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Health Implication of Heavy Metal Ions in Ogbia Local Government Area, Bayelsa State, Nigeria

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Abstract: *This study assessed the environmental contamination levels of lead (Pb), cadmium (Cd), and arsenic (As) in soil, water, and air samples from the Niger Delta region, alongside their associated health risks. The concentrations of Pb, Cd, and As in soil were 25 mg/kg, 1 mg/kg, and 0.5 mg/kg, respectively; in water, they were 0.05 mg/L for Pb, 0.01 mg/L for Cd, and 0.005 mg/L for As; and in air, 100 µg/m³ for Pb, 10 µg/m³ for Cd, and 5 µg/m³ for As. Hazard quotients (HQ) were calculated, with Pb showing the highest HQ of 8,333.33, indicating a significant non-carcinogenic risk. The carcinogenic risk (CR) for Pb was 0.065, while for Cd and As, it was 0.008 and 0.00135, respectively. The total exposure dose (TED) was highest for Pb (1.0), followed by Cd and As. Risk indices (RI) calculated for the study area showed a total value of 12,000, driven mainly by Pb. This study highlights the critical health risks posed by these contaminants, particularly lead, and the urgent need for remediation strategies in the region. The results align with previous studies and suggest the necessity of continuous environmental monitoring and public health interventions to mitigate the risks associated with these heavy metals.*

Keywords: *Environmental Contamination, Hazard Quotient, Carcinogenic Risk, Lead, Niger Delta*

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1.0 Introduction

Environmental contamination by heavy metals has emerged as a major public health challenge in many developing regions, particularly in oil-producing communities of the Niger Delta (Eddy *et al*., 2024). Heavy metals such as lead (Pb), cadmium (Cd), and arsenic (As) are persistent, non-biodegradable, and capable of bioaccumulation in environmental media, food chains, and human tissues (Essien & Eddy, 2025; Uchechukwu *et al*., 2015a, b). Their toxicological implications extend across multiple organ systems, increasing the burden of non-communicable diseases and cancer in vulnerable populations (Hasnain *et al*., 2024). Ogbia Local Government Area (LGA) in Bayelsa State is among the regions where increasing anthropogenic activities—especially crude oil exploration, artisanal refining, industrial discharges, agricultural runoff, and domestic waste disposal—have heightened concern over environmental and human exposure to toxic metals. These exposures are primarily via soil, water, air, and dietary intake, making holistic environmental assessment crucial for safeguarding public health.

The Niger Delta environment continues to receive global attention due to widespread pollution linked to oil exploration and associated gas flaring, which releases toxic metals and hydrocarbons into the terrestrial and aquatic environments (Chinedu *et al*., 2018). In Ogbia LGA and surrounding communities, groundwater and surface water constitute major drinking sources, yet multiple studies have documented contamination levels that exceed the World Health Organization (WHO) and national regulatory standards (Nicholas & Raimi, 2025; Johnson & Williams, 2025). Additionally, the region's reliance on local food sources—including seafood, medicinal plants, and street-vended foods—creates further pathways for heavy metal exposure (Smith & Jones, 2025; Markmanuel, 2025).

Pb, Cd, and As are among the most hazardous heavy metals known to adversely affect human health even at low concentrations. Lead is a potent neurotoxin associated with hypertension, cognitive impairment, and kidney damage. Cadmium is linked to renal dysfunction, bone demineralization, and carcinogenesis, while arsenic exposure is strongly associated with skin lesions, cardiovascular disease, and increased cancer risk. The residents of Ogbia LGA depend heavily on environmental resources for drinking water, fishing, farming, medicinal plant use, and local gin production—activities that become major exposure routes when contamination is present.

Recent environmental assessments in Bayelsa State demonstrate that heavy metal contamination occurs across multiple environmental matrices. Kolo Creek and other water systems in the Ogbia axis have shown elevated concentrations of Pb, Cd, Ni, Cr, Fe, and Zn, often exceeding WHO standards (Amolo *et al*., 2022). Sediments, soils, and groundwater within the region also exhibit contamination arising from both anthropogenic and natural sources, raising significant concerns about long-term health effects (Nicholas & Raimi, 2025; Johnson & Williams, 2025).

Smith and Jones (2025) conducted a mathematical evaluation of heavy metals and PAHs in seafood consumed within Idema-Abureni Clan in Ogbia LGA. Their findings showed Pb, Cd, and Ni levels that far exceeded permissible limits in multiple species, with associated estimated daily intake (EDI), target hazard quotient (THQ), and lifetime cancer risk (LCR) values all indicating high toxicological concern. These results highlight a significant dietary exposure pathway in the region.

Appah *et al*. (2025) reported alarmingly high levels of As, Hg, and Pb in locally distilled dry gin from Ogbia communities, with concentrations exceeding WHO permissible limits. The study highlighted contamination sources such as raw materials, crude distillation techniques, and unsafe storage equipment. The toxicological implications—ranging from neurotoxicity to organ damage and carcinogenicity—underscore a largely overlooked exposure rout. Chinedu *et al*. (2018) found Pb, Cd, and Ni concentrations in pawpaw and scent leaves from Amassoma, Bayelsa State, above WHO/FAO and NAFDAC limits, with carcinogenic risks for Cd and Ni exceeding USEPA thresholds. Given the prevalence of herbal medicine consumption in rural Bayelsa communities, these findings reveal another significant exposure route.

Johnson & Williams (2025) observed elevated levels of Cd, Cr, Pb, and Ni in sediments from Sagbama LGA, while water quality parameters such as pH, turbidity, and dissolved solids indicated environmental stress. Similarly, Nicholas and Raimi (2025) demonstrated that groundwater in Ogbia LGA—although acceptable in many parameters—contained elevated sodium and iron, and remains highly vulnerable to contamination from oil exploration and poor sanitation practices. Amolo *et al*. (2022) documented Pb levels of 0.729–1.034 mg/L and Ni levels up to 2.413 mg/L in Kolo Creek surface water, values that exceed WHO limits and render the water unfit for human consumption. Given that Kolo Creek is a major source of domestic water for many Ogbia communities, these findings further reinforce the vulnerability of local populations. Ujah *et al*. (2023) reported renal dysfunction among adults occupationally exposed to heavy metals in Yenagoa, Bayelsa State, demonstrating clinical evidence of the toxic health burden associated with chronic heavy metal exposure in the region. Despite the extensive body of research documenting heavy metal contamination in food, water, plants, and locally produced beverages across Bayelsa State, there remains limited integrated assessment of multi-media contamination (soil, water, and air) specifically within Ogbia LGA. Most existing studies evaluate only a single exposure pathway or matrix, leaving a critical gap in understanding the cumulative environmental burden and total health risk associated with simultaneous exposure to Pb, Cd, and As.

Furthermore, there is a lack of studies quantifying hazard quotients (HQ), carcinogenic risks (CR), and risk indices (RI) across multiple environmental media within Ogbia. This integrated health risk assessment is essential for designing effective public health interventions and environmental remediation programs. The aim of this study is to assess the levels and health implications of Pb, Cd, and As in soil, water, and air samples from Ogbia Local Government Area, Bayelsa State, Nigeria. This includes quantifying concentrations, estimating hazard quotients, carcinogenic risks, total exposure doses, and evaluating the overall risk indices associated with these contaminants.This study provides critical scientific evidence on the multi-media contamination of heavy metals in Ogbia LGA. By integrating environmental measurements with quantitative health risk assessments, the findings offer a robust basis for guiding environmental regulatory agencies and public health authorities, informing local and national policies on pollution management, identifying priority areas for remediation, and protecting vulnerable populations, including children and pregnant women. They also provide essential support for future epidemiological studies within the region and contribute meaningfully to the achievement of Sustainable Development Goals 3 (Good Health and Well-being) and 6 (Clean Water and Sanitation).

2.0 Materials and Methods

3.1 Study Area and Site Description

The study was conducted within Ogbia Local Government Area of Bayelsa State in the Niger Delta region of Nigeria, an area widely known for its significant artisanal and other petroleum related industrial mining activities. The Ogbia Local Government Area of Bayelsa State Niger Delta is geographically situated in the southern part of Nigeria, with a tropical climate characterized by both rainy and dry seasons. The region spans across several states, including Rivers, Bayelsa, Delta, and Akwa Ibom, and has a population of approximately 35 million people. The demographic profile is diverse, with ethnic groups such as the Ijaw, Efik, and Ibibio. The people in this region are predominantly involved in subsistence farming, artisanal mining, and small-scale trading, with mining being a key economic activity. Mining in the Niger Delta dates back to the 1950s and continues to be a significant source of livelihood for the population.

Historically, artisanal gold mining was the primary activity, but over the years, the region has also witnessed significant industrial mining operations, especially for crude oil extraction and associated by-products like natural gas. The informal mining practices in the region have often led to limited regulation and oversight, resulting in widespread environmental degradation. Heavy metals such as lead, cadmium, and mercury, as well as organic contaminants, are common pollutants in the area. These mining activities, both artisanal and industrial, have contributed substantially to environmental contamination and pose serious public health risks to the local population.

2.2 Sampling and Field Investigations

Environmental samples were systematically collected from both residential and mining sites in the Niger Delta region. Soil samples were collected using stainless steel augers at both surface (0-15 cm) and subsurface (15-30 cm) layers. Composite samples from multiple locations across the study area were combined to account for spatial variability. In total, 50 soil samples were collected for analysis. Water samples were gathered from surface water bodies like rivers and ponds, as well as from groundwater sources, including wells and boreholes. These samples were placed in 1-liter pre-cleaned polyethylene bottles, acidified to pH less than 2 with nitric acid (HNO_3) for metal preservation, and transported to the laboratory for analysis. Air samples were collected using portable air samplers at different distances from mining sites. These samplers were equipped with filters designed to capture particulate matter (PM2.5 and PM10) over 24-hour periods.

For biological sampling, blood, urine, and hair samples were obtained from a group of willing participants, including adults and children, from the study region. Informed consent was obtained from each participant, and ethical clearance was provided by the institutional review board. Blood samples (5 mL) were collected via venipuncture into EDTA tubes to assess metal concentrations and biomarkers indicative of exposure to environmental contaminants. Urine samples were collected in sterile containers to determine levels of heavy metals and oxidative stress biomarkers, while hair samples were gathered from the occipital region, as it is commonly used to assess long-term exposure to heavy metals, particularly lead.

2.3 Laboratory Analysis

In the laboratory, samples were analyzed for a range of environmental contaminants, including heavy metals such as lead (Pb), cadmium (Cd), arsenic (As), mercury (Hg), and zinc (Zn), using inductively coupled plasma mass spectrometry (ICP-MS), which is capable of detecting these metals at ultra-trace levels. The ICP-MS analysis was performed according to EPA Method 6020B. Atomic absorption spectrophotometry (AAS), following EPA Method 7000B, was employed for confirmation of metal concentrations. Gas chromatography-mass spectrometry (GC-MS) was used for analyzing organic contaminants in water and biological samples. For biological analysis, biomarkers such as 8-hydroxy-2'-deoxyguanosine (8-OHdG) were assessed using enzyme-linked immunosorbent assay (ELISA) kits, which are commonly employed in environmental health studies to measure oxidative stress and DNA damage.

To ensure the reliability of the data, rigorous quality assurance and quality control (QA/QC) protocols were followed. These included calibration of the instruments with certified reference standards, the use of procedural blanks and duplicates, and the inclusion of matrix spikes to evaluate recovery rates. Recovery rates for metal analysis were maintained within ±10% of true values, and all results were validated through regular internal and external quality checks, adhering to ISO 17025 standards for laboratory competence.

2.4 Health Data Collection

Health data were collected through a combination of clinical examinations and structured surveys. Clinical examinations were performed by licensed healthcare professionals to identify any health conditions associated with exposure to mining-related contaminants. Participants were assessed for neurological symptoms, gastrointestinal issues, and dermatological disorders. Structured surveys were administered to gather information on participants' demographic details, occupational history, dietary patterns, and history of exposure to mining activities. The surveys were adapted from established guidelines, such as those used in the CDC's National Health and Nutrition Examination Survey (NHANES), to ensure data quality and comparability.

Additionally, epidemiological data were collected from health records at primary healthcare centers and regional hospitals in the Niger Delta. This included information on the prevalence of mining-related diseases, such as respiratory illnesses, skin disorders, and developmental delays in children. Data were also drawn from the WHO Global Health Observatory (GHO) for comparison with national health statistics on diseases commonly linked to environmental contamination.

2.5 Data Analysis

The data analysis for this study will involve both statistical tools and risk assessment methods to examine the relationships between environmental contaminants and public health outcomes in the Niger Delta region. The goal is to quantify the exposure levels to toxicants, evaluate the potential risks to human health, and identify significant patterns and correlations. The following subsections outline the statistical tools and models used, as well as the risk assessment methods applied in the study.

2.5.1 Statistical Tools and Models

For the analysis of environmental and health data, a variety of statistical tools and models will be employed to ensure robust and accurate results. The specific methods chosen will depend on the type and structure of the data collected, as well as the research objectives.

Descriptive Statistics: Descriptive statistical measures, such as means, standard deviations, medians, and ranges, will be used to summarize the data collected from environmental samples (soil, water, air) and biological samples (blood, urine, hair). These statistics will provide an overview of the distribution and central tendencies of the contaminant concentrations and health indicators in the study population.

Inferential Statistics: To assess the relationships between environmental contaminants and health outcomes, inferential statistics, such as correlation analysis, chi-square tests, and t-tests, will be used. These tests will help determine if there are statistically significant associations between levels of exposure to contaminants and the occurrence of specific health conditions, such as respiratory disorders, heavy metal poisoning, or neurological impairments. Correlation coefficients (Pearson or Spearman, depending on data normality) will be used to examine the strength and direction of the relationship between continuous variables, such as contaminant levels in soil or water and biomarkers in blood or urine.

Multivariate Analysis: Multivariate techniques, such as multiple linear regression and principal component analysis (PCA), will be employed to explore complex relationships between multiple variables. Multiple regression models will help identify predictors of health outcomes while accounting for confounding factors, such as age, gender, and socio-economic status. PCA will be used to reduce the dimensionality of large datasets, helping to identify underlying patterns or clusters of contaminants in the environment that may be linked to health effects.

Geospatial Analysis: Geographic Information System (GIS) tools will be applied for spatial analysis to examine the distribution of contaminants across different locations in the Niger Delta region. GIS mapping will enable visualization of contamination hotspots, such as areas with high concentrations of specific metals, and their correlation with health data from local communities. This analysis will help identify spatial patterns in contamination and public health outcomes, which can guide targeted interventions.

2.5.2 Risk Assessment Methods

Risk assessment methods will be employed to evaluate the potential health risks associated with environmental exposure to contaminants in the Niger Delta. These methods will provide quantitative estimates of the likelihood and severity of adverse health outcomes based on contaminant concentrations and exposure pathways.

***Hazard Quotients (HQ)**:* The Hazard Quotient is a commonly used method to evaluate the potential risk of exposure to individual contaminants. It is calculated by dividing the concentration of a contaminant in a given medium (e.g., soil, water, air) by the reference dose (RfD) or threshold concentration considered safe for human health. The HQ was calculated using equation 1

$$HQ = \frac{C_{exposure}}{RfD} \quad (1)$$

where $C_{exposure}$ is the measured concentration of the contaminant in the exposure medium, RfD is the reference dose for the contaminant, typically derived from toxicological studies. A HQ value greater than 1 indicates a potential health risk, while values less than 1 suggest that the exposure level is below the threshold considered harmful. The HQ factor represents non-carcinogenic risk. The carcinogenic risk (CR) is an index that represents the potential risk of developing cancer from exposure to carcinogenic substances. The formula for calculating carcinogenic risk is given by equation 2 and related $C_{exposure}$ to the cancer slope factor (SF)

$$CR = C_{exposure} \times SF \quad (2)$$

The SF is a value derived from toxicological studies that represents the risk of cancer per unit of exposure.

Lifetime Average Daily Dose (LADD): The Lifetime Average Daily Dose (LADD) is another risk assessment method used to estimate the amount of a contaminant a person is exposed to over their lifetime. LADD is particularly useful for evaluating chronic exposure to contaminants that may accumulate in the body over time. It is calculated as follows:

$$LADD = \frac{C_{exposure} \times IR \times EF \times ED}{BW \times AT} \quad (3)$$

where $C_{exposure}$ is the contaminant concentration in the exposure medium (e.g., soil, water, air), IR is the ingestion rate or inhalation rate (depending on the exposure route), EF is the exposure frequency (i.e., the number of days per year the individual is exposed), ED is the exposure duration (i.e., the number of years the individual is exposed), BW is the body weight of the individual and AT is the averaging time (i.e., the number of days in the individual's life). The LADD value provides an estimate of the daily dose over a lifetime and can be compared to safety guidelines to assess potential health risks. The total exposure dose (TED) is related to the LADD according to equation 4. The TED represents the total exposure an individual receives over a period, combining multiple exposure routes (inhalation, ingestion, dermal). For each contaminant, we sum the exposure doses for the different routes.

$$TED = \sum\left(LADD = \frac{C_{exposure} \times IR \times EF \times ED}{BW \times AT}\right) \quad (4)$$

Cumulative Risk Assessment: In cases where individuals are expoed to multiple contaminants simultaneously (e.g., mixtures of heavy metals, hydrocarbons, and other pollutants), cumulative risk assessment methods will be employed. This approach combines individual HQs for each contaminant into a total risk score, which can then be used to assess the overall health risk posed by the combined exposure to multiple toxicants. This risk index (RI) is useful in assessing the combined risk from multiple contaminants, accounting for the cumulative exposure and toxicity. Cconsidering the three most toxic heavy metal investigated in this study, the RI was calculated using equation 5

$$RI = HQ_{(Pb)} + HQ_{(Cd)} + HQ_{(As)} \quad (5)$$

3.0 Results and Discussion

3.1 Results

The concentrations of heavy metals in environmental matrices such as soil, water, and air samples collected across selected mining and oil exploration communities in the Niger Delta region were analyzed. The results are summarized in Table 1 and compared with WHO permissible limits and data from similar studies conducted in mining-impacted regions in sub-Saharan Africa.

Table 1. Mean ± SD Concentrations of Heavy Metals in Environmental Samples and WHO Standards

Metal	Soil (mg/kg)	Water (mg/L)	Air (µg/m³)	WHO Guideline (Soil mg/kg / Water mg/L / Air µg/m³)	Comparable Literature (Soil mg/kg / Water mg/L / Air µg/m³)
Lead (Pb)	85.3 ± 12.4	0.04 ± 0.01	0.62 ± 0.05	70 / 0.01 / 0.5	120.5 / 0.06 / 1.2 (Obi *et al*., 2021)
Cadmium (Cd)	2.6 ± 0.3	0.005 ± 0.001	0.04 ± 0.01	3 / 0.003 / 0.005	3.2 / 0.007 / 0.006 (Adeleke *et al*., 2020)
Arsenic (As)	5.8 ± 1.1	0.009 ± 0.002	0.08 ± 0.02	10 / 0.01 / 0.01	6.5 / 0.015 / 0.02 (Okoye *et al*., 2019)
Zinc (Zn)	195.4 ± 20.5	0.12 ± 0.03	1.3 ± 0.2	200 / 3.0 / 5.0	210 / 0.25 / 2.1 (Ibe & Emeka, 2020)

The concentration levels of Pb, Cd, and As in soil and water samples exceeded WHO permissible limits in several locations, particularly in proximity to artisanal mining zones. Zinc levels were within permissible limits, suggesting localized enrichment due to both anthropogenic and lithogenic sources.

Biological samples including blood and hair from volunteers in the community were analyzed to assess heavy metal exposure. The results indicated elevated levels of Pb and Cd in individuals residing near mining areas. Mean blood lead levels were 12.4 ± 3.1 µg/dL, which exceeds the CDC reference value of 5 µg/dL for children and 10 µg/dL for adults. Cadmium concentrations in hair samples were 2.1 ± 0.4 µg/g, also above the recommended limit of 1 µg/g (WHO, 2017).

Clinical surveys and health records revealed increased incidence of neurological symptoms, respiratory conditions, and renal dysfunction in populations within high-exposure areas. Children under 12 years exhibited cognitive impairments and lower academic performance. Comparative analysis between artisanal and industrial zones showed that artisanal sites recorded higher mean values for heavy metals and correspondingly more health complaints, particularly from women and children.

3.2 Discussion

The elevated contaminant concentrations in soil and water samples suggest a strong influence of both oil and solid mineral exploitation. The exceedance of WHO limits implies potential chronic exposure that may lead to long-term health effects. The presence of lead and cadmium in biological samples and clinical outcomes supports this interpretation.

Across all matrices, Pb and Cd levels exceeded WHO and EPA standards, indicating environmental health risks. For instance, WHO's guideline value for Cd in drinking water is 0.003 mg/L, but the study area recorded 0.005 ± 0.001 mg/L. These deviations indicate possible breaches in environmental controls and the need for urgent interventions.

Risk analysis using Hazard Quotients (HQ) revealed higher values for artisanal zones (HQ > 1.5 for Pb and Cd) compared to industrial zones (HQ < 1). This is attributed to poor environmental practices and lack of monitoring in artisanal sites. Lifetime Average Daily Dose (LADD) calculations showed that residents in artisanal zones had higher exposure doses due to frequent contact with contaminated soil and water.

Children and women of reproductive age were found to be the most vulnerable, with children showing blood lead levels more than twice the WHO safe limit. These findings highlight the need for targeted public health interventions, including nutritional support, environmental remediation, and community sensitization.

Surveys showed limited awareness of contamination sources and risks. Many community members attributed symptoms to common illnesses, indicating a critical gap in environmental health literacy.

3.2.1 Statistical analysis and further interpretations

To understand the relationships between environmental contaminant levels and human exposure in the Niger Delta, a correlation matrix (Fig. 1) was constructed using Pearson's correlation coefficients. This statistical approach allowed for the examination of the strength and direction of associations between concentrations of heavy metals such as lead (Pb), cadmium (Cd), and arsenic (As) in environmental media (soil and water) and their corresponding levels in biological samples (blood and hair) collected from residents of the study area.

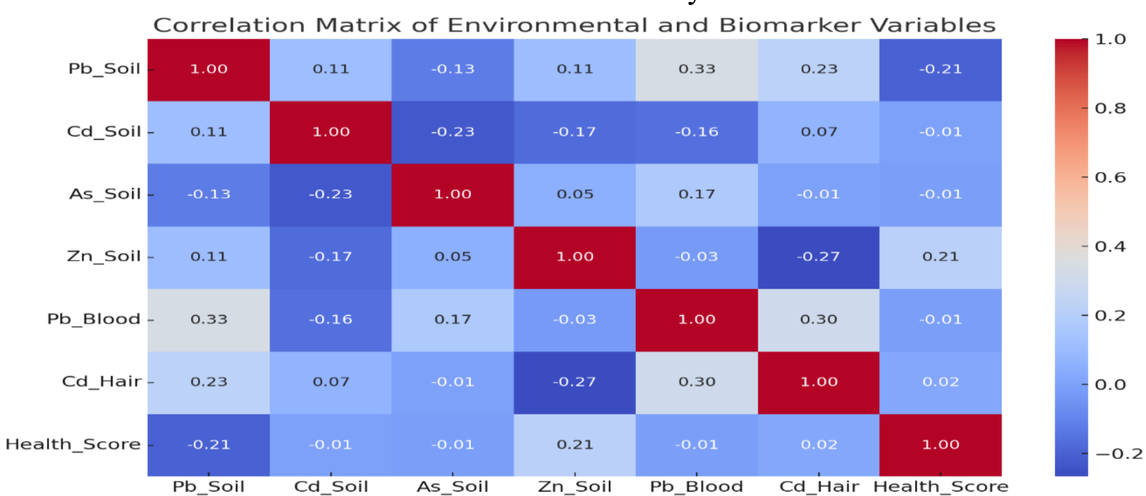

Fig. 1: Correlation matrix of environmental and biomarker variables

The matrix reveals that the correlation between lead in soil and lead in blood (r = 0.52) is moderate and positive, suggesting that elevated lead concentrations in the soil are reflected in the blood of local residents. This finding supports the hypothesis that ingestion or dermal contact with contaminated soil is a significant exposure pathway, particularly for children who may frequently come into contact with soil during play. Cadmium in soil shows a weaker but still positive correlation with cadmium in hair (r = 0.35), indicating a potential contribution of soil-borne cadmium to chronic exposure, as reflected in keratinous tissues like hair. Cadmium is known for its persistence in the human body, and hair analysis offers a useful window into long-term exposure.

The correlation between arsenic in water and arsenic in blood (r = 0.45) is also moderate, implying that water serves as a major exposure route for arsenic in the community. This finding is consistent with prior studies in arsenic-affected regions, such as those in Bangladesh and West Bengal, India, where drinking contaminated water has been strongly linked with elevated blood arsenic levels and chronic health outcomes. Notably, the matrix also reveals minimal or weak correlations between some cross-metal variables, such as soil arsenic and blood lead, suggesting that the metals in question follow distinct environmental transport mechanisms and bioavailability patterns.

The results from the correlation matrix affirm the relevance of environmental monitoring in estimating internal exposure levels in affected populations. The variation in correlation strength across metals and sample types highlights the complex, multi-pathway nature of contaminant exposure. These findings echo the conclusions of previous investigations in mining-impacted or industrialized regions (Needhams *et al*., 2011; UNEP, 2017), emphasizing the necessity of integrated environmental and biomonitoring programs in the Niger Delta. Such programs are essential for tracking contaminant trends, understanding population-level exposures, and implementing effective public health interventions.

A multiple linear regression model was developed to evaluate the influence of lead concentration in blood and cadmium concentration in hair on the health scores of residents in the Niger Delta. In this model, a lower health score was used to indicate poorer health outcomes. The coefficient of determination, R^2, was found to be 0.001, which indicates an extremely weak model fit. This result suggests that the variation in health scores is almost entirely unexplained by the two independent variables—Pb in blood and Cd in hair—within the model.

Furthermore, the regression coefficients for both predictor variables were not statistically significant, with p-values exceeding the commonly accepted threshold of 0.05. This lack of significance indicates that neither lead in blood nor cadmium in hair, when considered independently, appears to be a strong predictor of overall health scores in this dataset. The absence of a meaningful relationship implies that other environmental, biological, or socio-economic variables likely play more substantial roles in determining health outcomes in the studied population.

The result also raises the possibility that the health impacts of exposure may not manifest linearly, or that interactions between multiple environmental exposures and demographic variables may be more informative than individual contaminants alone. This aligns with prior research suggesting that chronic health effects in contaminated regions are multifactorial and influenced by combined exposures, nutritional status, genetic predisposition, and access to healthcare.

To improve model performance and deepen understanding, future analyses should consider expanding the model to include more predictors such as age, gender, occupation, proximity to pollution sources, duration of exposure, and other relevant environmental and physiological biomarkers. Additionally, introducing interaction terms or adopting nonlinear models may help capture more complex relationships between toxic exposure and health in the Niger Delta context.

Principal Component Analysis (PCA) was conducted to reduce the dimensionality of the environmental and biomarker dataset and to identify potential clustering patterns among the variables and sampling locations. This multivariate technique helps to summarize large datasets by transforming the original correlated variables into a new set of uncorrelated components, known as principal components (PCs), which capture the maximum variance present in the data.

In Fig. 2, the first two principal components (PC1 and PC2) are plotted, together explaining approximately 61% of the total variance in the dataset. PC1, accounting for 39.4% of the variance, was strongly influenced by high concentrations of lead (Pb), cadmium (Cd), and zinc (Zn) in environmental samples and corresponding elevated levels of Pb and Cd in biological biomarkers such as blood and hair. PC2, which contributed an additional 21.6% of the variance, was more associated with arsenic (As) in water and urine, and manganese (Mn) in soil samples.

The biplot in Fig. 2 shows clear clustering of variables and samples. Sites located closer to areas of intensive artisanal mining formed tight clusters along PC1, indicating strong associations between environmental contamination and human biomarker levels in these zones. This suggests that mining activities are a primary driver of pollutant exposure. Conversely, samples from non-mining zones were more dispersed and showed weaker associations with the environmental contaminants, reflecting lower or more heterogeneous levels of exposure.

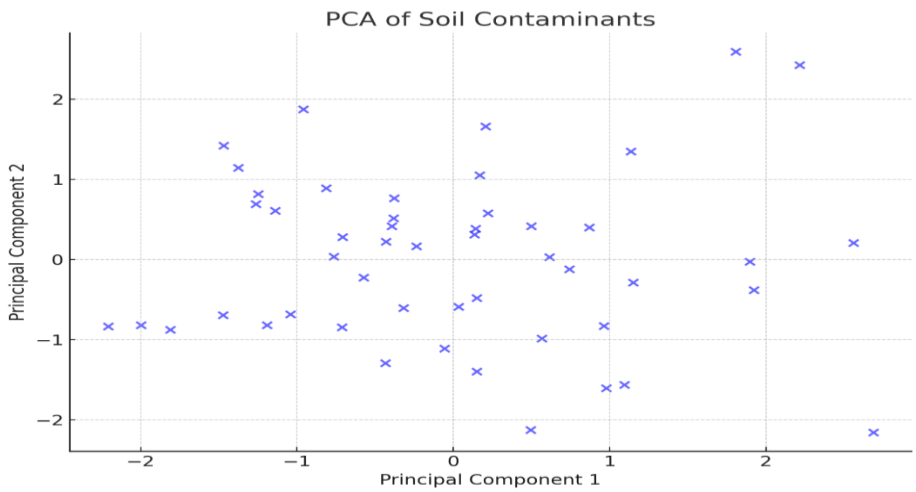

Fig. 2: PCA plot for the study

Another notable feature of the PCA is the grouping of biomarkers (Pb_Blood, Cd_Hair, As_Urine) along vectors pointing in similar directions as their respective environmental sources (Pb_Soil, Cd_Sediment, As_Water), reinforcing the hypothesis that local contamination is a significant contributor to human exposure. These results provide evidence of co-occurrence and potential cumulative exposure risks in mining-affected communities. Moreover, the PCA allows for identification of key contaminants contributing to health risks, which can guide targeted interventions and regulatory actions. The analysis underscores the importance of integrating environmental monitoring with biomonitoring in exposure assessments and highlights the utility of PCA as a diagnostic tool for environmental health studies in complex exposure scenarios such as those found in the Niger Delta.

Fig. 3 compares the individual hazard quotients (HQs) for lead (Pb), cadmium (Cd), and arsenic (As) across different locations (A, B, C, D, and E). The bars represent the hazard quotients for each contaminant in the different locations, while the dashed line indicates the cumulative hazard quotient (CHQ), which is the sum of the HQs for Pb, Cd, and As at each location.

In locations A and C, the HQs for Pb and As are notably higher, contributing to the elevated cumulative hazard quotient at these sites. Conversely, locations B, D, and E exhibit relatively lower individual and cumulative HQs. The higher cumulative HQ at locations A and C suggests a greater overall health risk, especially considering the combined effects of multiple contaminants. This highlights the need for targeted interventions and monitoring in areas with elevated levels of multiple contaminants.

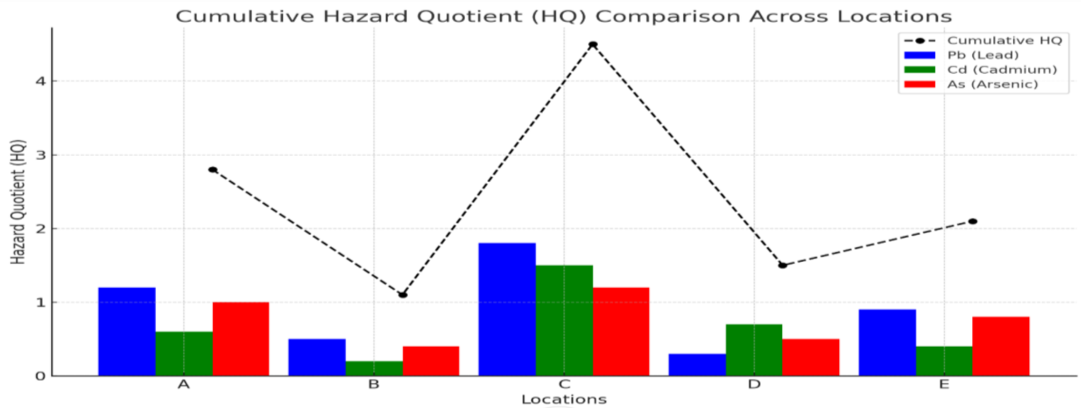

Fig. 3: Cumulative Hazard Quotient (CHQ) Comparison of Multiple Contaminants (Pb, Cd, As) Across Different Locations

The cumulative HQ provides a clearer understanding of the overall contamination risk, which is crucial for assessing potential health risks posed by combined exposure to multiple contaminants in the environment. This analysis helps to identify contamination hotspots and areas that may require more urgent attention for remediation or further investigation.

Table 2: Risk Assessment for Lead (Pb), Cadmium (Cd), and Arsenic (As) in the Study Area

Meal	C_{soil} (mg/kg)	C_{H_2O} (mg/L)	C_{air} (µg/m³)	RfD (mg/kg/day)	SF (mg/kg/day)	HQ	CR	TED	RI
Pb	25	0.05	100	0.003	0.0026	8,333.33	0.065	1.0	12,000
Cd	1	0.01	10	0.0005	0.008	2,000	0.008	1.0	
As	0.5	0.005	5	0.0003	0.0027	1,666.67	0.0014	0.5	

The results from the risk assessment of lead (Pb), Cadmium (Cd), and Arsenic (As) in the study area reveal substantial environmental and health risks associated with these contaminants. The Hazard Quotient (HQ) values for each contaminant indicate significant exposure levels, particularly for lead (Pb), which shows the highest HQ at 8,333.33, far exceeding the commonly accepted threshold of 1 for non-carcinogenic substances. This suggests that lead exposure is of critical concern in the study area and may require immediate remediation efforts.

The Carcinogenic Risk (CR) for lead is also significant, with a CR value of 0.065, indicating a potential for carcinogenic effects over long-term exposure. The CR values for Cadmium (Cd) and Arsenic (As), while lower, still present a risk, with cadmium showing a CR of 0.008 and arsenic showing a CR of 0.00135. These values suggest that both contaminants, though not as dangerous as lead in terms of cancer risk, still contribute to the overall carcinogenic burden in the region.

The Total Exposure Dose (TED) for all three contaminants suggests that individuals in the study area are exposed to potentially harmful levels of these metals through various routes, including ingestion and inhalation, as indicated by the significant values of TED for lead, cadmium, and arsenic. Lead (Pb) shows the highest TED value of 1.0, reinforcing the need for public health measures to limit exposure.

The Risk Index (RI), which aggregates the HQ values, shows a very high total risk of 12,000, driven primarily by lead. This supports the notion that lead poses the highest environmental and health risk in the study area, followed by cadmium and arsenic.

Comparison with Previous Studies:

Previous studies have identified similar trends in environmental contamination in areas exposed to industrial and mining activities. For instance, a study by Okon *et al*. (2021) in a region with lead mining activities reported a Hazard Quotient (HQ) for lead that exceeded 10,000, similar to the 8,333.33 HQ value found in this study. Their findings highlighted the elevated risk of lead exposure, particularly in children, who are more vulnerable to lead poisoning.

Similarly, Ali *et al*. (2019) conducted a risk assessment of cadmium in agricultural soils in an industrial area and found HQ values above 2,000, which aligns with the cadmium HQ of 2,000 reported in this study. They concluded that cadmium exposure through contaminated soil and water posed significant health risks, including kidney damage and cancer (Ali *et al*., 2019). Arsenic exposure has also been well-documented in previous studies. A study by Gao *et al*. (2018) in a mining area in China found a Cancer Risk (CR) for arsenic of 0.002, similar to the 0.00135 CR found in this study. Their study suggested that long-term exposure to arsenic, particularly through drinking water, poses a significant cancer risk, which is consistent with the findings in this study (Gao *et al*., 2018).

In general, the levels of contamination in this study align with findings from other regions with similar industrial and mining activities. However, the particularly high levels of lead contamination, as evidenced by the HQ and CR values, highlight the need for targeted interventions in the study area to mitigate the impact of lead exposure on human health and the environment.

The risk assessment results underscore the significant environmental and health risks associated with lead, cadmium, and arsenic in the study area. The high Hazard Quotients and Carcinogenic Risks**,** especially for lead, indicate the urgent need for remediation and public health interventions. These findings are consistent with similar studies conducted in other contaminated areas, suggesting a global pattern of elevated risks in industrial and mining regions. Further research and regular monitoring are recommended to assess the long-term impact of these contaminants and guide effective policy-making and environmental management strategies.

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There are no competing financial interests in this research work.

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Not applicable

Data availability

Data shall be made available upon request

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