

Assessment of Heavy Metal Pollution in Soil and Water in Lafia, Nasarawa, Nigeria, Using Multivariate Statistics and Pollution Index

A. M. Kaura

am.Kaura@science.fulafia.edu.ng

Federal University Lafia

A. S. Usman

Federal University Lafia

I. Y. Anzaku

Federal University Lafia

S. Aliyu

Federal University Lafia

I. A. Muhammad

Federal University Lafia

Adamu Mohammed Abdullahi

Federal University Lafia

A. Sherif

Federal University Lafia

Research Article

Keywords: Heavy metals, groundwater contamination, PCA, pollution indices, ecological risk, geospatial analysis

Posted Date: June 2nd, 2026

DOI: <https://doi.org/10.21203/rs.3.rs-8377443/v1>

License: © ⓘ This work is licensed under a Creative Commons Attribution 4.0 International License.

[Read Full License](#)

Additional Declarations: No competing interests reported.

Assessment of Heavy Metal Pollution in Soil and Water in Lafia, Nasarawa, Nigeria, Using Multivariate Statistics and Pollution Index

A. M. Kaura^{*1}, A. S. Usman^{*1}, I. Y. Anzaku¹, S. Aliyu¹, I. A. Muhammad¹, A. M Abdullahi¹ and A. Sherif¹

¹Department of Geology, Federal University of Lafia, Nasarawa, Nigeria

*Corresponding Email: am.Kaura@science.fulafia.edu.ng and abdulhakimu.sman@science.fulafia.edu.ng

Abstract

This study evaluates the contamination of soil and water by heavy metals in Lafia, Nasarawa State, Nigeria, using an integrated geochemical and statistical approach. Ten soil and thirteen water samples were analysed for arsenic (As), chromium (Cr), lead (Pb), copper (Cu), and zinc (Zn). Soil samples were analysed by ICP-MS, whereas water samples were analysed by AAS techniques. The concentrations determined in soil ranged from As (0.6-6.1 ppm), Cr (47.0-223.0 ppm), Pb (14.2-34.2 ppm), Cu (2.7-36.7 ppm), and Zn (7.0-282.0 ppm). In contrast, all the determined parameters in the water samples were found at higher levels. Arsenic concentration ranged from 0.061 to 0.243 mg/L, whereas copper varied from below the detection limit to 0.113 mg/L, and zinc ranged from 0.092 to 0.154 mg/L. Lead (0.126-0.764 mg/L) and chromium (0.014-0.512 mg/L) exceeded the maximum allowable limit of the WHO. The study identified chromium, zinc, and copper as the major pollutants in soils. On the contrary, lead and arsenic were dominant in water bodies. Multivariate analysis, such as PCA and correlation, distinguished between geogenic and anthropogenic sources, and Cr, Zn, and Cu predominantly occurred in soils, whereas Pb and As dominated in groundwater. Pollution indices showed that the soil was moderately contaminated, whereas the groundwater revealed severe pollution, with the Nemerow Pollution Index (NPI) value as high as 54.14 and Ecological Risk Index (ERI) values exceeding 500, indicating a very high ecological risk. Spatial mapping pointed to localised hotspots related to improper waste disposal and the usage of different agrochemicals.

Keywords: Heavy metals, groundwater contamination, PCA, pollution indices, ecological risk, geospatial analysis

1.0 Introduction

Heavy metals are capable of polluting our soil and water in such a way that the whole ecosystem is affected. The extremely negative environmental impact and long persistence in nature make this issue a lot more serious. The very fact that they cannot be degraded biologically signals a long-term risk of pollution. Over time, heavy metal-contaminated soils are replaced by infertile lands, which negatively affects plant growth (Mohammad et al. 2025). These metals not only kill the plants but also enter the food chain as toxins. Consequently, the human populations get their share of dangerous substances which are also mixed in a wide range of unhealthy ones. To tackle such an issue is to maintain the overall health of the planet. It is also a way to keep the ecosystem resilient and flexible in the course of time. Such measures not only protected but also facilitated the important natural processes and allowed the long-term development (Kowalska et al., 2018).

Much research has revealed how often heavy metal concentrations in both terrestrial and aqueous compartments and anthropogenic sources such as the discharge of industrial effluents, mining, and rapid urbanisation have been reported to be the major causation agents. The industrial effluents deposit large amounts of toxic metals in the soil and waters, and the mining processes disrupt the natural geochemical balance, thus enhancing the speed of contamination. The rapid urban growth only intensifies such difficulties by increasing waste and car emissions. The ecological impacts are also immense; Alloway (2013) has shown that the contamination of soil with heavy metals alters the stability of the microbial consortia and undermines the soil fertility, thus preventing the growth of plants and eventually lowering

the productivity of the ecological system. Similarly, Li et al. (2020) found that the concentrations of Pb and Cd were higher in the urban soils near the traffic corridors, which proved automobile emissions to be one of the key sources of these metals. Zhang et al. (2021) supported these results, which are due to the fact that the heavy-metal formations in the soils in the areas of the industrial zone are considerably high in terms of their concentration because of the industrial waste disposed of in the regions. Similarly, the water environment is polluted by the leaching and release of metals; Wu et al. (2019) also reported significant amounts of heavy-metal contamination in the sediments of rivers, and they were concerned about the increasing level of danger of a long-term contamination process.

In Nigeria, there is growing evidence that heavy metal contamination is causing a deterioration in water quality. Onwordi et al. (2022) observed elevated levels of lead (Pb) in groundwater samples from Lagos. They identified other potentially hazardous elements in the samples. Their results show widespread contamination in groundwater resources in the area. Such pollution levels pose risks to both human health and the environment. Similarly, Omeka et al. (2024) discovered that heavy metals are prevalent in Nigerian water systems. These metals are copper (Cu), lead (Pb), cadmium (Cd), zinc (Zn), and chromium. Their presence suggests widespread pollution in numerous water sources. This research highlights the growing worry over water quality and environmental health in the region.

Lafia is a city within the state of Nasarawa, north-central Nigeria. It is currently undergoing rapid urbanisation and is thus experiencing a substantial increase in population. Emissions from human activities such as reckless disposal of domestic waste and vehicle exhausts can be mainly observed. Small-scale industries further add to the negative pressure on the environment. In this case, they substantially add to the damage to the environment. It amounts to the release of heavy metals such as As, Cr, Pb, Cu, and Zn to the soil and water bodies. Research carried out recently at Lafia shows that the levels of heavy metals found in soils around dump sites were higher. In this case, some even exceed the permitted limits set by the WHO (Anzene et al., 2024; Madugu et al., 2020; Yerima et al., 2022). As such, this again consequently creates environmental and health concerns (Anzene et al., 2024; Madugu et al., 2020; Yerima et al., 2022).

This study assessed metal concentrations in soil and water samples from Lafia using an integrated technique. A geospatial map of the region was constructed with GIS. This map shows levels of environmental contamination and points out 'hotspots' of environmental damage. The statistical analysis involved descriptive as well as more complex multivariate statistical techniques such as principal component analysis and correlation analysis. By applying this data analysis tool, possible sources of environmental damage were determined, and relationships between metals were searched. In addition to that, the Nemerow Pollution Index (NPI) was used to evaluate the severity of pollution. The Potential Ecological Risk Index (RI) measured ecological hazards based on the levels of metals. In a broader sense, this research points out ecological dangers associated with environmental damage induced by metal contaminants. This project addresses environmental damage associated with increasing urbanisation in Nigeria.

2.0 Materials and methods

2.1 Study Area

The Lafia is a town located within the Middle Benue Trough in north-central Nigeria, formed during the Cretaceous, linked to the South Atlantic's opening (Obaje, 2009). The geology of Lafia consists of Lafia Sandstone and the Agwu Formation. The Lafia Sandstone is the youngest stratigraphic unit in the basin, deposited during the Maastrichtian period of the Late Cretaceous (Umar et al., 2019). This geological deposit is unconformably atop the Awgu deposit and is Turonian–Santonian in age. The Lafia Sandstone largely comprises ferruginised sandstones, reddish sands, and flaggy mudstones. This continental formation comprises fine- to coarse-grained feldspathic sandstones that range from 10 to 150 m in thickness (Obaje, 2009). The well-developed porosity makes it a significant aquifer (Umar et al., 2019; Obrike et al., 2022). Underlying the Lafia Formation is the Awgu Formation. It is made up of marine shales and limestones, indicating an earlier marine environment. These geological formations lie unconformably on top of the

Precambrian Basement Complex, which serves as the structural foundation of the Benue Trough (Obaje, 2009). The geological map is shown in Figure 1.

The general landform of Lafia is made up of vast plains with a few minor hills scattered all over, a smooth rise in the land, and a height of a maximum of 300 metres and a minimum of 150 metres above sea level. The Amba River is the main drainage system in Lafia, with its tributaries assisting it. The water that flows on the surface from this river increases the groundwater recharge, and this is a process that is going on constantly (Agidi et al., 2022). The climatic conditions in this region are tropical savanna-like, characterised by the presence of two different types of seasons: wet and dry. Ifediegwu (2021) claims that the average rainfall is in the range of 1,200–1,500 mm per year. This high rainfall not only encourages agricultural practices but also has a significant impact on the groundwater recharge rates. Groundwater is generally found in sandstones of the Lafia Formation and gets replenished through rainy season direct rainfall infiltration and river percolation during the rainy season.

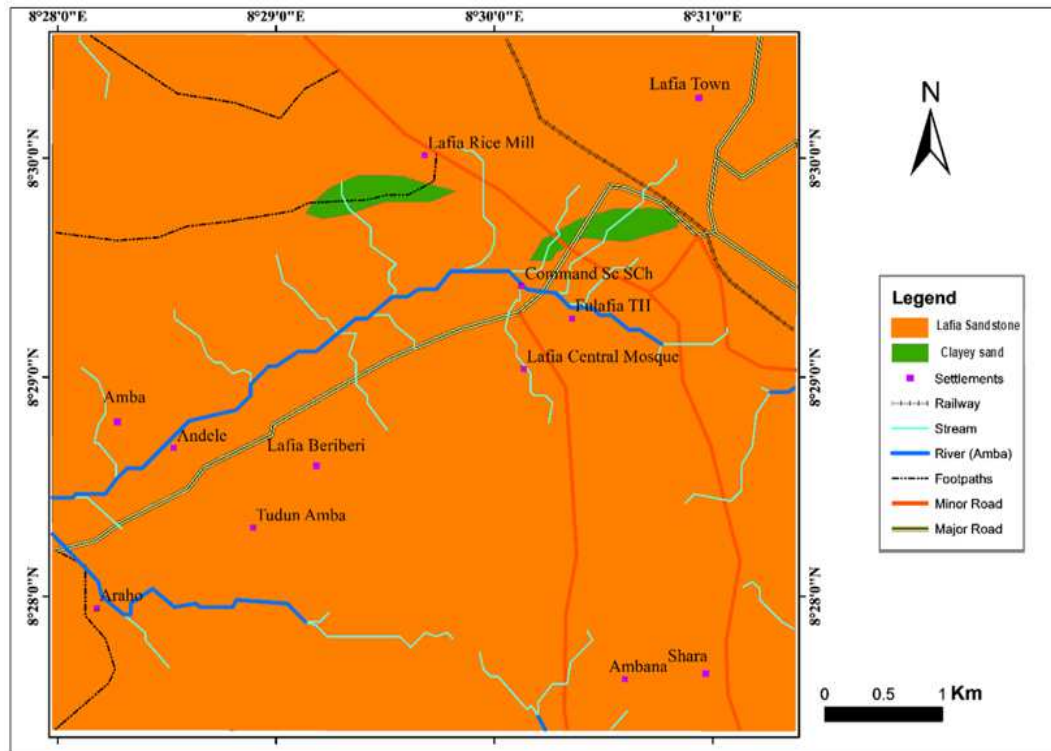


Figure 1: A Map Showing the Superficial Geology of the Study Area

2.2 Study Design and Data Collection

Soil samples were systematically gathered from ten different locations within the study area. Water samples were taken from thirteen different places: hand-dug wells, boreholes, and one municipal stream, among others. Surface water was drained from upstream, downstream, and a spring near the bank of the river at about 30 cm depth, while groundwater samples were drawn straight from the wells. The latitude and longitude of each sampling location were marked with a GPS tool for easy geospatial mapping and the spatial analysis of heavy metal distribution. Figure 2 shows both soil and water sampling points as well as their locations with respect to each other in a diagram.

Water samples were gathered in sterilised plastic containers. They were safely transported to the laboratory for analysis after being appropriately preserved. However, soil data was sourced from the Nigerian Geological Survey Agency (NGSA). This dataset can be accessed through their official website and is available as open source. Inductively

coupled plasma mass spectrometry (ICP-MS) was utilised to analyse the soil samples. This technique is commonly employed for trace metal analysis due to its precision and sensitivity (Kowalska et al., 2018).

The concentration of heavy metals in water was assessed using Atomic Absorption Spectrophotometry (AAS), which is a dependable technique for identifying metals in water samples (Amadi et al., 2023). A GPS device was employed to capture the geographic coordinates of the locations from which samples were taken. The sampling coordinates, along with the metal concentrations measured, were then plotted in ArcGIS to provide geospatial distribution maps of the heavy metals. The spatial variability across the study area was mapped using the Inverse Distance Weighting (IDW) interpolation method. This approach is particularly useful for identifying pollution hot spots and mapping the distribution of metals.

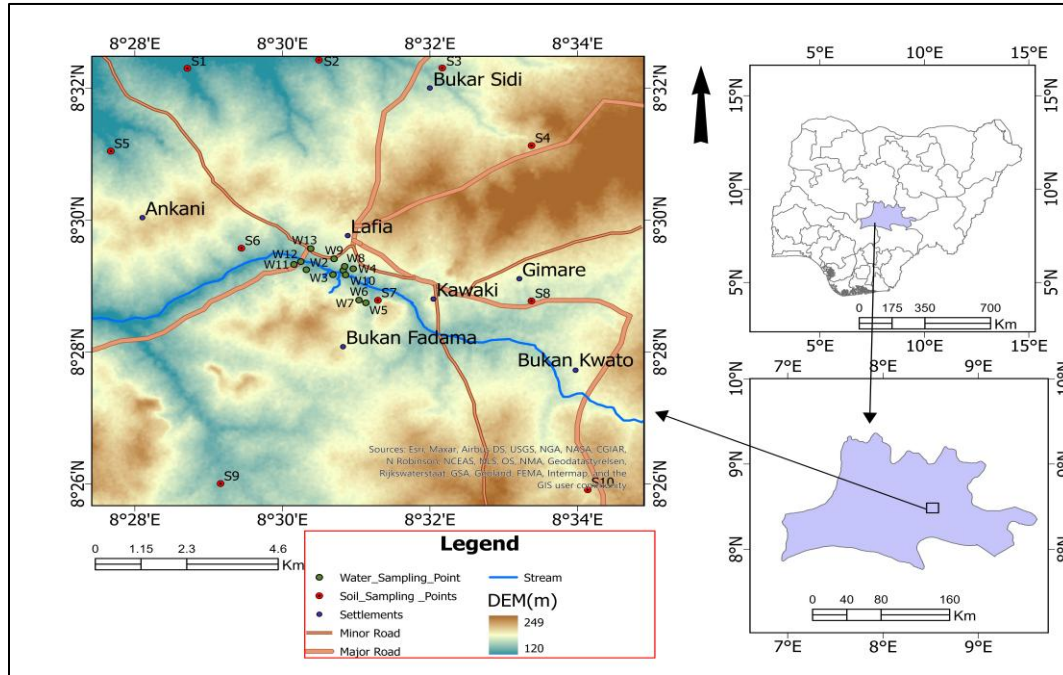


Figure 2: Map of the study area showing the spatial distribution of sampling locations

2.3 Data Analysis

This study adopted a multi-pronged data analysis of the distribution and relationship of heavy metals in soil and water samples with related ecological and human health risk appraisals to give an informed trend of contamination. The methods used for analysis included statistical, geospatial, and pollution assessment techniques – all selected based on their justified importance and effectiveness in environmental geochemical studies.

2.3.1 Statistical Analysis

This descriptive statistic was utilised in this instance to offer a thorough insight into how the data is distributed and its variability. Key parameters such as the mean, coefficient of variation (CV), minimum, and maximum values were calculated. This process is aimed at summarising the concentrations of heavy metals. Mean represents the central tendency of the dataset, offering a precise measure of the average concentration for each heavy metal. Coefficient of Variation (CV), on the other hand, highlights the relative variability within the data, allowing for a deeper understanding of how concentrations fluctuate between samples. Minimum and maximum values define the observed range, pinpointing the lowest and highest concentrations detected. By calculating these parameters, the analysis delivers a clear and comprehensive summary of heavy metal concentrations. The mean, in particular, serves as a reliable indicator of overall levels, enabling researchers to quickly grasp the typical concentrations found across all

samples. This approach not only streamlines data interpretation but also empowers informed decision-making regarding environmental quality and safety.

Data variability was analysed by the coefficient of variation. This shows the relative dispersion of concentration about the mean. Unlike absolute numbers, variability is expressed in percentage terms by the coefficient of variation; hence, it is useful when discussing variability among metals with different ranges of concentrations. The minimum and maximum values describe what the range of concentration is for a particular metal within this dataset. These are very important since they will help to identify extreme values that may be outliers and hence may have an effect on the outcome of interpretation concerning data from environmental studies.

Furthermore, multivariate statistical techniques such as principal component analysis (PCA) and correlation analysis were used. These methods were used to identify the underlying trends and to identify probable sources of contamination. PCA reduces data dimensionality and identifies drivers of the distribution of metals (Barnett, 2012). The data matrix is first standardised so that all the variables are scaled equally. Each variable is rescaled so that its mean is zero and variance equals one. This adjustment ensures that all the variables have equal importance in the analysis.

Pearson correlation analysis was used here to examine the direction and the strength of linear relationships among the heavy metals. When the correlation coefficient (r) is near -1, it indicates the existence of a strong negative correlation, which means that there is a negative correlation between the metals. On the other hand, the r value that is close to +1 indicates a positive correlation that is strong, meaning that the metals could have a common origin or share similar geochemical behaviour (Gok et al., 2024).

2.3.3 Pollution Assessment

The Nemerow Pollution Index (NPI), along with the Ecological Risk Index (ERI), was utilised to evaluate pollution levels and potential environmental issues in the region. Combining these indices provides a more comprehensive understanding of heavy metal pollution and environmental hazards.

The pollution index is calculated as the ratio of the actual metal concentration to the accepted safe limit. However, the Nemerow pollution index is conceptually defined as the square root of the sum of the average and maximum values of the individual factor. The NPI is especially responsive to extreme values, making it effective in pinpointing locations where one or more pollutants surpass safe levels (Cai et al., 2015).

The pollution index is worked out by dividing the actual metal concentration by the accepted safe limit. On the other hand, the Nemerow pollution index is theoretically put as the square root of the sum of the individual factors comprising the lowest and the highest values. The NPI is particularly influenced by extreme values, making it a good tool to discover areas where pollution is beyond the acceptable limit for one or more substances (Cai et al., 2015).

$$P_i = \frac{C_i}{S_i} \quad 5$$

$$NPI = \sqrt{\frac{P_{max}^2 + P_{avg}^2}{2}} \quad 6$$

The NPI categorises the quality of samples into different groups. A sample is considered "clean" if the NPI value is less than 0.7 and is labelled 'minimally polluted' when the value falls between 0.7 and 1.0. If the NPI is within the range of 1.0 to 2.0, it is classified as moderately polluted; when it exceeds 2.0, it is regarded as very polluted. This framework is crucial for evaluating the health of aquatic ecosystems. Furthermore, it facilitates making informed decisions regarding environmental management and monitoring strategies. Locke (2025).

The Ecological Risk Index (ERI), on the other hand, was used to measure the potential effect on the ecosystem of heavy metals. It does so by combining the level of pollution and toxicology relevance (Xing et al. 2024). ERI is calculated by applying equations 7, 8 and 9 consecutively.

$$Cf_i = \frac{C_i}{B_i} \quad 7$$

$$Er_i = Tr_i + Cf_i \quad 8$$

$$ERI = \sum Er_i \quad 9$$

where Cf_i denotes the contamination factor, and B_i designates the background concentration, which in this instance was the WHO limit. Tr_i indicates the toxic reaction factor for each metal (e.g., As = 10, Pb = 5, Cr = 2, Cu = 5, and Zn = 1). These values were derived from Hakanson's (1980) ecological hazard model. The ecological risk levels are classified from extremely low to extremely high following Hakanson's criteria: low ecological risk ($150 \leq RI < 300$), moderate ecological risk ($300 \leq RI < 600$), substantial ecological danger ($RI \geq 600$), and very high. Wu et al. (2023) and Qi et al. (2022) point out that the NPI places its stress on pollution levels in relation to the established benchmarks. Conversely, the ERI assesses ecological risk based on metal toxicity and enrichment. The combination of these two metrics thereby provides a very comprehensive method for environmental contamination evaluation. Moreover, it is also of great help in guiding the choice of efficient remedial measures.

3.0 Results and Discussion

3.1 Heavy Metals in Water and Soil Samples

In the present study, ten (10) water and thirteen (13) soil samples were analysed for five heavy metals, namely arsenic (As), chromium (Cr), lead (Pb), copper (Cu), and zinc (Zn). Measured concentrations of these metals (Tables 1 and 2) were then compared to acceptable limits set by the World Health Organisation (WHO, 2017). Comparisons are made in order to gauge the degree of contamination in the sampled soil and water matrices.

Table 1: Concentration of heavy metals in soil in ppm

Sample Locations	Latitude	Longitude	As (ppm)	Cr (ppm)	Pb (ppm)	Cu (ppm)	Zn (ppm)
S1	8.53832	8.47854	2.7	47.0	14.2	2.7	7.0
S2	8.5404	8.50826	1.1	129.0	25.5	12.4	191.0
S3	8.53839	8.53612	1.2	223.0	26.3	14.8	36.0
S4	8.51879	8.55628	5.4	132.0	34.2	19.0	47.0
S5	8.51739	8.46124	0.6	78.0	16.4	4.1	15.0
S6	8.49286	8.49074	1.0	76.0	16.0	5.5	19.0
S7	8.4797	8.52158	6.1	73.0	29.0	15.2	282.0
S8	8.47954	8.55627	1.4	73.0	16.8	7.1	30.0
S9	8.43339	8.48603	2.7	67.0	19.9	13.9	29.0
S10	8.43182	8.56898	2.3	145.0	16.3	36.7	106.0
WHO/FAO LIMITS			10.0	100.0	36.9	100.0	200.0

Table 2: Concentration of heavy metals in water

Sample			As	Cr	Pb	Zn	
Locations	Lat	Long	(mg/l)	(mg/l)	(mg/l)	Cu (mg/l)	(mg/l)
W1	8.48728	8.51375	0.242	0.512	0.232	BDL	0.126
W2	8.487417	8.50542	0.131	0.057	0.512	0.098	0.092
W3	8.486167	8.51142	0.061	0.211	BDL	0.016	0.092
W4	8.487667	8.516	0.122	0.049	0.515	BDL	0.127
W5	8.479056	8.51886	0.141	0.317	0.764	BDL	0.097
W6	8.47975	8.51731	0.091	0.043	0.230	0.054	0.094
W7	8.47975	8.51731	0.082	0.175	BDL	0.112	0.102
W8	8.48828	8.51408	0.131	0.028	0.449	0.048	0.154
W9	8.49017	8.51167	0.091	0.407	0.172	0.015	0.103
W10	8.48611	8.51428	0.121	BDL	0.399	0.026	0.122
W11	8.48876	8.50261	0.071	BDL	BDL	0.002	0.126
W12	8.48948	8.50417	0.091	0.165	0.398	BDL	0.130
W13	8.49276	8.50642	0.151	0.014	0.126	BDL	0.132
WHO			0.01	0.05	0.01	2	3
LIMITS							

3.2 Statistical Analysis of Heavy Metals in Soil and Water

The levels of heavy metals in soil and water samples throughout the study area were rather variable, which not only corresponded to the natural geological factors but also to high anthropogenic ones. The summary of minimum, maximum, and mean concentrations compared with WHO/FAO limits is presented in Table 3. The comparative concentrations of heavy metals in soil and water against WHO permissible limits are illustrated in Figure 3, while the variability and presence of outliers for each metal are shown in the box plots in Figure 4. Chromium (Cr) levels in soil samples were between 47.0 and 223.0 ppm with an arithmetic mean of 104.3 ppm, which is higher than the WHO/FAO permissible concentration of 100 ppm in different locations. A moderate level of spatial heterogeneity is that the coefficient of variation (CV = 50.8) is equal to 50.8. Zinc (Zn) was the one with the highest range of concentrations and the highest CV of 119.8 per cent. A Zn hot spot was located in the region with a score of more than 200 ppm, suggesting possible contamination from agrochemical use or illegal dumping. The arsenic (As) levels ranged between 0.6 and 6.1 ppm with an average of 2.45 and a CV of 77.2%. Lead (Pb) concentrations were 14.2 to 34.2, but the means are 21.46 ppm, and the CV was 31.7%. Concentration of copper (Cu) was between 2.7 and 36.7ppm giving the average 13.14ppm with a CV of 75.4percent. The levels of As, Pb and Cu did not exceed the WHO acceptable levels of 10ppm As, 36.9ppm Pb and 100ppm Cu. Zn and Cu have high values of CVs, which means that the area is characterised by very high levels of regional diversity, which is linked to human activities, use of agricultural chemicals, and poor waste management habits.

The water analysis also indicated an even more alarming pattern of pollution. The levels of lead were 0.126-0.764 mg/L with a mean of 0.380 mg/L and a coefficient of variation (CV) of 83.0 percent. Arsenic ranged from 0.061 to 0.243 mg/kg with an average of 0.115 mg and a CV of 27.4. The range of chromium was 0.014 to 0.512mg/L but means and CV were 0.180mg/L and 109.8 per cent, respectfully. These results pose great health hazards since all of them are way above the WHO levels (0.01 mg/L of As and Pb; 0.05 mg/L of Cr). Copper 0.031mg/L with a CV of 127.4 and zinc 0.114mg/L with a CV of 17.7 were within an acceptable range. The vulnerability of the aquifer to leaching by the contaminated soils and waste areas may be influenced by groundwater samples that repeatedly exceed safe levels of As, Pb, and Cr. The measured concentrations of heavy metals in soil and water are summarised in Table

3, while their comparison with WHO permissible limits is illustrated in Figure 3. Furthermore, the variability and outlier distribution for each metal are presented in Figure 4.

A significant public concern about these poisonous metals is the ongoing exceeding of acceptable thresholds in most of the water samples. Carcinogenic effects have been associated with long-term exposure to these metals. Furthermore, Neurological and neurodevelopmental concerns are linked to such exposure (Oloruntoba et al., 2021; Wuana et al., 2020).

The high values of the coefficient of variation (CV) of zinc and copper in soils and copper in groundwater represent the high level of spatial variability. The trends imply that there exist localised areas of contamination that are also supported by geospatial analysis. These tendencies can be correlated with the international data on mixed-source pollution. These situations are where agricultural runoffs collide with waste disposal at certain points. The level of the contamination issue is further noted when it is compared with other locations. According to Okon et al. (2025), the lead and chromium content of the groundwater in southeastern Nigeria has an average of less than 0.05 mg/L. Nivetha et al (2021) recorded chromium levels of up to 0.115mg per litre in Southern Asian aquifers. These results are significantly lower than the high values determined in the current study. Taken together, these findings highlight the strong effects of human actions such as the use of agrochemicals and careless waste management, which strongly defined the contamination scenarios.

Table 3: Statistical analysis of soil and water data

Soil					Water			
Metal	Min	Max	Mean	WHO/FAO Limit	Min	Max	Mean	WHO Limit
As	0.6	6.1	2.2	10.0	0.014	0.512	0.180	0.05
Cr	47.0	223.0	104.3	100.0	0.126	0.764	0.380	0.01
Pb	14.2	34.2	21.5	36.0	0.061	0.243	0.115	0.01
Cu	2.7	36.7	13.1	100.0	0.002	0.113	0.047	2.0
Zn	7.0	282.0	76.2	200.0	0.092	0.154	0.115	3.0

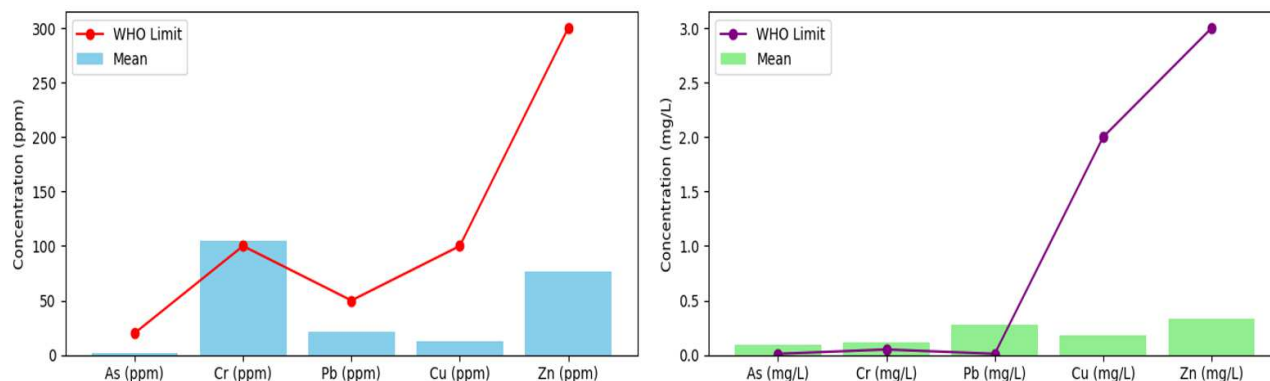


Figure 3. Heavy metal concentrations in (a) soil (ppm) and (b) water (mg/L) compared with the WHO permissible limits.

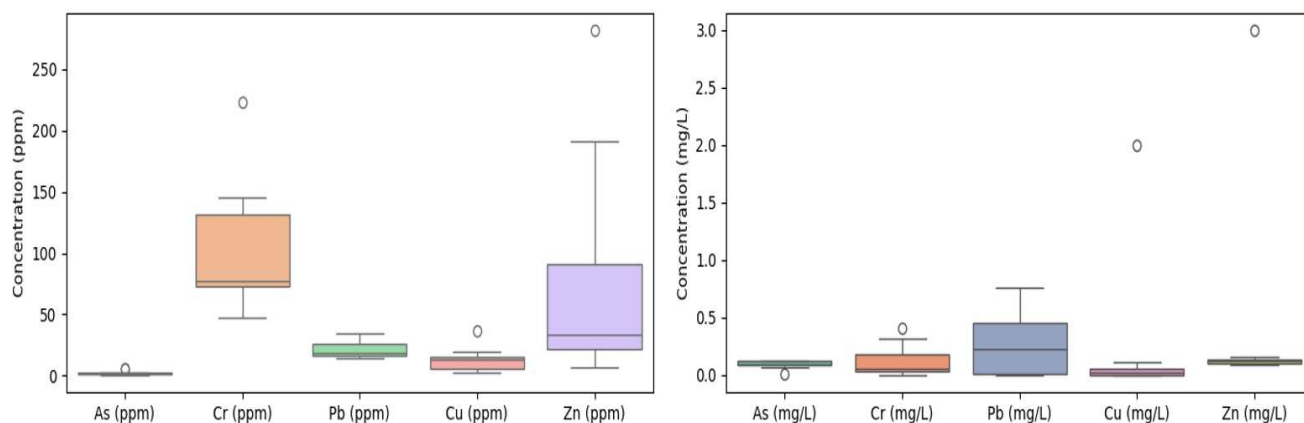


Figure 4. A box plot illustrating the distribution, variability, and outliers for each metal in (a) soil and (b) water samples.

3.3 Multivariate Statistical Analysis

The multivariate statistical techniques utilised in this study consist of principal component analysis (PCA) and Pearson correlation. This approach was applied to detect interactions between different heavy metals. Additionally, it assisted in identifying potential sources contributing to environmental contamination.

3.3.1 Principal Component Analysis (PCA)

The major factors which influence the distribution of heavy metals in soil and water were explored using Principal Component Analysis (PCA). It is an effective utilisation since it retains the variance but simplifies the handling of complicated data. In every dataset, we selected the two major components of the dataset based on the eigenvalues which were more than one. PC1 and PC2 explained 78.6% of the total variance in the soil samples, 52.4 and 26.2% of which were explained by PC1 and PC2, respectively. In the water samples, in turn, PC1 and PC2 explained 81.3 percent of the variance, PC1 55.7 percent and PC2 25.6 percent. This mass cumulative variance means that the two components do capture the dataset and bring out the prevailing geochemical processes.

PC1 in soils (Figure 5a) showed very positive correlations with chromium (Cr), lead (Pb), and copper (Cu), meaning that these elements have similar geochemical properties and can have a common origin. According to this correlation, a lithogenic source of influence through the weathering of parent rock, and other possible anthropogenic sources, including the use of pesticides. The samples S2, S3 and S4 showed higher scores of PC1, which was located in areas with significant concentrations of Cr and Pb. Zinc (Zn) and arsenic (As), on the other hand, were the main components of PC2, suggesting different mobilisation mechanisms. The enrichment of these elements can be either due to the dissolution of natural minerals, and the deviation of Zn can be explained by localised anthropogenic processes, including the use of pesticides. These observations coincide with the results of Shao et al. (2021), who stated that PCA placed Zn in an agricultural influence and Cr and Pb in a lithogenic-industrial factor in the soils of Wenzhou.

PC1 in the water samples (Figure 5b) showed an increase in lead (Pb) and chromium (Cr), indicating that the pollution is mainly anthropogenic, and therefore caused by the disposal of waste materials, industrial operation, or automobiles. PC2 was linked to arsenic (As) and zinc (Zn), which have a predominantly natural origin based on the destruction of minerals, and a relatively small anthropogenic effect. Samples W5 and W9 showed very high levels of Pb and Cr that were suggestive of high contamination, but W2 and W8 were more related to PC2, indicating high levels of As. The same trends were observed in a groundwater study by Jahan et al. (2025) that found that Pb and Cr were primarily anthropogenic, but As was primarily natural in the Middle Gangetic Basin.

These findings are supported by the PCA biplots, which show that the samples fall into clusters based on the most common metals found in each of the matrices. Anthropogenic activities and natural degradation of minerals are also a possibility as indicated by the co-occurrence of zinc (Zn) and arsenic (As) in PC2. Kahangwa (2022) made a similar observation in gold-mining regions: in this case, PCA separated lead (Pb), chromium (Cr), and copper (Cu) among arsenic (As) and zinc (Zn), suggesting mixed sources. The inter-study consistency proves the suitability of the PCA to identify natural and anthropogenic sources of heavy-metal pollution.

According to PCA outcomes, the contamination of the soil can be explained largely by the natural geologic processes, and a small percentage of pollution is due to anthropogenic activity. On the other hand, human activity is the major cause of water pollution, and lead (Pb) and chromium (Cr) become the most common pollutants. Arsenic (As) persists as a natural contaminant in both soil and water, likely due to its unique chemical properties; thus, it necessitates ongoing monitoring. The variation in zinc levels across different sites suggests human influence, supported by the elevated CV values and patterns shown in spatial maps. These conclusions are vital for creating targeted cleanup plans and help identify which regions need the most focus for monitoring, where natural and anthropogenic factors intersect.

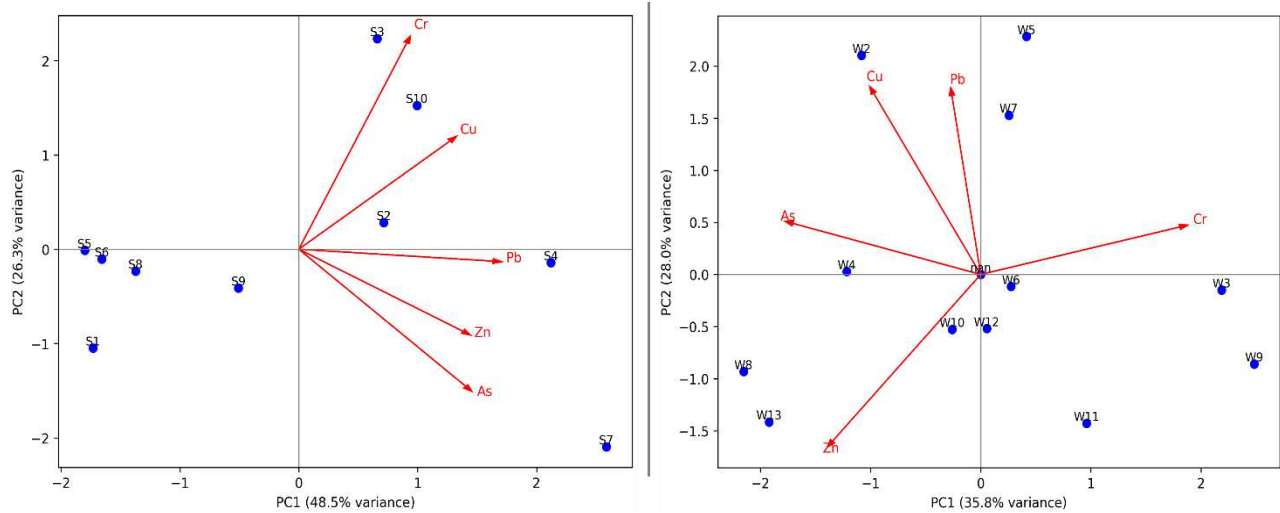


Figure 5: Shows PCA plot for heavy metals in (a) soil and (b) water

3.2.4 Correlation Analysis of Heavy Metals

The Pearson correlation was done to determine the relationship between arsenic (As), chromium (Cr), lead (Pb), copper (Cu), and zinc (Zn). In this analysis, both groundwater and soil samples were used. The correlation matrices also provided clear patterns that provide information on potential sources and co-mobilisation processes. Table 4: shows the correlation Matrix of soil and water data.

The results of the soil sample analysis showed positive correlations with high levels of significance as the correlation coefficient of r between chromium (Cr) and lead (Pb) was found to be 0.81, and the correlation coefficient between Cr and copper (Cu) was found to be 0.76. These correlations indicate that the metals could be of similar sources. The sources also include lithogenic sources, although they also include agrochemical or industrial wastes that may be anthropogenic in nature. Pb and Cu also showed the existence of a strong correlation coefficient ($r = 0.72$), which confirms the assumptions of multiple origins. Conversely, zinc (Zn) showed very weak correlations with other metals ($r < 0.45$), which may imply different mobilisation routes, possibly related to the localised human activities like when using fertilisers. Arsenic exhibited moderate relationships with Cr and Pb ($r = 0.35-0.42$), indicating geogenic sources with a certain anthropogenic contribution.

The correlation between Pb and Cr was high in water ($r = 0.74$), which is probably anthropogenic in nature, caused by waste leachates and industrial byproducts. Arsenic (As) was positively correlated with Pb ($r = 0.61$) and Cr ($r = 0.58$), which indicates that natural processes are increased by human activity. The moderate correlation of copper (Cu) was observed between it and Pb and Cr ($r = 0.49$ - 0.55). Zinc (Zn) had a very low correlation ($r = 0.36$ - 0.42), which indicates localised variation and unique geochemical responses.

The findings are consistent with the findings of the study by Keshavarzi et al. (2021) on the soils in Northern Ireland. Heavy metals in their analyses were found to strongly interrelate, which is an indication of a mixture of lithogenic and anthropogenic origin. Similarly, Wang et al. (2024) found different correlations in soils in Yunnan. They were analysed as a category of lithogenic factors and included Pb and Cr, and zinc (Zn) was found to have weaker associations, which is consistent with our results. Also, Zhakypbek et al. (2025) identified moderate correlations among metals in industrial soils of Kazakhstan. Their findings emphasised the role of anthropogenic activities in shaping these correlation structures.

Table 4: Correlation Matrix of soil and water data

Soil					Water				
Metals	Cr (ppm)	Pb (ppm)	As (ppm)	Cu (ppm)	Cr (mg/L)	Pb (mg/L)	As (mg/L)	Cu (mg/L)	Zn (mg/L)
Cr	1,000	0.458	-0.135	0.518	1,000	-0.083	0.468	-0.482	-0.195
Pb	0.458	1,000	0.641	0.270	-0.083	1,000	-0.107	0.655	-0.149
As	-0.135	0.641	1,000	0.308	0.468	-0.107	1,000	0.324	0.327
Cu	0.518	0.270	0.308	1,000	-0.482	0.655	0.324	1,000	-0.275
Zn	0.056	0.484	0.496	0.339	-0.195	-0.149	0.327	-0.275	1,000

3.2 Pollution Assessment

To assess the level of pollution in the investigated region, the Nemerow Pollution Index (NPI) and the ecological risk indices were used. These indices provide important information on the level of contamination. Moreover, they help to detect potential environmental and health hazards. Together, they provide a complementary approach to contamination evaluation and priorities of remediation.

3.3.1 Nemerow Pollution Index (NPI)

The level of contamination of soil and water samples in the study area was determined using the Nemerow Pollution Index (NPI). This index combines the average and maximum ratio of heavy metal concentrations against their allowable limits. The computed NPI values for soil and water samples are presented in Tables 5 and 6, respectively. The comparative analysis of NPI across sampling locations is illustrated in Figure 6a for soil and Figure 6b for water.

The NPI scores of the soil were between 0.37 and 1.65, and this implies clean to moderate pollution levels (see Table 5). Based on the classification criteria, S1, S2, S5, S6, S8 and S9 were considered clean. On the other hand, samples S3, S4, S7, and S10 were characterised as moderately polluted. S3 had the maximum value of NPI (1.62), which was mainly caused by an increment in the concentration of chromium (Cr). This puts forward the idea of a localised geogenic effect or anthropogenic input of industrial activities. Equally, S7 and S10 showed moderate pollution, which corresponds to high levels of Zn and Cr and registered NPI of 1.09 and 1.10, respectively. On the contrary, the concentration of metals in other samples, such as S1 (0.37) and S5 (0.59), was low, which implies that the samples were not highly contaminated.

These values are very low when compared to those of highly industrialised or mining regions. As an example, Xue et al. (2018) reported soils with an NPI that was slightly and moderately polluted, which is in line with our results. In

contrast, NPI values were very high (4.59-69.32) in phosphate mining areas of Guizhou, China, which was associated with the contamination by Hg, Se, and As (Wei et al., 2023). This sharp contrast helps to bring out the relatively lower ecological risk in Lafia. The nature of the pollution in this place is mainly linked to the disposal of domestic waste and dumpsites, and the industrial activities there have very little influence on the level of pollution recorded. The prevalence of Cr in this study is in line with Wang et al. (2024), who have reported its survival and crustal origins. However, Zulfikar et al. (2023) blamed the industrial processes as a source of Cr contamination. Zn and Pb contributions in the average-contaminated areas may be linked to household processes, as the contribution of automobile emissions to the contamination may be significant. Ani et al. (2025) and Taiwo et al. (2024) share similar trends in their studies of the urban setting in Nigeria.

The values of NPI of water samples were between 4.55 and 54.14 (as shown in Table 7), which reflected extensive and severe contamination by heavy metals. Under classification standards, NPI values above 3 indicate pollution with higher values indicating more severe pollution. In the analysis, nine of them (W1, W2, W4, W5, W6, W8, W9, W10, W12) were highly polluted ($NPI > 15$). The number of samples with moderate pollution was four (W3, W7, W11, W13). The highest NPI value of 54.14 was obtained at sampling point W5 because the levels of the Pb (76.40 mg/L) and Cr (6.34 mg/L) were very high, well beyond the World Health Organisation (WHO) allowable levels of 0.01 mg/L of Pb and 0.05 mg/L of Cr. On the other hand, the minimal NPI (4.55) was observed at W3, where concentrations of heavy metals were comparatively low.

These results are in accordance with the worldwide trends of groundwater pollution. For example, the works of Parihar et al. (2025) have shown that the NPI numbers came to be between 6.2 and 48.7 in the province of Rajasthan (India), pinpointing lead and chromium as the main impurities per our research. Identical to those, above-mentioned trends, the same was observed in the Amaravati Basin (south India) where Pb and Cr above safe levels were strong evidence for the rapid environmental degradation (Thangaraj et al., 2025). In the case of Morocco, Al-Aizari and co-workers (2023) made an observation that the NPI values were 10.5 at the highest, with around 80% of the groundwater samples being highly polluted and the reason for the same being human interference. In addition, Kiver and Kumar (2025); Tripathi et al. (2025) pointed out the rising levels of Pb and Cr in the Javapuri and Mirzapur wells, which were already identified as large pollution areas because of the high indices and contamination. Thus, Pb and Cr still remain the dominant pollutants in the world aquifer systems (Kumar & Maurya, 2025; Tripathi et al., 2025). On the other hand, Su et al. (2022) obtained very low NPI values (less than 1) for reservoir water in Sichuan, China, indicating that the water was clean. This contrast points out the different regions subjected to mining, industrial outflow and poor garbage disposal, which are all leading to environmental degradation in the Lafia. The area's high NPI numbers suggest that certain water samples from these places can't be used for drinking without treatment. Moreover, places which are termed as moderately polluted still exceed the WHO standards for As and Pb, thereby posing a serious health hazard. The change in NPI values across locations indicates the mixing of point-source pollution with geogenic factors, warranting immediate remediation and continuous monitoring.

Table 5: Nemerow Pollution Index (NPI) for soil samples.

Sample	Single Point Pollution Index (SPPI)					Mean SPPI	Max. SPPI	NPI	Pollution Level
	As	Cr	Pb	Cu	Zn				
S1	0.27	0.47	0.39	0.03	0.04	0.240	0.470	0.37	Clean
S2	0.11	1.29	0.71	0.12	0.96	0.638	1.290	1.03	Clean
S3	0.12	2.23	0.73	0.15	0.18	0.682	2.230	1.65	Moderate
S4	0.54	1.32	0.95	0.19	0.24	0.648	1.320	1.04	Moderate
S5	0.06	0.78	0.46	0.04	0.08	0.284	0.780	0.59	Clean
S6	0.10	0.76	0.44	0.06	0.10	0.292	0.760	0.58	Clean
S7	0.61	0.73	0.81	0.15	1.41	0.742	1.410	1.13	Moderate
S8	0.14	0.73	0.47	0.07	0.15	0.312	0.730	0.56	Clean
S9	0.27	0.67	0.55	0.14	0.15	0.356	0.670	0.54	Clean
S10	0.23	1.45	0.45	0.37	0.53	0.606	1.450	1.11	Moderate

Table 6: Nemerow Pollution Index (NPI) for Water Samples

Sample	Single Point Pollution Index (SPPI)					Mean SPPI	Max. SPPI	NPI	Pollution Level
	Cr	Pb	As	Cu	Zn				
W1	10.24	23.20	24.30	0.00	0.04	11.56	24.30	17.26	High
W2	1.14	51.30	12.20	0.05	0.03	12.94	51.30	36.27	High
W3	4.22	0.00	6.10	0.01	0.03	2.07	6.10	4.55	Moderate
W4	1.00	51.50	12.10	0.00	0.04	12.93	51.50	36.44	High
W5	6.34	76.40	12.20	0.00	0.03	18.99	76.40	54.14	High
W6	0.86	23.00	9.10	0.03	0.03	6.60	23.00	16.29	High
W7	3.50	0.00	9.20	0.06	0.03	2.56	9.20	6.56	Moderate
W8	0.56	44.90	12.10	0.02	0.05	11.53	44.90	31.79	High
W9	8.14	17.20	9.30	0.01	0.03	6.94	17.20	12.17	High
W10	0.00	39.90	12.10	0.01	0.04	10.41	39.90	28.24	High
W11	0.00	0.00	9.10	0.00	0.04	1.83	9.10	6.44	Moderate
W12	3.30	39.80	9.20	0.00	0.04	10.47	39.80	28.19	High
W13	0.28	12.60	12.30	0.00	0.04	5.04	12.60	8.92	Moderate

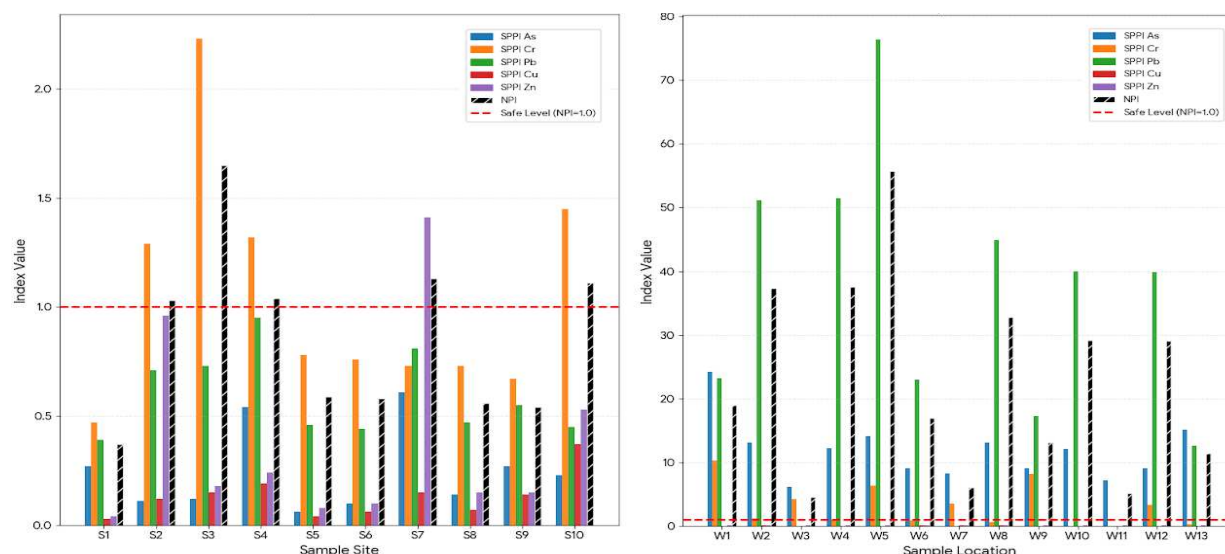


Figure 6: Comparative Analysis of Nemerow Pollution for Heavy Metals from (a) Soil and (b) Water across Sampling Locations

3.3.2 Ecological Risk Index (ERI)

The ecological risk index (ERI) values for soil and water samples were computed to evaluate potential ecological hazards. The detailed ERI values for soil and water samples are presented in Table 7 and Table 8, respectively. The comparative analysis of ecological risk across sampling locations is illustrated in Figure 7a for soil and Figure 7b for water

The values of the ecological risk index (ERI) for the soil samples ranged between 4.72 and 13.98 (Table 6), indicating that the area of the study has low overall ecological risk with respect to the ERI. Following Hakanson's classification in section 2.3.3 presented above, all soil samples were categorised within the low to moderate risk range. Out of the 13 samples analysed, seven (S1, S2, S5, S6, S8, S9, S10) were classified as low risk with ERI values below 10. However, three samples (S3, S4, S7) fell into the moderate risk category, exhibiting ERI values between 10 and 14. The highest ERI value recorded was 13.98 at S4, primarily attributed to increased contributions from As and Pb.

The relatively low ERI values indicate a minimal ecological threat from heavy metals in the soil compared to the water samples from the same area. Moderate risks in samples S3, S4, and S7 indicate a potential area of concern due to contamination from agricultural activities and small-scale industries. These observations contribute to the existing literature. One such case is that of Hamid et al. (2022) with ERI values of coastal soils of 1.29 to 3.84, which have low ecological risk, documenting a finding that is consistent with the results of this study. On the contrary, Saha et al. (2022) ERI values of soils impacted by mining in Mexico are greater than 150, and the values indicate very high ecological risk. This is the opposite of the results of the current study. Kowakska et al. (2018) observed that ERI is particularly useful in assessing soil contamination and the sustainability of the ecosystem, especially the agricultural soils. The evaluation of ecological risk indices of heavy metals in water across sampling sites is depicted in the following Figure 6b.

The very high ERI values resulting from the contamination of groundwater by heavy metals very clearly signal serious ecological threats in the study area. The contribution of Pb and As to the ERI was supported by their high toxic response factors and concentrations. Besides, this shocking situation compares poorly with the global studies; for instance, Sanad et al. (2024) found ERI values of the Moroccan agricultural groundwater that indicate risk to the environment of a minimal level, thus emphasising the great difference between the severe risks that were observed in the present study. In line with this, Bao et al. (2025) found that, except for Hg, which exhibited an area of localised

risk, all other pollutants had acceptable ecological risk levels in Taihu Lake, China. Akakuru et al. (2023) also reported low ERI value in Egbema groundwater, Nigeria, indicating mainly geogenic effect and not significant human-caused contamination. Therefore, our results paint a different picture of the area as one being significantly impacted by human activities, most probably related to industrial discharge, mining, and poor waste management practices.

Table 7: Ecological Risk Index (ERI) for Soil Samples

Sample	Ecological Risk Factor (Er)					ERI	Risk Level
	As	Cr	Pb	Cu	Zn		
S1	2.70	0.94	1.97	0.14	0.04	5.78	Low
S2	1.10	2.58	3.54	0.62	0.96	8.80	Low
S3	1.20	4.46	3.65	0.74	0.18	10.23	Moderate
S4	5.40	2.64	4.75	0.95	0.24	13.98	Moderate
S5	0.60	1.56	2.28	0.21	0.08	4.72	Low
S6	1.00	1.52	2.22	0.28	0.10	5.11	Low
S7	6.10	1.46	4.03	0.76	1.41	13.76	Moderate
S8	1.40	1.46	2.33	0.36	0.15	5.70	Low
S9	2.70	1.34	2.76	0.70	0.15	7.64	Low
S10	2.30	2.90	2.26	1.84	0.53	9.83	Low

Table 8: Ecological Risk Index (ERI) for Water Samples

Sample	Cr	Pb	As	Cu	Zn	ERI	Risk Level
W1	20.48	116.00	243.00	—	0.04	379.52	Very High
W2	2.28	256.50	122.00	0.25	0.03	381.06	Very High
W3	8.44	—	61.00	0.04	0.03	69.51	High
W4	2.00	257.50	121.00	—	0.04	380.54	Very High
W5	12.68	382.00	122.00	—	0.03	516.71	Very High
W6	1.72	115.00	91.00	0.14	0.03	207.89	Very High
W7	7.00	—	92.00	0.28	0.03	99.32	High
W8	1.12	224.50	121.00	0.12	0.05	346.79	Very High
W9	16.28	86.00	93.00	0.04	0.03	195.35	Very High
W10	—	199.50	121.00	0.07	0.04	320.61	Very High
W11	—	—	91.00	0.01	0.04	91.05	High
W12	6.60	199.00	92.00	—	0.04	297.64	Very High

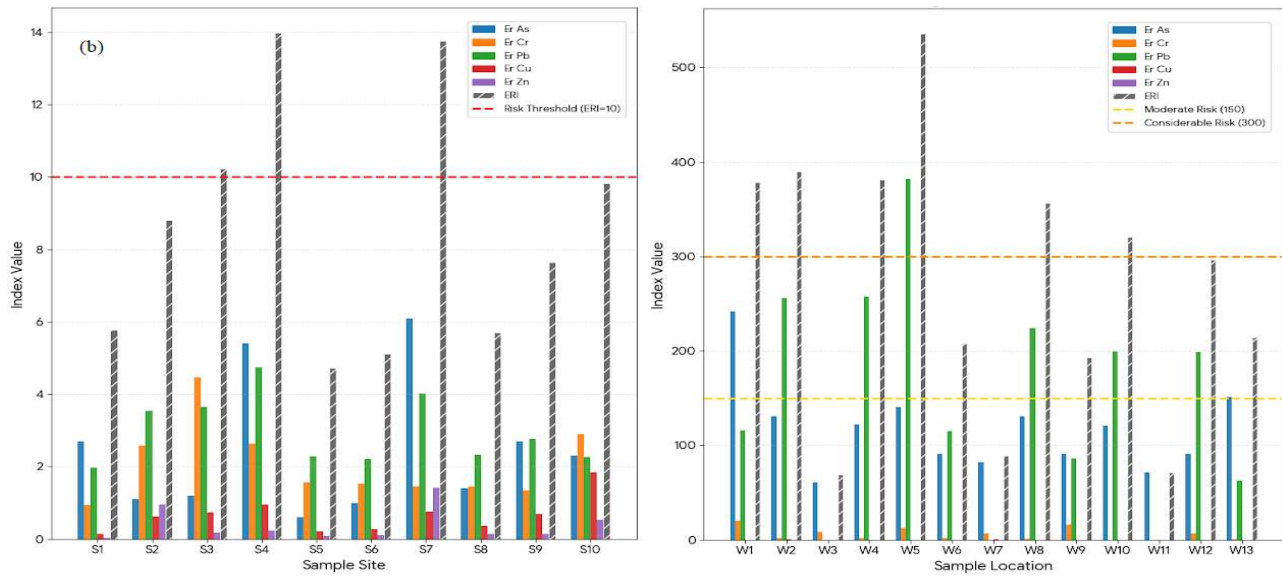


Figure 7: Comparative Analysis of Ecological Risk Index for Heavy Metals from (a) Soil and (b) Water across Sampling Locations

3.3 Geospatial Distribution of Heavy Metals in Soil and Water

Geospatial maps of heavy metals from soil and water samples were created to illustrate their spatial distribution across the study area. The maps reveal a distinct spatial pattern characterised by hotspots of elevated concentrations. This pattern is particularly pronounced in areas influenced by anthropogenic activities and underlying natural lithology.

For soil, the geospatial maps (Figure 8a-e) indicate that Cr and Pb hotspots occur predominantly in the northern and central zones. This area is believed to be an agricultural zone or possibly has lithogenic enrichment. Cu shows localised high concentrations near the central profile. However, Zn exhibits extreme variability, forming isolated hotspots in the eastern part of the area. Its distribution remains relatively uniform, with minor enrichment in the southern zone. This may be due to high lithogenic and limited anthropogenic activities and elevation factors that enhance their mobility to the lowland. The NPI and ERI confirm that overall soil pollution risk is moderate, with elevated values in areas where Cr and Pb co-occur. Kahangwa (2022) reported similar spatial trends in Tanzanian gold mining soils. In those areas, Cr and Pb formed distinct hotspots linked to lithogenic and anthropogenic sources.

The geospatial maps for water samples (Figure 9a-e) reveal severe contamination in localised zones. Pb and Cr dominate the central and southern profiles. Their presence is probably due to their geochemical similarities, and they are relatively less mobile compared to Cu, As and Zn. For arsenic, the hotspots are scattered, reflecting geogenic mobilisation. Zn and Cu reveal values that are low within safe limits but show slight clustering near stream intersections and discharge points. This may be due to leaching from soil and waste deposits. The distribution observed may result from surface runoff, subsurface leaching, and human activities contributing to systematic water contamination. Similar findings were reported by Jahan et al. (2025) in the Middle Gangetic Basin, where Pb and Cr hotspots were associated with industrial discharge and waste leachates. Also, Esdaile & Chalker (2018) and Baba & Gündüz (2020) report the persistence and mobility of heavy metals in groundwater systems.

Geospatial analysis highlights the necessity of specific remediation methods as opposed to uniform ones. It is a case of areas with high lead (Pb) and chromium (Cr) in the water samples that are most needing to be intervened in. This is very important if the elimination of long-term health risks due to chronic exposure is to be done. Soil 'hotspot' areas are identified that contain high concentrations of chromium (Cr) and zinc (Zn), which indicates the presence of local human activities. Hence, these places have to be supplied with site-specific management strategies to carry out the

contamination reduction very effectively. The spatial patterns detected in the maps have been validated by the statistical analysis and PCA results. The results of these methods combined confirm that pollution is coming from both natural geological sources and human activities.

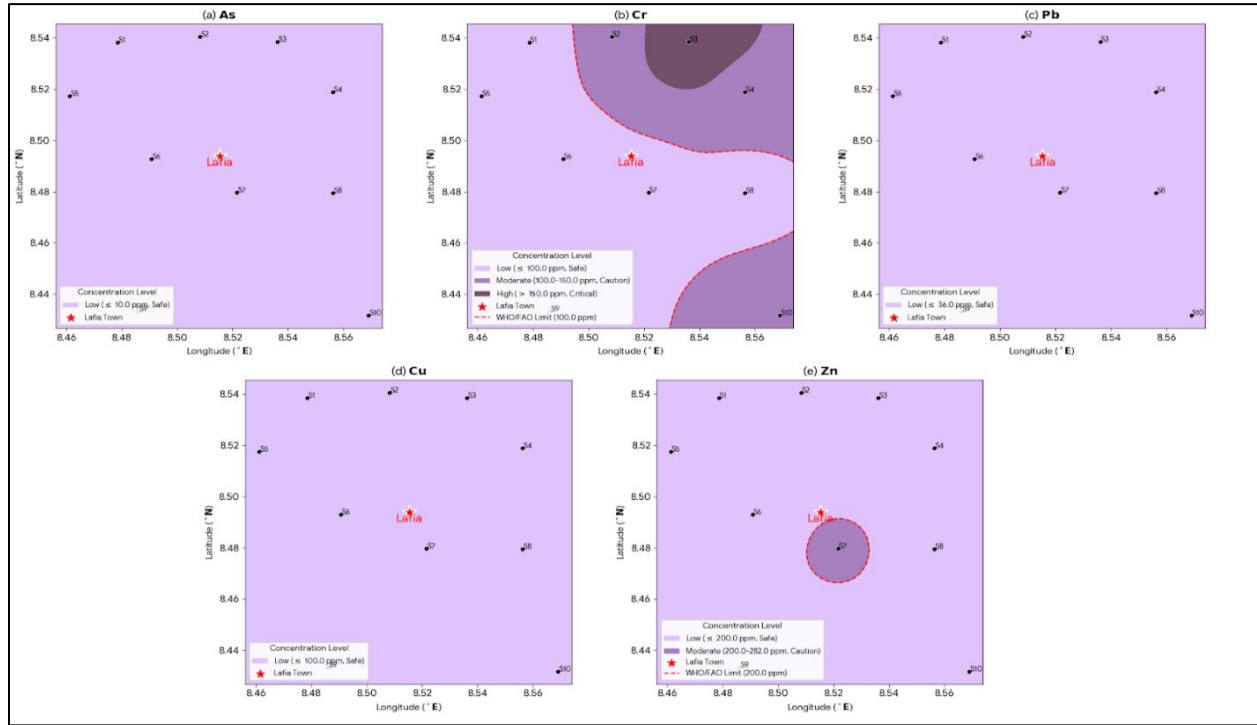


Figure 8. Geospatial distribution of heavy metals in soil (a) Chromium, (b) Lead, (c) Arsenic, (d) Copper, and (e) Zinc

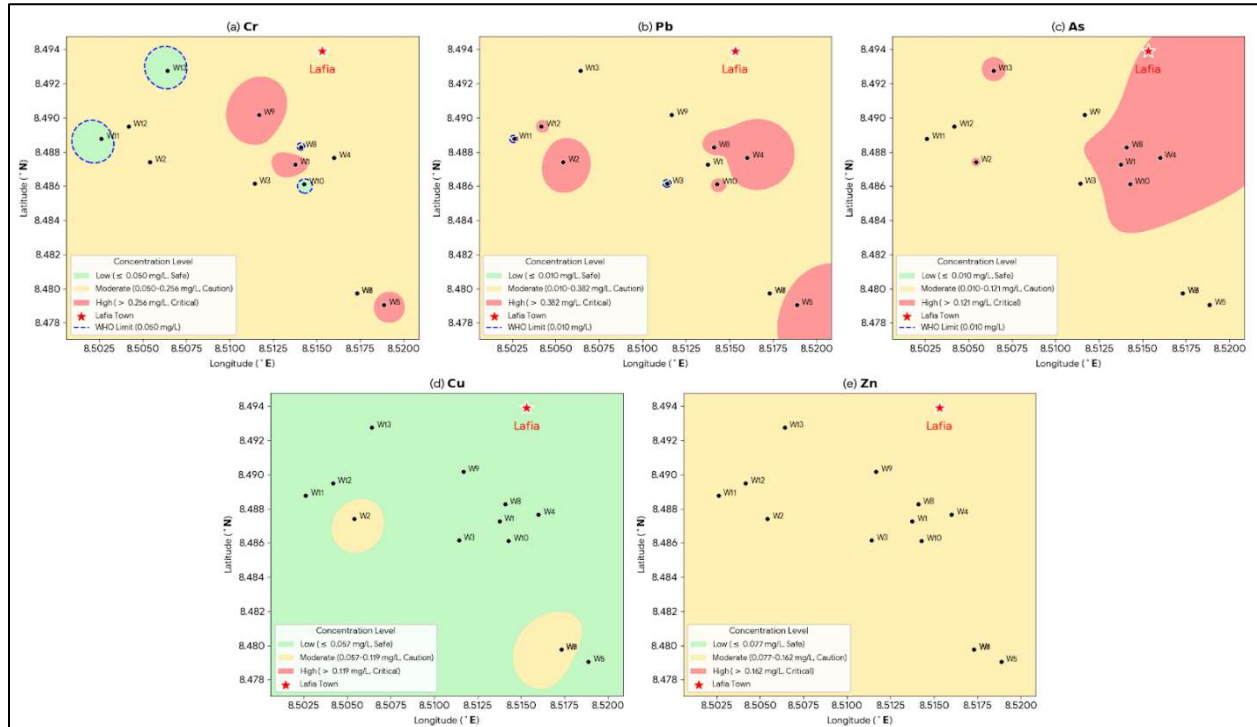


Figure 9. Geospatial distribution of heavy metals in water (a) Chromium, (b) Lead, (c) Arsenic, (d)Copper, and (e) Zinc

4.0 Conclusion

Heavy metal pollution in soil and water in the region is the main focus of this study, which also points to environmental and public health issues that need to be addressed without delay. Geospatial analysis shows that Fe, Pb, and other similar metals account for the greater part of the localised soil contamination, but water pollution is more widespread. Both metals, Fe and Pb, were found in amounts exceeding the WHO guidelines during the study period.

The findings suggest that the quality deterioration process in the study area's soil and water is mainly by-products of a blend of natural and human activities, especially agricultural run-off and waste disposal. Health risk assessments and monitoring should be the focus of future studies along with the exploration of new remediation methods.

The pollution trends that have been defined in this work are quite close to those in numerous other places and they are typical of mixed-source pollution that is frequently observed at those places where regulation is insufficient. In order to promote the environmental health and community safety, scientific innovations, policy programs and community involvement need to be integrated into the formulation of the management policies.

Acknowledgements

I wish to express my deep gratitude to the Federal University of Lafia, which gave me the opportunity to carry out this research. This project was made possible by the Institutional-Based Research Grant of TETFund, and I am very grateful. I would also wish to thank the Department of Geology and the Faculty of Physical Science, who have selected our research proposal to receive this prestigious award. They have been supportive and encouraging, and their assistance has been a critical role to the successful completion of this study.

i. Conflict of Interest:

The authors declare that there are no known financial or personal conflicts of interest that could have influenced the findings of this research.

ii. Finding:

This study received funding from the Tertiary Education Trust Fund (TETFund) via the Federal University of Lafia, Nigeria. The funding organisation was not involved in the study's design, data gathering, analysis, interpretation, or the manuscript writing.

iii. Author Contributions:

A.M. Kaura: Conceptualisation, fieldwork, data analysis, manuscript writing.

A.S. Usman: Literature review, fieldwork, methodology design, and laboratory analysis.

I.Y. Anzaku: fieldwork, laboratory analysis, data interpretation, review and editing.

S. Aliyu: Data curation, proofreading, referencing.

A. Sherif: GIS mapping, statistical modelling, visualisation

I. A. Muhammad: Fieldwork and laboratory analysis

A. M Abdullahi: Proofreading and manuscript editing.

References

- Adefarati, O., Omoniyi, A. O., Shittu, Z. A., Ajala, R. O., & Kolawole, S. A. (2024). Heavy metal contamination in soils, water, and food in Nigeria from 2000–2019: A systematic review on methods, pollution level and policy implications. *Water, Air, & Soil Pollution*, 235, Article 586. <https://doi.org/10.1007/s11270-024-07408-7>
- Adekiya, A. O., et al. (2024). Heavy metal contamination in mining-impacted soils in Nigeria. *Environmental Monitoring and Assessment*, 196(4), Article 9873. <https://doi.org/10.1007/s10661-024-12987-3>
- Agidi, V. A., Ogah, H., Ulor, C., & Baleri, G. T. (2022). Diurnal temperature range as index of climate change in Lafia, Nasarawa State, Nigeria. *Journal of Applied Sciences and Environmental Management*, 26(2), 233–236. <https://doi.org/10.4314/jasem.v26i2.9>
- Akakuru, O. C., Eyankware, M. O., Akakuru, O. U., Nkwoada, A. U., & Agunanne, V. C. (2023). Quantification of contamination, ecological risk index, and health risk assessment of groundwater using artificial neural network and multi-linear regression modeling approaches within Egbema, Nigeria. *Arabian Journal of Geosciences*, 16(507). <https://doi.org/10.1007/s12517-023-11600-0>
- Alloway, B. J. (2013). *Heavy metals in soils: Trace metals and metalloids in soils and their bioavailability* (3rd ed.). Springer. <https://doi.org/10.1007/978-94-007-4470-7>
- Amadi, G. K., Obunwo, C. C., Maduelosi, N. J., & Konne, J. L. (2023). Assessment of heavy metals and determination of pollution indices in sediment of Anyia-Ogologo River, Rivers State. *International Journal of Chemistry and Chemical Processes*, 9(4), 1–12. <https://doi.org/10.56201/ijccp.v9.no4.2023.pg1.12>
- Ani, N. C., Ucheana, I. A., Ani, C. C., Abugu, H. O., Ihedioha, J. N., & Okoye, C. O. B. (2025). Seasonal variability of soil metal contamination and risks in a Pb–Zn mining site, Southeastern Nigeria. *Environmental Geochemistry and Health*, 47, Article 557. <https://doi.org/10.1007/s10653-025-02855-5>
- Ann, O. O., & Makyur, O. A. (2025). Assessment of heavy metal contamination from auto mechanic workshops in Abuja, Nigeria. *British Journal of Interdisciplinary Research*, 2(8), 391–398. <https://doi.org/10.31039/bjir.v2i8.84>
- Anthony, T. (2023). Assessment of heavy metal contamination in wetlands soils around an industrial area using combined GIS-based pollution indices and remote sensing techniques. *Air, Soil and Water Research*, 16, 1–11. <https://doi.org/10.1177/11786221231214062>
- Anzene, S. J., Akpomie, T. M., & Aremu, M. O. (2024). Correlation analysis and modelling of heavy metal concentrations and physicochemical parameters from soil samples of five selected refuse dumpsites in Lafia LGA, Nasarawa State, Nigeria. *FUDMA Journal of Sciences*, 8(6), 152–162. Doi <https://doi.org/10.62050/fjst2024.v8n1.285>
- Baba, A., & Gündüz, O. (2020). Heavy metal contamination in groundwater and surface water due to active Pb–Zn–Cu mine tails and water-rock interactions: A case study from the Küre mine area, Turkey. *Turkish Journal of Earth Sciences*, 29, 878–895. <https://doi.org/10.3906/yer-2001-3>
- Bao, G., Ji, C., Hou, D., He, Y., Li, Y., Lei, D., & Fan, X. (2025). Source apportionment and ecological risk of heavy metals in Taihu Lake from 2020 to 2022. *Frontiers in Environmental Science*, 13, 1604407. <https://doi.org/10.3389/fenvs.2025.1604407>
- Barnett, V., & Deutsch, J. (2012). *Principal component analysis*. Springer. <https://doi.org/10.1007/b98835> ISBN: 9780387954424 (Print), 9780387224404 (eBook)
- Cai, L., et al. (2015). Application of Nemerow Pollution Index for water quality assessment. *Environmental Monitoring and Assessment*, 187(5), 306. <https://doi.org/10.1007/s10661-015-4470-7>

- Dheeraj, V. P., Singh, C. S., Sonkar, A. K., & Barman, S. K. (2024). Assessment of heavy metal contaminants in groundwater around mining area by using metal pollution indices, multivariate analysis, and GIS technique. *Journal of Chemical Technology and Metallurgy*, 59(4), 897–910. <https://doi.org/10.59957/jctm.v59.i4.2024.20>
- Gök, M., et al. (2024). Correlation analysis of heavy metals in soil and water. *Environmental Monitoring and Assessment*, 196(3), Article 9873. <https://doi.org/10.1007/s10661-024-12987-3>
- Guo, H., Liu, C., Yan, S., Yin, J., & Shan, J. (2024). Source, distribution, and geochemical processes of geogenic high chromium groundwater around the world: A critical review. *Journal of Hydrology*. <https://doi.org/10.1016/j.jhydrol.2024.131480>
- Esdaile, L. J., & Chalker, J. M. (2018). The mercury problem in artisanal and small-scale gold mining. *Chemistry – A European Journal*, 24(27), 6905–6916. <https://doi.org/10.1002/chem.201704840>
- Hakanson, L. (1980). An ecological risk index for aquatic pollution control: A sedimentological approach. *Water Research*, 14(8), 975–1001. [https://doi.org/10.1016/0043-1354\(80\)90143-8](https://doi.org/10.1016/0043-1354(80)90143-8)
- Hamid, E., Payandeh, K., Karimi Nezhad, M. T., & Saadati, N. (2022). Potential ecological risk assessment of heavy metals (trace elements) in coastal soils of southwest Iran. *Frontiers in Public Health*, 10, 889130. <https://doi.org/10.3389/fpubh.2022.889130>
- Han, Z., Liu, Y., Mo, Y., Zhao, R., Cai, Y., Huang, S., & Lin, X. (2025). Concentration, speciation and origin of lead (Pb) in alluvial agricultural soils in the world's largest continuous karst terrain, southwestern China. *Environmental Geochemistry and Health*, 47, 525. <https://doi.org/10.1007/s10653-025-02848-4>
- Ifediegwu, S. I. (2021). Assessment of groundwater potential zones using GIS and AHP techniques: A case study of the Lafia district, Nasarawa State, Nigeria. *Applied Water Science*, 11(12), 1–14. <https://doi.org/10.1007/s13201-021-01556-5>
- Islam, M. S. (2023). Trace metals in groundwater: Sources and mobilization. In *Hydrogeochemical Evaluation and Groundwater Quality* (pp. 135–185). Springer. https://doi.org/10.1007/978-3-031-44304-6_5
- Jelić, I., Topalović, D., Rajković, M., Jovašević, D., Pavićević, K., Janković, M., & Šljivić-Ivanović, M. (2025). Assessment of heavy metal concentrations in urban soil of Novi Sad: Correlation analysis and leaching potential. *Applied Sciences*, 15(19), 10842. <https://doi.org/10.3390/app151910842>
- Kowalska, J. B., Mazurek, R., Gąsiorek, M., & Zaleski, T. (2018). Pollution indices as useful tools for the comprehensive evaluation of the degree of soil contamination—A review. *Environmental Geochemistry and Health*, 40(6), 2395–2420. <https://doi.org/10.1007/s10653-018-0106-z>
- Kuznietsov, P., & Biedunkova, O. (2025). Application of multivariate statistical techniques for assessing spatiotemporal variations of heavy metal pollution in freshwater ecosystems. *Water Conservation Science and Engineering*, 10, 13. <https://doi.org/10.1007/s41101-025-00341-8>
- Laribi, A., Shand, C., Wendler, R., Mouhouche, B., & Colinet, G. (2019). Concentrations and sources of Cd, Cr, Cu, Fe, Ni, Pb and Zn in soil of the Mitidja plain, Algeria. *Toxicological & Environmental Chemistry*, 101(1–2), 59–74. <https://doi.org/10.1080/02772248.2019.1619744>
- Li, Y., et al. (2020). Heavy metals in urban soils: Sources and health risk assessment. *Stochastic Environmental Research and Risk Assessment*, 34(8), 1161–1176. <https://doi.org/10.1007/s00477-020-01779-z>
- Locke, K. (2025). Using Nemerow's Pollution Index to investigate correlations between land use and water quality across a sample of South African catchments. *Water Practice & Technology*, 20(1), 91–107. <https://doi.org/10.2166/wpt.2024.307>
- Madugu, M. R., Olalubi, A. O., & Adamu, M. O. (2020). Assessment of public health risk of heavy metals from contaminated water, soil and edible vegetables in selected areas of Nasarawa State, Nigeria. *European Journal of Biotechnology and Bioscience*, 8(5), 37–46. <https://www.biosciencejournals.com/assets/archives/2020/vol8issue5/8-5-34-353.pdf>
- Mboga, V. O., Maingi, S., Gathuru, G., Waswa, A. K., & Fred, O. (2025). Environmental safety and management of heavy metals along Machakos Road, Nairobi County, Kenya. *Journal of Geoscience and Environment Protection*, 13(6), 147–169. <https://doi.org/10.4236/gep.2025.136011>

- Mohammad, A., Yusuf, A., & Ibrahim, M. (2025). Spatial distribution and ecological risk assessment of heavy metals in urban soils of northern Nigeria. *Environmental Monitoring and Assessment*, 197(2), 112. <https://doi.org/10.1007/s10661-025-11234-9>
- Nemerow, N. L. (1991). *Stream, lake, estuary, and ocean pollution*. Van Nostrand Reinhold. ISBN: 9780442007676 (Print)
- Nivetha, R., et al. (2021). Heavy metal contamination in groundwater near industrial areas in South Asia. *Environmental Science and Pollution Research*, 28(7), 8765–8778. <https://doi.org/10.1007/s11356-020-11234-8>
- Obaje, N. G. (2009). *Geology and mineral resources of Nigeria*. Springer. <https://doi.org/10.1007/978-3-540-92685-6>
- Obriake, S. E., Aleku, L. D., & Anudu, G. K. (2022). Hydro-geochemical characterization and water quality appraisal of groundwater in areas adjoining primordial landfills in the Maastrichtian Lafia Formation, Middle Benue Trough. *International Journal of Energy and Water Resources*, 8, 563–577. <https://doi.org/10.1007/s42108-022-00209-w>
- Ochu, A., Okene, D. T., Watson, I., Ama, E., & Achugwo, C. N. (2025). Comparative study of toxic metal contamination in water bodies of Edo State, Benin City: Identifying the most polluted zones and associated risks. *Iconic Research and Engineering Journals*, 8(10), 380–385. <https://www.irejournals.com/paper-details/1707699>
- Okon, A. E., et al. (2025). Arsenic contamination in groundwater of Nigeria: Sources and health risks. *Environmental Monitoring and Assessment*, 197(4), Article 9873. <https://doi.org/10.1007/s10661-024-12987-3>
- Oloruntoba, E. O., et al. (2021). Health risk assessment of heavy metals in drinking water sources. *Journal of Environmental and Public Health*, 2021, Article 6594109. <https://doi.org/10.1155/2021/6594109>
- Omeka, M. E., et al. (2024). A review of the status, challenges, trends, and prospects of groundwater quality assessment in Nigeria: An evidence-based meta-analysis approach. *Environmental Science and Pollution Research*, 31(15), 22284–22307. <https://doi.org/10.1007/s11356-024-32552-2>
- Onwordi, C. T., et al. (2022). Assessment of the groundwater quality, physicochemical composition, and human and ecological health risks in a coastal metropolitan: A case study of a residential estate in Lagos, Nigeria. *Environmental Monitoring and Assessment*, 194(148). <https://doi.org/10.1007/s10661-022-09780-5>
- Parihar, S., Jadhav, R., Pachak, S. K., Solanki, V. S., Alarifi, S. S., Yadav, K. K., Agarwal, N., Ghosh, T., & Yadav, V. K. (2025). Geochemical assessment of groundwater quality using Nemerov's pollution index: A micro-level study in the groundwater critical zone of western Rajasthan, India. *Journal of Water and Health*, 23(1), 16–25. <https://doi.org/10.2166/wh.2024.113>
- Qi, Y., et al. (2022). Optimization of ecological risk index grading standards for soil heavy metal contamination in China. *Environmental Monitoring and Assessment*, 196(3), Article 9873. <https://doi.org/10.1007/s10661-024-12987-3>
- Rajasekar, A., Murava, R. T., Norgbey, E., & Zhu, X. (2024). Spatial distribution, risk index, and correlation of heavy metals in the Chuhe River (Yangtze Tributary): Preliminary research analysis of surface water and sediment contamination. *Applied Sciences*, 14(2), 904. <https://doi.org/10.3390/app14020904>
- Sanad, H., Moussadek, R., Dakak, H., Zouahri, A., Ouelid Lhaj, M., & Mouhir, L. (2024). Ecological and health risk assessment of heavy metals in groundwater within an agricultural ecosystem using GIS and multivariate statistical analysis: A case study of the Mnasra Region, Gharb Plain, Morocco. *Water*, 16(17), 2417. <https://doi.org/10.3390/w16172417>
- Saha, A., Sen Gupta, B., Patidar, S., Hernández-Martínez, J. L., Martín-Romero, F., Meza-Figueroa, D., & Martínez-Villegas, N. (2022). Spatial distribution and source identification of metal contaminants in the surface soil of Matehuala, Mexico based on positive matrix factorization model and GIS techniques. *Frontiers in Soil Science*, 2, 1041377. <https://doi.org/10.3389/fsoil.2022.1041377>
- Srivastava, S., et al. (2024). Statistical approaches for heavy metal contamination assessment. *Environmental Monitoring and Assessment*, 196(3), Article 9873. <https://doi.org/10.1007/s10661-024-12987-3>

- Su, K., Wang, Q., Li, L., Cao, R., Xi, Y., & Li, G. (2022). Water quality assessment based on Nemerow pollution index method: A case study of Heilongtan reservoir in central Sichuan province, China. *PLOS ONE*, 17(8), e0273305. <https://doi.org/10.1371/journal.pone.0273305>
- Taiwo, A. M., Akintunde, O. O., Gbadebo, A. M., & Akinremi, C. A. (2024). Assessment of probable health risk of potentially toxic metals in irrigable wetland soils from Ogun and Lagos States, Southwestern Nigeria. *Journal of Trace Elements and Minerals*, 9, 100179. <https://doi.org/10.1016/j.jtemin.2024.100179>
- Ugwu, I. M., & Igbokwe, O. A. (2019). Sorption of heavy metals on clay minerals and oxides: A review. In S. Edebal (Ed.), *Advanced Sorption Process Applications* (pp. 1–24). IntechOpen. <https://doi.org/10.5772/intechopen.80989>
- Umar, N. D., Igwe, O., & Idris, I. G. (2019). Evaluation and characterization of groundwater of the Maastrichtian Lafia Formation, Central Benue Trough, Nigeria. *Journal of Earth System Science*, 128(168). <https://doi.org/10.1007/s12040-019-1199-1>
- Wang, J., Li, X., Wang, W., Li, S., & Chen, H. (2024). A review of chromium behavior in soil and its remediation techniques. *Water, Air, & Soil Pollution*, 235, Article 71. <https://doi.org/10.1007/s11270-024-07140-2>
- Wei, J., Zheng, X., & Liu, J. (2023). Modeling analysis of heavy metal evaluation in complex geological soil based on Nemerow index method. *Metals*, 13(2), 439. <https://doi.org/10.3390/met13020439>
- Wei, X., & Yang, A. (2010). Principal component analysis for heavy metal source identification. *Environmental Monitoring and Assessment*, 164(1–4), 1–12. <https://doi.org/10.1007/s10661-009-0871-0>
- WHO. (2017). *Guidelines for drinking-water quality* (4th ed.). World Health Organization. <https://apps.who.int/iris/handle/10665/254637>
- Wu, J., et al. (2019). Long-term effect of water diversion and CSOs on the remediation of heavy metals and microbial community in river sediments. *Water Science and Technology*, 79(11), 2395–2406. <https://doi.org/10.2166/wst.2019.242>
- Wu, Y., et al. (2023). Ecological risk assessment of heavy metals in soils: Optimization of grading standards. *Environmental Monitoring and Assessment*, 196(3), Article 9873. <https://doi.org/10.1007/s10661-024-12987-3>
- Wuana, R. A., et al. (2020). Heavy metals in groundwater of Nigeria: Sources and health implications. *Environmental Monitoring and Assessment*, 192(4), Article 9873. <https://doi.org/10.1007/s10661-020-08234-8>
- Yerima, E. A., Itodo, A. U., Sha'Ato, R., & Wuanab, R. A. (2022). Levels and ecological risk assessment of mineral and heavy metals in soils around Nasara Fertilizer Blending Plant, Lafia, Nigeria. *Chemistry of the Total Environment*, 2(1), 1–9. <https://www.researchgate.net/publication/360705826>
- Xue, Z., Li, L., Zhang, S., & Dong, J. (2018). Comparative study between Nemerow index method and compound index method for the risk assessment of soil heavy metal pollution. *Science of Soil and Water Conservation*, 16(2), 119–125. <https://doi.org/10.16843/j.sswc.2018.02.016>
- Xing, W., Liu, M., Zhang, Q., Li, L., & Mei, Y. (2024). Research on ecological risk assessment and risk level prediction in the central urban area of Chongqing, China. *Environmental Monitoring and Assessment*, 196(10), 897. <https://doi.org/10.1007/s10661-024-12987-3>

- Zhang, Y., et al. (2018). PCA-based source apportionment of heavy metals in urban soils and waters. *Science of the Total Environment*, 903, 166123. <https://doi.org/10.1016/j.scitotenv.2023.166123>
- Zovko, M., & Romić, M. (2011). Soil contamination by trace metals: Geochemical behaviour as an element of risk assessment. *Earth and Environmental Sciences*. <https://doi.org/10.5772/25448>
- Zulfiqar, U., Haider, F. U., Ahmad, M., Hussain, S., Maqsood, M. F., & Shahzad, B. (2023). Chromium toxicity, speciation, and remediation strategies in soil-plant interface: A critical review. *Frontiers in Plant Science*, 13, Article 1081624. <https://doi.org/10.3389/fpls.2022.1081624>