risk (HI = 2.81), and multivariate analysis mainly connected AMD and mining tailings leachate to contamination patterns. According to stakeholder interviews (n = 90), most people were aware that water quality is getting worse (91%) but have little to no information about chronic metal toxicity (62% ignorant), and the respondents underlined the necessity of community-led water surveillance and monitoring, stronger effluent regulations, and remedial infrastructure. Therefore, to improve environmental quality and safeguard the livelihoods of the roughly 15,000 residents of Maiganga who depend on the hydrological system, integrated remediation alternatives such as built wetlands, phytoremediation, and participatory surveillance are advised.

Keywords: Community engagement, Ecological restoration, Geoaccumulation, Heavy metals, hydrological system, Livelihood

I. INTRODUCTION

Coal remains a key component of Nigeria's industrial and energy policies with the Maiganga coal field in Gombe, generating power and creating jobs locally. However, the cost of coal extraction has become more tangible, especially in poorly regulated situations, and poorer economies that lack adequate monitoring and mitigation facilities are most affected (Abiodun and Ogunkunle, 2022; Uloko *et al.*, 2025a). Also, acidic wastewater containing potentially hazardous elements (PTEs) is disposed of by coal mining and associated beneficiations, contaminating both land and water.

The Benue Trough sedimentary sequence is home to the Maiganga Coal Mine, which is situated near Kumo, in Akko Local Government Area. Seasonal wet-dry cycling hydrology of the region facilitates the mobilization of contaminants in rainfall, thereby increasing the danger of exposure for communities in close proximity (Oruonye *et al.*, 2016). High levels of Pb, Cd, As, and Cr in water, soil, and vegetation have been found in other similar mining regions in Nigeria, with levels frequently exceeding FAO/WHO acceptable limits (Barde *et al.*, 2024; Adewumi and Laniyan, 2023). The ecological effects of this include reduced aquatic biodiversity, altered pH levels, decreased soil fertility, and long-term human exposure resulting in neurological, renal, and developmental diseases (Jaishankar *et al.*, 2014; Sodhi *et al.*, 2022). Despite the existence of these issues, there is a dearth of empirical research into the prevalence, spatial distribution, and health effects of coal-induced pollution in Maiganga. Local perspectives from communities on how this issue should be addressed are equally lacking. Integrating them into scientific management recommendations would be made easier with an awareness of local perceptions. In order to guarantee environmental health and resilient livelihoods in areas affected by mining, this integrated method integrates environmental chemistry with social inquiry, which is in line with Nigeria's Sustainable Development Goals (SDGs) 3, 6, 13, and 15. The objectives of the present study are fourfold: i).To evaluate the spatial and seasonal variations in contaminant levels (heavy metals and physicochemical parameters) in water, soil, sediment, and food crops along the hydrological gradient; ii). To identify the sources and interrelationships of contamination using statistical and geospatial analyses, and map the distribution of pollutants in the study area; iii). To assess the potential health risks associated with exposure to contaminants for both adults and children through ingestion and dermal contact pathways; iv).. To incorporate community perceptions and stakeholder insights to inform mitigation strategies and policy recommendations aimed at reducing environmental and health impacts.

II. METHODOLOGY

2.1 Study Area

Maiganga is situated in the Akko Local Government Area of Gombe State, northeastern Nigeria (10°11'N, 11°17'E), and approximately 10 kilometers south of Kumo. The region's geomorphology is defined by a tropical climate akin to Sudan with a gently undulating topography and 800-1000 mm of yearly rainfall. Ephemeral streams that are tributaries to the Gongola River system, a significant source of water for both agriculture and residential use, make up the surface hydrology (Tahir *et al*., 2025). The coal mining area is home to numerous communities, including Fongo, Komta, Kwibah Alatai, Kwilapandi, and Maiganga town, which together have a population of around 15,000 people. Small-scale ruminant rearing and subsistence farming are the main drivers of the local economy (Abubakar *et al*., 2025).

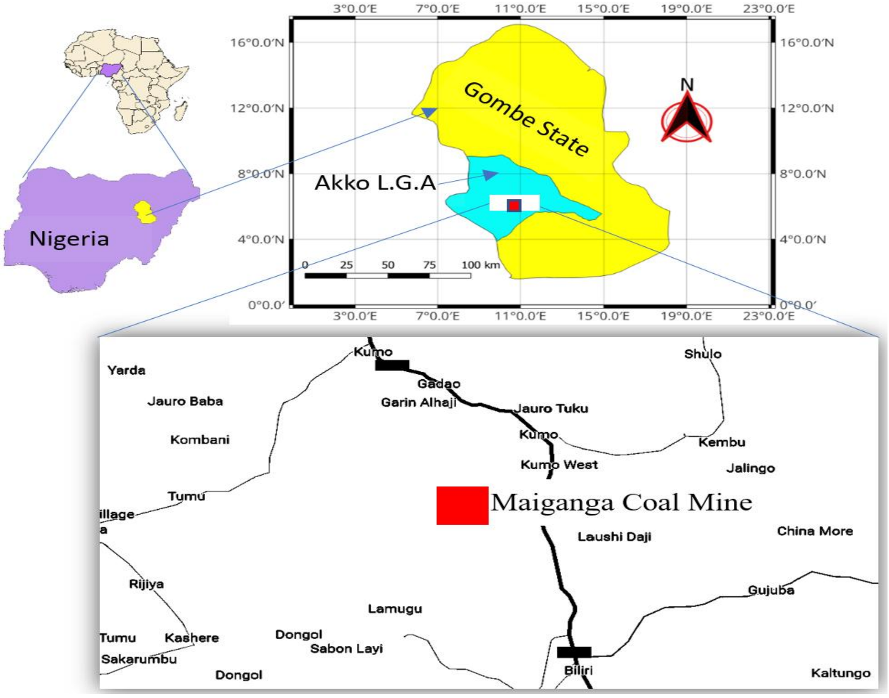

Figure 1: Map of the study area showing the location of Maiganga Coal Mine.

2.2 Sampling Framework

Sampling was undertaken in two contrasting hydrological periods, the dry (April-May) and wet (September) seasons of 2025 to capture temporal variations in contaminant levels. Six sampling sites were selected along the hydrological gradient. For water (n = 36), soil (n = 36, 0–20 cm depth), sediment (n = 36), and food crops (maize and sorghum; n = 24), triplicate samples were taken at each location. Pre-cleaned 1.5 L HDPE bottles were used to collect water samples, which were then acidified with HNO_3 to a pH of less than 2. Stainless-steel augers were used to collect soil and sediment samples, which were then combined to create representative samples. Prior to analysis, all samples were kept in storage at 4°C. In accordance with USEPA (2022) rules, sampling coordinates were georeferenced using a Garmin GPS receiver.

Table 1. Sampling Locations and Descriptions

Site Code	Location Name	Description	Approx. Distance (km)	Coordinates (Lat, Long)
S1	Mine Site	Proximal discharge point	0.0	10.1805°N, 11.3238°E
S2	Fongo	Downstream	1.5	10.1728°N, 11.3211°E
S3	Komta	Downstream	3.0	10.1659°N, 11.3174°E
S4	Kwibah Alatai	Midstream	4.5	10.1574°N, 11.3127°E
S5	Kwilapandi	Far downstream	6.0	10.1502°N, 11.3079°E
S6	Control Site	Upstream, unaffected area	10.0	10.1897°N, 11.3315°E

2.3 Analytical Procedures

To guarantee analytical consistency and eliminate coarse debris, soil and sediment samples were air-dried, homogenized, and sieved (2 mm). The digestion of the sample was conducted in accordance with USEPA Method 3050B, which uses hydrogen peroxide and nitric acid digestion for trace metal measurement in solid matrices (EPA, 2000; Han and Gu, 2023a). Ultrapure nitric acid was used to acidify water samples to a pH of less than 2, and the American Public Health Association's (APHA, 2022) guidelines were followed for digestion. They were measured by Atomic Absorption Spectrophotometry (AAS; PerkinElmer AAnalyst 400) for PTEs (Pb, Cd, As, Cr, Fe, Mn, Cu, and Zn).

Field blanks, triplicate analyses, and calibration with National Institute of Standards and Technology (NIST)-certified reference materials (SRM 1640a and 2711a for water and soils, respectively) were among the extensive quality assurance and quality control (QA/QC) procedures used to guarantee data reliability. In accordance with international best standards, recovery rates between 90 and 110 percent and relative standard deviations below 5 percent demonstrated the maintenance and verification of analytical precision (Adewumi and Laniyan, 2023; Chris *et al*., 2023)

To evaluate the impact of AMD, physicochemical parameters were examined, including pH, electrical conductivity (EC), total dissolved solids (TDS), total suspended solids (TSS), nitrate (NO_3^-), chemical oxygen demand (COD), biochemical oxygen demand (BOD), and total petroleum hydrocarbons (TPH). These markers shed light on organic load, salinity, acidity, and general aquatic health (Khelifi *et al*., 2020).

2.4 Statistical and Geospatial Analysis

Seasonal and regional fluctuations in polluted soils were assessed by data analysis utilizing descriptive and inferential statistics using SPSS v28 (IBM Corp., 2021). Seasonal and spatial variations were evaluated using paired t-tests at a 95% confidence level ($p < 0.05$), while the significant difference test between sampling sites was conducted using one-way analysis of variance (ANOVA) (Wung, 2024). Potential origins and interrelationships among metal routes were identified using Principal Component Analysis (PCA) and Pearson correlation matrices, while the distribution of contaminants was depicted using spatial interpolation (Inverse Distance Weighting, IDW) in ArcGIS 10.8 (Chen *et al*., 2022). According to Aghababai Beni *et al*. (2023), Monte Carlo simulations using Python v3.13 were used to quantify the uncertainty in risk estimations by changing exposure parameters across 10,000 iterations, producing probabilistic exposure profiles.

2.5 Health Risk Assessment

The United States Environmental Protection Agency (USEPA) standard models for ingestion and dermal exposure pathways were used to estimate the risks to human health for both adults and children (USEPA, 2022). These exposure pathways were chosen because they are the most common ways for people to be exposed to heavy metals in contaminated soils. The Hazard Quotient (HQ) was calculated as the ratio of the Average Daily Dose (ADD) to the corresponding Reference Dose (RfD) for each metal, and the ADD for each exposure pathway was determined using USEPA (2011) equations:

$HQ = ADD / RfD$

The Hazard Index (HI), representing the cumulative non-carcinogenic risk from multiple heavy metals, was determined as:

$HI = \Sigma HQ\_i$

An HI value greater than 1 ($HI > 1$) indicates potential non-carcinogenic health risks, while values below 1 suggest negligible risk (USEPA, 2011; Chen *et al*., 2022).

Carcinogenic risk (CR) for arsenic (As) and hexavalent chromium [Cr(VI)] was estimated as:

$CR = ADD \times SF$

where SF represents the slope factor $(mg/kg/day)^{-1}$. Individual metal CR values were added up to determine the overall cancer risk, with tolerable limits falling between 10^{-6} and 10^{-4} (WHO, 2017; Ali *et al*., 2019; USEPA, 2022). In order to assess the total health effects of heavy metal exposure in the study area, risk characterization combined both carcinogenic and non-carcinogenic indices.

2.6 Stakeholder Engagement

In order to integrate local viewpoints, semi-structured interviews were conducted with 90 stakeholders from 15 household heads each from communities of Fongo, Komta, and Kwibah Alatai, Kwilapandi, Maiganga, and Lafarge staff also participated. Interviews explored awareness of problems with water quality, perceived health impacts, adaptive reactions, and proposed mitigation strategies following Denscombe (2021). Data were coded thematically in order to extract prevailing narratives and insights that were pertinent to policy. Interviews explored awareness of water quality issues, perceived health effects, adaptive responses, and preferred mitigation measures. Data were coded thematically following Denscombe (2021) to extract dominant narratives and policy-relevant insights.

2.7 Ethical Considerations

The study obtained approval from Federal University of Kashere Ethics Committee, and community consent was secured through village leaders, ensuring voluntary participation and data confidentiality.

III. RESULTS

Tables 1–4 below summarizes the result findings from the study (physicochemical analyses, heavy metal concentrations, statistical and geospatial modeling, human health risk evaluation, and stakeholder engagement outcomes).

3.1 Physicochemical Characteristics of Water

The physicochemical parameters determined at each of the six sampling locations are shown in Table 1. indicating rising acidity near the coal mine as a result of acid mine drainage (AMD), pH values ranged from 4.2–5.1 at the mine site (S1) to 6.7–7.3 at the control site (S6). Total dissolved solids (TDS) and electrical conductivity (EC) were considerably higher at S1–S3 than at downstream and control locations ($p < 0.05$), indicating increased ionic concentrations from effluent discharge and mineral leaching.

Table 1. Physicochemical Characteristics of Surface Water around Maiganga Coal Mine

Parameter	S1	S2	S3	S4	S5	S6 (Ctrl)	WHO Limit
pH	4.2 ± 0.1^{d}	4.8 ± 0.2^{cd}	5.1 ± 0.5^{c}	6.2 ± 0.2^{b}	6.5 ± 0.3^{b}	7.3 ± 0.4^{a}	6.5 – 8.5
EC (µS/cm)	$1{,}890 \pm 65.6^{a}$	$1{,}540 \pm 91.0^{b}$	$1{,}320 \pm 36.0^{c}$	940 ± 25.1^{d}	860 ± 36.0^{d}	480 ± 20.2^{e}	1,500
TDS (mg/L)	$1{,}120 \pm 7.2^{a}$	960 ± 15.6^{b}	880 ± 11.1^{c}	610 ± 12.1^{d}	520 ± 7.1^{e}	300 ± 13.2^{f}	1,000
BOD (mg/L)	12.4 ± 0.3^{a}	10.8 ± 0.5^{ab}	9.2 ± 1.1^{bc}	8.6 ± 1.3^{c}	6.8 ± 1.3^{d}	4.2 ± 0.5^{e}	10
COD (mg/L)	35.2 ± 1.5^{a}	30.5 ± 7.1^{ab}	28.1 ± 1.8^{bc}	22.3 ± 1.7^{cd}	18.6 ± 2.7^{d}	11.4 ± 1.1^{e}	20
NO_3^- (mg/L)	14.2 ± 0.9^{a}	13.6 ± 1.8^{a}	12.4 ± 4.2^{ab}	10.8 ± 2.6^{abc}	9.2 ± 1.2^{bc}	7.5 ± 1.6^{c}	50

TPH (mg/L)	0.15± 0.1^{a}	0.11± 0.2^{ab}	0.09± 0.0^{ab}	0.07± 0.1^{ab}	0.05± 0.1^{b}	0.03± 0.0^{b}	0.1

3.2 Heavy Metal Concentrations in Environmental Media

Concentrations of eight potentially toxic elements (PTEs) were determined in water, soil, sediment, and crop samples.

Table 2. Mean concentrations (mg/L) of potentially toxic elements (PTEs) in surface water around Maiganga coal mine

Metal	S1	S2	S3	S4	S5	S6 (Ctrl)	WHO Limit (2017)
Pb	0.15± 0.1^{a}	0.12±0.1^{ab}	0.09±0.0^{ab}	0.06±0.0^{ab}	0.04±0.0^{b}	0.02±0.0^{b}	0.01
Cd	0.03±0.0^{a}	0.02±0.0^{ab}	0.02±0.0^{ab}	0.01±0.0^{ab}	0.01±0.0^{ab}	0.00±0.0^{b}	0.003
As	0.04±0.01^{a}	0.03±0.02^{ab}	0.03±0.010^{ab}	0.02±0.01^{abc}	0.01±0.01^{bc}	0.00±0.00^{c}	0.01
Cr	0.07±0.0^{a}	0.05±0.0^{ab}	0.04±0.0^{abc}	0.03±0.0^{bc}	0.02±0.0^{bc}	0.01±0.0^{c}	0.05
Fe	1.25±0.6^{a}	0.98±0.8^{ab}	0.85±0.3^{ab}	0.63±0.2^{ab}	0.55±0.2^{ab}	0.28±0.2^{b}	0.30
Mn	0.46±0.2^{a}	0.38±0.4^{ab}	0.30±0.2^{ab}	0.22±0.1^{ab}	0.18±0.1^{ab}	0.09±0.1^{b}	0.10
Cu	0.12±0.1^{a}	0.10±0.4^{ab}	0.08±0.0^{ab}	0.06±0.0^{b}	0.05±0.1^{b}	0.03±0.0^{b}	2.00
Zn	0.54± 0.1^{a}	0.47± 0.4^{ab}	0.41± 0.0^{ab}	0.33± 0.0^{b}	0.30± 0.1^{b}	0.18± 0.1^{b}	3.00

3.3 Mean Concentrations of Potentially Toxic Elements (PTEs) in Crops

Three metals, namely Pb, Cd, and As concentrations in water and soil exceeded FAO/WHO permissible limits, with maximum values at S1. The control site recorded background levels. Bioaccumulation in crops confirms metal transfer through the soil–plant–human pathway.

Table 3. Mean Concentrations of Potentially Toxic Elements (PTEs) in Crops (Maize and Sorghum)

Medium	Metal	S1	S2	S3	S4	S5	S6 (Control)	WHO/FAO Limit
Water (mg/L)	Pb	0.15±0.0^{a}	0.12±0.0^{ab}	0.10±0.1^{abc}	0.06±0.0^{bcd}	0.04±0.0^{cd}	0.01±0.0^{d}	0.01
	Cd	0.03±0.0^{a}	0.025±0.0^{ab}	0.018±0.0^{abc}	0.012±0.0^{bc}	0.008±0.0^{c}	0.002±0.0^{c}	0.003
	As	0.04±0.0^{a}	0.033±0.0^{a}	0.027±0.0^{ab}	0.019±0.0^{bc}	0.011±0.0^{bc}	0.004±0.0^{c}	0.01
	Cr	0.09±0.0^{a}	0.07±0.0^{ab}	0.06±0.0^{abc}	0.04±0.0^{bcd}	0.03± 0.0^{cd}	0.02±0.0^{d}	0.05
Soil (mg/kg)	Pb	96±5.0a	84±9.9b	75±3.5b	62±4.0c	54±3.0c	32±2.7d	50
	Cd	3.4±0.9^{a}	3.1±0.9^{ab}	2.6±10.5^{ab}	2.1±0.4^{ab}	1.5±0.2^{ab}	0.7±0.2^{b}	1
	As	9.5±0.9^{a}	8.7±1.4^{a}	7.9±0.9^{ab}	6.4±1.1^{b}	5.8±0.8^{bc}	3.6±1.9^{c}	5
	Cr	112±12.5^{a}	104±3.6^{ab}	95±7.0^{bc}	82±7.0^{cd}	78±6.1^{de}	64±9.0^{e}	100
Sediment (mg/kg)	Pb	118±17.4^{a}	102±7.2^{b}	95±4.0^{b}	74±5.0^{c}	68±6.6^{c}	40±6.2^{d}	50
	Cd	4.2±0.4^{a}	3.6±0.4^{a}	2.9±0.4^{b}	2.1±0.3^{c}	1.4±0.4^{d}	0.8±0.4^{d}	1
Crop (mg/kg)	Pb	2.3±0.9^{a}	1.8±0.7^{ab}	1.5±0.4^{b}	1.1±0.3^{bc}	0.9±0.1^{bc}	0.3±0.2^{c}	0.3
	Cd	0.8±0.4^{a}	0.6±0.2^{ab}	0.5±0.4^{abc}	0.3±0.3^{bc}	0.2±0.2^{bc}	0.1±0.1^{c}	0.1

3.4 Statistical and Geospatial Analyses

The Pearson correlation analysis revealed strong positive connections between Pb and Cd (r = 0.88), Cd and Fe (r = 0.82), and As and Cr (r = 0.76). These relationships indicate that these metals are likely moving together from acid mine drainage and waste material runoff. Principal Component Analysis, found two main factors that accounted for 78.4% of the variation in the data, as shown in Table 4. The first component (PC1) appears to represent pollution coming from acid mine drainage, including lead, cadmium, iron, manganese, and electrical conductivity. Whereas the second component (PC2) seems to be related to farming activities or natural geological sources, covering arsenic, chromium, and nitrate. Maps created using spatial interpolation techniques showed that metal concentrations were highest within 2 kilometers of the mine opening and gradually showed radical decrease as you moved further away downstream.

Table 4. Principal Component Loadings of Heavy Metals and Environmental Parameters

Variable	PC1	PC2
Pb	0.91	0.08
Cd	0.87	0.10
Fe	0.83	0.18
Mn	0.79	0.22
EC	0.76	0.24
As	0.22	0.85
Cr	0.19	0.82
NO_3^-	0.25	0.79
Variance explained (%)	56.2	22.2
Cumulative variance (%)	56.2	78.4

3.4 Human Health Risk Assessment

The deterministic and probabilistic risk assessments showed elevated non-carcinogenic and carcinogenic risks, particularly for children (Table 5). Pb and Cd contributed most to total hazard indices (HI). Children's HI values exceeded the safety threshold (HI > 1), indicating potential neurological and developmental risks primarily from Pb ingestion. The carcinogenic risk (CR) for As slightly surpassed the acceptable range (10^{-6}–10^{-4}), signifying chronic exposure concerns.

Table 5. Summary of Non-Carcinogenic and Carcinogenic Risks

Exposure Group	Metal	ADD (mg/kg/day)	HQ	HI	Carcinogenic Risk (CR)
Children	Pb	0.0051	1.85	2.81	—
	Cd	0.0012	0.62		—
	As	0.0008	0.34		2.3×10^{-4}
Adults	Pb	0.0032	1.10	1.78	—
	Cd	0.0009	0.45		—
	As	0.0006	0.23		1.1×10^{-5}

ADD = Average Daily Dose; HQ = Hazard Quotient; HI = Hazard Index; CR = Carcinogenic Risk.
HI > 1 indicates potential non-carcinogenic health risk, while acceptable carcinogenic risk (CR) values range from 1×10^{-6} to 1×10^{-4}

3.5 Stakeholder Awareness and Perception

Data was derived from semi-structured interviews with 90 respondents, including Lafarge staff, farmers, and household representatives across five Maiganga communities (Fongo, Komta, Kwibah Alatai, Kwilapandi, and Maiganga itself). According to stakeholder responses, 91% of respondents noticed visible water quality deterioration, 84% reported crop yield decline, and 62% lacked awareness of metal toxicity. Over two-thirds (69%) expressed willingness to participate in local monitoring programs. Most respondents prioritized borehole provision, stricter effluent control, and environmental education as mitigation measures

Table 6. Summary of Stakeholder Awareness and Perceptions

Indicator	Response Category	Percentage (%)	Interpretation
Awareness of water quality changes	Yes	91	Majority of respondents observed visible changes in water color, odor, or turbidity since mining began.

Reported decline in crop yield	Yes	84	Substantial reduction in maize and sorghum yields attributed to poor irrigation water quality.
Awareness of metal toxicity	Unaware	62	Limited knowledge of chronic health effects linked to heavy metal exposure.
Willingness to participate in community monitoring	Yes	69	Strong community interest in participatory water quality surveillance programs.
Preferred mitigation interventions	Provision of boreholes	78	Top priority intervention to reduce reliance on contaminated surface water.
	Stricter effluent regulation	74	Demand for enforcement of mining discharge standards by regulatory agencies.
	Environmental education programs	71	Need for awareness campaigns on safe water use and pollution risks.

IV. DISCUSSION

4.1 Hydrochemical Conditions and Acid Mine Drainage Influence

The low pH values and high EC and TDS are consistent with acid mine drainage (AMD) influence, which is confirmed by high AMD near the mine site, as is the case in other Nigerian coalfields (Abiodun and Ogunkunle, 2022; Uloko *et al*., 2025a). AMD results from the oxidation of pyrite and other sulfide minerals, which releases sulfuric acid and metal ions (Sodhi *et al*., 2022). Studies from other coalfields, such as those in the Enugu and Okaba coal belts, reported similar hydrochemical profiles, low pH, high conductivity, and elevated Fe (Adewumi and Laniyan, 2023). The downstream spatial decline in acidity and ion concentrations reflects dilution and attenuation, including metal adsorption onto sediments and vegetation uptake (Han and Gu 2023).

4.2 Metal Contamination Patterns and Environmental Implications

The concentrations of Pb, Cd, and As in the water and soil at Maiganga exceeded WHO and FAO/WHO limits, and present an ecological and public health risk to the local communities. The enrichment and geoaccumulation indices show moderate to heavy pollution, which agrees with results from Umar *et al*. (2025) in the mining districts of Niger State, and Adewumi and Laniyan (2023) study on contamination, ecological, and human health risks of heavy metals in water from a Pb–Zn–F mining area, in North Eastern Nigeria. Elevated Pb levels (0.15 mg/L) near the mine suggest high anthropogenic loading from coal combustion residues and leachate discharge, which is consistent with the mobilization of Pb in other local and international coalfields through acid mine drainage and surface runoff (AbdulHameed *et al*., 2010; Bai *et al*., 2024; Uloko *et al*., 2025b).

Cd is a particularly mobile and bioavailable pollutant, which is often associated with soil acidification and root uptake by crop plants (Barde *et al*., 2024). The high As values may reflect sulfide-bearing strata disrupted by mining (Aghababai Beni *et al*., 2023). Sediment data indicate a very high metal retention, suggesting a possibility of remobilization during flooding, a concern for management under a changing rainfall regime (Jonah and Anyanwu, 2023). Pb and Cd values exceeded FAO/WHO limits by factors of 7–8, indicating soil–plant transfer in crops. In areas with artisanal mining, ongoing consumption of contaminated cereals would represent a significant source of metals to daily intake, as observed in Zamfara and Taraba States (Chris *et al*., 2023).

4.3 Source Apportionment and Spatial Trends

The Principal Component Analysis (PCA) results clearly distinguish between AMD derived and diffuse secondary agricultural contamination sources (Barde *et al*., 2024). The first component's strong loadings which accounted for the largest share of variance for Pb, Cd, Fe, and Mn confirm AMD as the primary contamination driver, consistent with Adewumi and Laniyan (2021), Barde *et al*. (2024) and Uloko *et al*. (2025). The second (PC2) component's As, Cr, and NO_3^-

association implied minor contributions of inputs from agricultural activities, particularly fertilizer use, irrigation return flows and geological background levels (Adewumi and Laniyan, 2023). These associations suggest that trace element recruitment is not solely mining-induced but also influenced by land-use practices and natural geochemical background levels as well (Adewumi and Laniyan, 2023; Umar *et al*., 2025).

Spatial interpolation (IDW) in ArcGIS revealed a declining gradient of metal concentration with increasing distance from the mine site, signifying a localized contamination hotspot anchored on the discharge point (S1) and progressively moving downstream toward the control site (S6). This decay pattern of pollutant intensity which is exponential, mirrors global AMD-impacted river ecosystems where metal adsorption and sedimentation processes reduce contaminant loads downstream (Bai *et al*., 2024; Han and Gu, 2023).

Overall, the PCA and geospatial analysis further confirm that AMD contamination from coal extraction activities intensity decreases exponentially with distance from the mine, a trend typical of AMD-affected catchments globally (Ali et al., 2019) and is the predominant pollution source in this study and elsewhere (Bai *et al*., 2024), while agricultural and natural geogenic inputs contribute modestly to the overall contaminant profile

4.4 Health Risk Implications

The elevated Hazard Index (HI) values for children (2.81) indicates a significant non-carcinogenic risks, especially neurotoxicity associated with Pb exposure in potential neurodevelopmental and cognitive impairments (Jaishankar *et al*., 2014). In other similar studies elsewhere, chronic Pb exposure has been linked to behavioral disorders and reduced IQ in children (Adewumi and Laniyan, 2023). Additionally, cadmium is associated with renal dysfunction and bone demineralization, while arsenic carries both non-carcinogenic and carcinogenic hazards (Shetty *et al*., 2024) compound the overall health burden. Comparable risk magnitudes have been reported in northern Nigerian mining zones by Adewumi and Laniyan (2023) and Chris *et al*. (2023), indicating a broader public health concern. Similar HI magnitudes have been reported in mining-impacted areas of northern Nigeria as reported by Adewumi and Laniyan (2023) who found hazard indices >1 in both adult and child populations downstream of Pb–Zn–F mines in northeastern Nigeria. Their findings underscore broad regional vulnerability to heavy metal exposure in mining zones. Bawa and AbdulHameed (2025) have also documented HI ≥ 1 from consumption of vegetables irrigated with metal-contaminated water in Plateau State, reinforcing that non-carcinogenic risk is pervasive across agricultural and mining settings.

The probabilistic Monte Carlo simulations validated the deterministic results, showing that >75% of child exposure scenarios yielded HI > 1. This highlights the urgency of providing alternative safe water sources and implementing community-level health surveillance. The consistency between deterministic and probabilistic approaches strengthens confidence in the conclusion that children in Maiganga are exposed to adverse health risks. Comparable probabilistic results appear in other environmental health studies in Nigeria and Ghana, where high proportions of simulations exceeded safety thresholds, particularly for Pb and As exposures Aghababai Beni *et al*., 2021 and Abdullahi *et al*., 2024). Taken together, these results highlight the urgent need for interventions, including and not restricted to provision of alternative clean water sources, health surveillance (especially for children), and interventions to reduce exposure. Without mitigation, the current trajectory poses enduring risks to cognitive development, renal health, and lifetime cancer probability in the local population (Khelifi *et al*., 2020).

4.5 Community Knowledge, Attitudes, and Adaptive Responses

Despite visible signs of water pollution, discoloration, odor, and changes in turbidity, community understanding of health risks posed by metal toxicity remains limited, mirroring the findings of Oruonye *et al*. (2016) regarding post-resettlement awareness gaps in Maiganga. About 62% of respondents did not recognize the chronic toxicity of metals under reference. This agrees with findings in similar Nigerian contexts as reported by Eze and Onyeke (2025) in Enugu State, where only a small fraction of respondents were aware of heavy metal contamination and its health consequences. Similarly, in Kano State, studies of leafy vegetable consumers revealed widespread consumption of produce despite low risk awareness of heavy metals present in the food chain (Abdullahi *et al*., 2024).

However, a sizeable number of respondents (91%) reported deterioration in water quality, and 84% also observed declines in crop yields. Importantly, there is a high willingness 69% to participate in local water quality monitoring or related environmental actions, suggesting fertile ground for participatory environmental governance. For sustainable remediation, technical interventions alone (e.g., constructed wetlands, effluent treatment) are unlikely to succeed without strong local ownership. Environmental education, awareness raising, and capacity building should be integrated at all levels. Local experiences show that when communities are engaged and informed, uptake of water treatment practices and safe agricultural behaviors increases substantially (Adewumi and Laniyan, 2023; Bai *et al*., 2024). Therefore, while knowledge gaps persist (Abdullahi and Ibrahim, 2009), the community's observations and attitudes present a promising resource. Harnessing this through structured education, participatory monitoring, and inclusive decision-making will be essential for adaptive responses that are enduring and context-appropriate.

4.6 Toward Sustainable Mitigation Strategies

The proposed integrated mitigation framework of constructed wetlands, effluent regulation, and community led monitoring, is theoretically sound, supported by evidence from Nigerian contexts, and consistent with best practices for low-cost AMD remediation in sub-Saharan Africa (Sodhi *et al*., 2022). Constructed wetlands using *Phragmites australis, Pennisetum purpureum* and *Typha latifolia* have shown that constructed wetlands are scalable and can be utilized to treat mining-related contamination using both surface- and subsurface-flow constructed wetlands (SSFCW) with 70–90% metal removal efficiency under similar tropical conditions (Aghababai Beni *et al*., 2023). Moreover, community-based "citizen monitors" programs have demonstrated potential for institutionalizing water sampling and reporting, making it more transparent and accountable, as in Bayelsa State, where the Health of Mother Earth Foundation (HOMEF) trained local residents in pollution monitoring and reporting to increase public awareness and responsiveness to pollution incidents (Egbilika, 2024). Embedding these mitigation strategies within state-level environmental planning under the State Environmental Protection Agency (GOSEPA) would also build greater resilience for the long term and connect to SDG 6 (Clean Water) and SDG 15 (Life on Land) to better integrate remediation actions within ongoing governance, ensuring funding and policy continuity.

4.7 Comparative Context

The case for Maiganga reinforces environmental and health risk patterns in multiple coal-mining regions across sub-Saharan Africa coal regions, such as the Okoba and the Iron Mines of Itakpe and Agbaja, in Kogi State (Nigeria), Hwange Basin (Zimbabwe) and the Tete Basin (Mozambique), where AMD-driven heavy metal pollution threatens water security (Sodhi *et al*., 2022). Recent studies have implicated AMD, in other regions like the Moatize district of Tete Province (Mozambique), where assessments of water, soil, and sediment around coal mines show moderate to high heavy-metal contamination (Marove *et al*., 2022). Metrics such as the Heavy Metal Pollution Index (HPI) and Enrichment Factor (EF) in Moatize revealed that values for Pb, Cr, Mn and As frequently surpass safe limits for drinking water and agricultural application, posing serious ecological and human health risks (Marove *et al*., 2022).

However, Maiganga's relatively small mining scale offers a unique opportunity to reverse degradation through early intervention. The study thus provides a replicable model for participatory pollution mitigation in Nigeria's emerging coal corridors. The Maiganga case reflects environmental and health risk patterns observed in multiple coal-mining regions across sub-Saharan Africa, reinforcing the urgency of early intervention. For example, in the Hwange Basin (Zimbabwe), recent studies document that acid mine drainage (AMD) from legacy coal mines leads to elevated levels of manganese (Mn), arsenic (As), and other metals in the Deka River, with concentrations in some cases far exceeding national water quality standards (Masere and Zvikwete, 2023).

Unlike some of these larger or older coalfields, Maiganga's smaller scale and more recent operational footprint present a strategic advantage, such that the damage may be more localized and less entrenched, improving the feasibility of remediation (Abiodun and Ogunkunle, 2022). In a national context, studies of Nigerian coal regions as reported by Abiodun and Ogunkunle (2022) on acid mine drainage across Nigeria, suggest that pollution is often detected late, allowing AMD and heavy metal accumulation to become widespread before action is taken. In contrast, Maiganga's engagement with community stakeholders, earlier detection of contamination, and defined spatial sampling offer a more proactive and sustainable model. Taken together, these comparative cases underscore that Maiganga can serve as a replicable, best-practice template for integrated pollution management in Nigeria's growing coal corridors, combining scientific risk assessment, policy regulation, and community participation early rather than waiting for widespread environmental degradation as mirrowed by Masere and Zvikwete (2023) in their studies on the impacts of coal mining on Deka River.

V. CONCLUSION AND RECOMMENDATIONS

This study provides compelling evidence of acid mine drainage (AMD)-driven contamination in the Maiganga coal mine area, where elevated concentrations of Pb, Cd, and As in water, soil, sediment, and food crops exceed international safety limits. The spatial and statistical analyses confirm that these pollutants originate primarily from mine effluents and associated leachates, reflecting limited containment and treatment of mining waste. The high Hazard Index (HI > 1) values, especially for children, reveal a pressing non-carcinogenic health risk, while probabilistic risk modelling highlights long-term exposure concerns. These findings underscore that unchecked coal extraction in Maiganga threatens both ecological integrity and public health, particularly in communities relying on contaminated streams and farmland for daily subsistence. Despite these risks, community interviews indicate strong awareness of water quality decline and willingness to engage in local remediation, demonstrating a foundation for community-driven water governance. Harnessing this social capital is vital to improving environmental resilience in mining-affected landscapes. To mitigate these challenges, the study recommends the following actions, which if effectively implemented, would promote environmental justice, protect public health, and contribute to the sustainable development goals (SDGs) 3, 6, 12, and 15:

1. Enforcement of stricter regulatory oversight on discharge quality from the Maiganga mine through the Federal Ministry of Environment and NESREA, to ensure compliance with national and WHO effluent standards, with regular audits should be mandated for mine operators.
2. Establish constructed wetlands and vegetative buffer zones around the mine's drainage network to filter heavy metals and neutralize acidic runoff, as proven effective in other mining regions (Adewumi and Laniyan, 2023; Barde *et al*., 2024).
3. Institutionalize citizen science programs especially in high risk areas such as Fongo, Komta, and Kwilapandi, to enable local residents to participate in periodic water testing and environmental reporting, supported by training and low-cost testing kits.
4. Implement targeted health screening for vulnerable groups, especially children and women and continuous awareness campaigns on safe water use and the health impacts of PTEs.
5. Incorporate the present findings into state-level environmental management plans and promote alternative livelihoods (e.g., aquaculture, eco-restoration projects) to reduce dependence on contaminated natural resources.

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