PRINT ISSN 1119-8362
Electronic ISSN 2659-1499

Full-text Available Online at
https://www.ajol.info/index.php/jasem
https://www.bioline.org.br/ja

J. Appl. Sci. Environ. Manage.
Vol. 29 (12) 3726-3738 Dec. 2025

Pollution Loads and Ecological Risk Assessment of Heavy Metals in the Urban Soil from various locations throughout Bayelsa State, Nigeria.

[1*]OSISANYA, WO; [2]AGHO, IF; [3]NEVOH, GO; [4]AKPEJI, HB; [5]JOEL, ES

*[1]*Department of Physics, Faculty of Science, Federal University of Petroleum Resources Effurun, Delta State, Nigeria.*
[2]Department of Microbiology, Faculty of Life Science, University of Benin, Benin City, Edo state, Nigeria
[3]Petroleum Analysis Laboratory Department, Petroleum Training Institute, Effurun, Delta State, Nigeria.
[4]Department of Science Laboratory and Technology, Faculty of Science, Federal University of Petroleum Resources Effurun, Delta State, Nigeria.
[5]Department of Earth Sciences, Anchor University, Lagos, Nigeria

**Corresponding author email: wasiu.osisanya@uniben.edu*
**ORCID: https://orcid.org/0000-0001-7280-9771*
**Tel: +234(0)8150914664*

Co-Authors Email: agho.funmilola@yahoo.com; nevoh_go@pti.edu.ng; akpeji.honesty@fupre.edu.ng; ejoel@aul.edu.ng

ABSTRACT: The detection of heavy metals (HM) in soil has emerged as a significant issue amid growing environmental awareness, revealing the intricate interplay between anthropogenic influences and natural elements that impact our terrestrial ecosystems. Consequently, the objective of this paper was to evaluate the Pollution Loads and Ecological Risk Assessment of Heavy Metals in the Urban Soil from various locations throughout Delta State, Nigeria using appropriate standard procedures. Data obtained show that the mean and standard deviation concentrations of heavy metals in soil samples within the study area were Zn (19.08 and 9.19)mg/kg; Cr(13.92 and 6.22)mg/kg, Cu (10.56 and 4.95)mg/kg; Pb(4.69 and 1.99)mg/kg, Cd (2.045and 1.86)mg/kg, Co(9.524and 4.49)mg/kg, Ni(3.23and 1.36)mg/kg and As (0.003(mg/kg) respectively An ecological risk assessment was conducted in the specified study area, noted for its modified soil conditions. Findings obtained from several heavy metal indices, namely the Potential Ecological Risk Assessment (ERI), Geoaccumulation Index (Igeo), Degree of Contamination (Cdeg), and Nemerow Pollution Index (PNI), revealed that considerable human activities—like automobile maintenance, waste disposal, and farming practices—are the main sources of heavy metals in the soil of the examined area. Nevertheless, the information from Igeo was inconsistent with the conclusions drawn from the ERI, which proposed that the soil samples were not contaminated. Furthermore, Cdeg assessments suggested that the level of contamination in the soil was minimal for agricultural and farming purposes being the major occupation of the inhabitants.

DOI: https://dx.doi.org/10.4314/jasem.v29i12.7

Cite this Article as: OSISANYA, W. O; AGHO, I. F; NEVOH, G. O; AKPEJI, H. B; JOEL, E. S (2025). Pollution Loads and Ecological Risk Assessment of Heavy Metals in the Urban Soil from various locations throughout Bayelsa State, Nigeria. *J. Appl. Sci. Environ. Manage.* 29 (12) 3726-3738

Dates: Received: 12August, 2025; Revised: 20 November 2025; Accepted: 23 December 2025; Published: 31 December 2025

Keywords: Soil Pollution; Ecological Risk Assessment; Pollution indices; Heavy metals; Contamination.

The presence of heavy metal (HM) contamination in urban soils represents a significant environmental challenge, posing potential threats to both human health and ecological systems. Evaluating pollution levels and the associated ecological risks necessitates a comprehensive analysis of the various types and concentrations of heavy metals, their origins, and the possible effects they may have on the environment and living organisms (Eyankware, *et al.*, 2024). One of the primary pathways for heavy metals to enter the

**Corresponding author email: wasiu.osisanya@uniben.edu*
**ORCID: https://orcid.org/0000-0001-7280-9771*
**Tel: +234(0)8150914664*

environment is through rapid industrialization (Igwe et al., 2022), notably through dust *emissions* from cement production, which play a considerable role in heavy metal pollution (Ulakpa, *et al*., 2021). Soil frequently serves as the primary reservoir for heavy metals that enter the ecosystem (Omene, *et al.,* 2025; Odesa, *et al.*, 2024a). In addition, heavy metals serve as important markers for assessing environmental pollution levels (Sánchez-Castro, *et al.,* 2023). The buildup of heavy metals (HMs) diminishes both the quality and yield of agricultural produce while also having detrimental effects on soil quality and its physical and chemical characteristics (Baruah *et al.,* 2021; Singh *et al.,* 2021). Over the past few decades, the expansion of industries, urbanization, and agricultural methods have led to an accumulation of heavy metals (HMs) in the soil, which are elements that pose potential hazards (Sánchez-Castro, *et al.,* 2023; Xiao, *et al.,* 2021; Choudhury, *et al.,* 2021; Odesa, *et al.*, 2024b; Paul, *et al.*, 2019). The resulting impacts and consequences of these pollutants are influenced by a variety of geo-environmental factors, such as the geological characteristics of the bedrock and the types of human activities involved, including the application of agricultural chemicals (Eyankware, *et al.,* 2018; Eyankware and Akakuru, 2022). Elevated levels of heavy metals in the soil can increase the likelihood of their uptake by plants (Eyankware, *et al.*, 2023). The ongoing decline of the environment, exacerbated by rapid urbanization and industrial expansion, has surfaced as a critical global issue, particularly impacting estuaries and wetlands that serve as reservoirs for leachates, effluents, emissions, and residues from fossil fuels; fertilizer runoff; and agricultural chemicals, including herbicides and pesticides, alongside sewage and municipal waste (Adesuyi, *et al.,* 2015; Adesuyi, 2020). In Lagos State, Nigeria, intensive agricultural practices, modifications to drainage systems, and urban sprawl have dramatically altered the region's natural hydrological patterns and wetland ecosystems. While these transformations have brought considerable economic advantages to the state and its residents, they have simultaneously led to the degradation and loss of over 90% of the wetlands in the area (Ajibola, *et al.,* 2012). The remaining wetlands within the landscape frequently experience a deterioration of their ecological functions and biological integrity, influenced by both natural phenomena and anthropogenic activities. The decline can be attributed to several factors, including the encroachment of invasive plant species, alterations in hydrology, excessive nutrient runoff, sediment accumulation, and a variety of pollutants (Obiefuna, *et al.,* 2013). Furthermore, insufficient compliance with waste management regulations, suboptimal urban development practices, and a lack of proactive measures from governmental bodies have exacerbated the issues related to improper waste disposal in these areas (Ogundele, *et al.,* 2020). The presence of heavy metals in wetland soils is particularly concerning due to their toxic nature, persistence in the ecosystem, and potential for bioaccumulation (Njoku, *et al.*, 2013; Eyankware, *et al.,* 2025; Adesuyi, *et al.,* 2018). Consequently, thorough risk assessments concerning the buildup of heavy metals in agricultural regions are essential for guaranteeing the safe application of inorganic fertilizers, organic waste, and pesticides in crop cultivation (Obasi, *et al.,* 2022). Heavy metals present in the soil may accumulate in less soluble forms, infiltrate soil solutions, and eventually leach into groundwater, thereby endangering water quality (Eyankware *et al.,* 2016). According to Igwe, *et al.,* (2022), these metals are classified as xenobiotic, which signifies their alien characteristics to biological systems, along with their high mobility and enduring presence in the soil ecosystem. These metals emerge from the soil, become part of the food web, and experience biomagnification at elevated trophic levels, leading to metabolic disruptions in human beings (Zhuang, *et al.,* 2020; Hang, *et al.,* 2017). Consequently, they present a threat to food safety and interfere with various biological processes, potentially resulting in significant health risks for humans (Golui, *et al.*, 2017). Heavy metals present in the soil can accumulate in less soluble forms, infiltrate soil solutions, and ultimately leach into groundwater, thereby degrading water quality (Akakuru *et al.,* 2025). Recognized as xenobiotic substances, these metals are foreign to biological systems, exhibit high mobility, and remain persistent within the soil ecosystem (Eyankware, *et al.*, 2024). These metals stem from the soil, permeate the food web, and experience biomagnification at elevated trophic levels, leading to disruptions in human metabolic functions (Jiang, *et al.,* 2014). Consequently, such metals pose risks to food safety and disrupt various biological processes, thereby representing considerable health hazards for humans (Eyankware, *et al.*, 2021b). Hence, the objective of this paper was to evaluate the pollution loads and ecological risk assessment of heavy metals in the urban soil from various locations throughout Delta State, Nigeria.

MATERIALS AND METHOD

Description of the study area: The freshwater region is characterized by a plain that stretches northward from the mangrove swamps, typically lying below an elevation of 20 meters. This lower Niger floodplain is largely made up of fertile silt and clay, and it is

particularly vulnerable to frequent flooding due to river overflow. In the northeastern part of the area, the average thickness of the sediment reaches approximately 45 meters, whereas in the southwestern beach ridge barrier regions, it exceeds 9 meters. This floodplain represents a unique geomorphic feature, occasionally disrupted by small hogback ridges and shallow swamp basins, primarily oriented to the west and south (Aisuebeogun, 1995).
.

This region is marked by substantial rainfall, accompanied by a brief dry season that typically occurs from November to March. Situated within Nigeria's tropical rainfall belt, it features extensive back swamps. The volume of precipitation received is sufficient to support crop cultivation throughout the year, with the wet season lasting no fewer than 340 days (Oku, 2003).

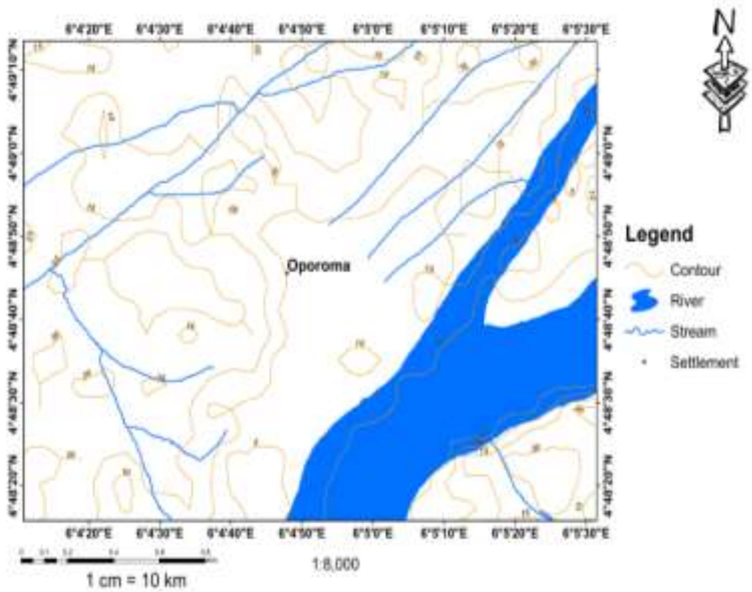

Fig.1: Topographical map of the study area

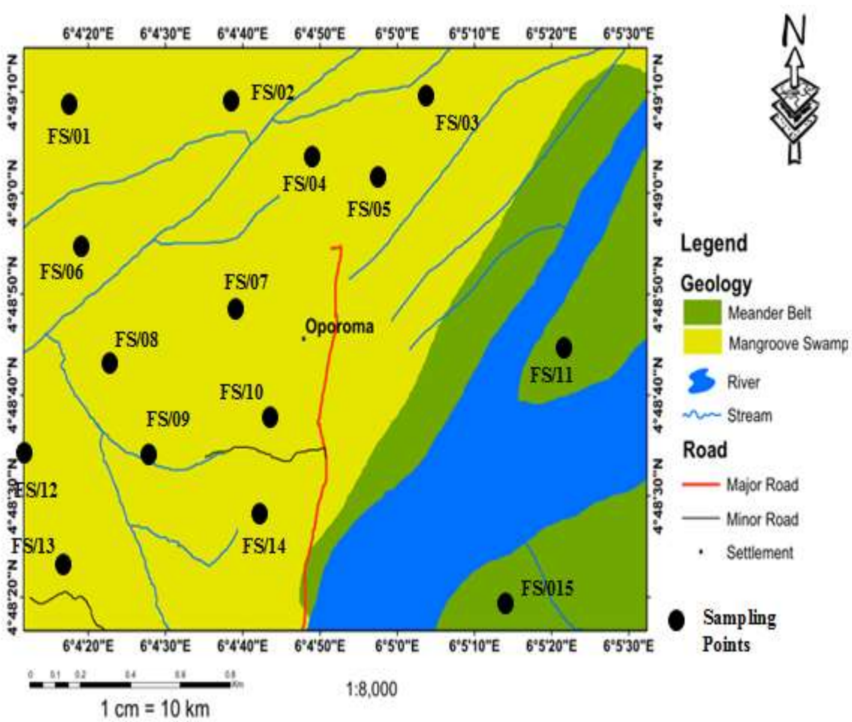

Fig. 2: Geology map of the study area showing sampling points

Sampling points: A total of fifteen (15) soil samples were randomly gathered from various locations throughout Oporoma, Bayelsa State, Nigeria, with a maximum separation of 20 kilometers. Control samples, labeled TA-1 and TA-2, were sourced from two separate sites. At each location where samples were collected, no fewer than three composite samples were taken. Soil was extracted using a steel auger to a depth ranging from 0 to 15 centimeters, and the collected material was subsequently placed in transparent plastic bags. Once in the laboratory, the samples were air-dried over several days by being spread out on a clear plastic sheet positioned on a bench. Following this, the soil was sieved through a 2 mm mesh and repackaged in clear plastic bags for subsequent analysis. Twenty grams of the sieved, air-dried soil samples were carefully placed into well-cleaned 250 cm³ conical flasks, and 100 cm³ of 0.5 M nitric acid was subsequently added. These flasks were then agitated using a mechanical shaker for at least 30 minutes. After this shaking process, the resulting mixtures were filtered through ashless Whatman filter paper 40 and the filtrate was collected in 100 cm³ plastic bottles. Prior to any treatment, control samples were analyzed to determine the baseline concentrations of the target analytes, after which they were spiked with specific amounts of Arsenic (As), Cobalt (Co), Chromium (Cr), Cadmium (Cd), Copper (Cu), Lead (Pb), Nickel (Ni), and Zinc (Zn). Subsequently, the complete procedure was carried out to assess the recovery rates associated with the extraction process. The percentage recoveries were determined by analyzing the differences between the initial concentrations and those found in the spiked samples. To create the solutions for spiking cadmium samples, cadmium nitrate of general-purpose reagent quality, which has a minimum purity of 99 percent, was utilized. Conversely, the solutions formulated for spiking lead, copper, and zinc samples incorporated analytical-grade lead nitrate salt as well as analytical-grade particles of copper and zinc. Furthermore, a reagent blank specific to each metal was created and processed through the complete procedure before being utilized for sample analysis. Calibration curves were generated using analytical grade metals and metal salts. The concentrations of cadmium, copper, lead, and zinc were determined with the use of a Varian Techtron AA6 atomic absorption spectrophotometer, accompanied by the appropriate metallic hollow cathode lamps. Acetylene gas acted as the fuel source, while air functioned as the supporting medium. Throughout the analysis, an oxidizing flame was consistently maintained. Calibration curves were employed to determine the concentrations of the four metals. Initially, a reagent blank was used to set the instrument to a zero baseline. Subsequently, standard solutions were aspirated, followed by the aspiration of extracts obtained from soil samples.

Statistical Data Analysis: Calculation of Soil Pollution Indices: Calibration curves were employed to determine the concentrations of the four metals. To establish a baseline, a reagent blank was utilized to set the instrument to zero. Subsequently, standard solutions were aspirated, followed by the aspiration of extracts obtained from soil samples.

Data Analysis: In order to conduct Pearson correlation analysis and Principal Component Analysis (PCA), the data were examined utilizing the SPSS statistical software.

Potential ecological risk index:

$$E_r^i = C_f^i * T_r^i = T_r^i * {}^{C_i}/_{C_b} \quad (1)$$

The concept of the potential ecological risk index was initially introduced by Hakanson, (1980).

where E_r^i denotes the potential ecological risk index of metal i^{th}; T_r^i is the toxic response factor of the ith metal. In this study, the T_r^i of Zn, Cr, Pb, Cu, Ni, and Cd are 1, 2, 5, 5, 5 and 30, respectively (Weihua, *et al.*, 2010; Islam, *et al.*, 2015). The C_f^i values of each heavy metal (table 1 and 2) are obtained from (Eq. 1). To quantitatively express E_r^i, five criteria grades were employed: $E_r^i < 40$, $40 \le E_r^i < 80$, $80 \le E_r^i < 160$, $160 \le E_r^i < 320$ and ≥ 320 signifying low, moderate, considerable, high and very high risk, respectively (Hakanson, 1980; Ogunkunle and Fatoba 2013; Riyad, *et al.*, 2015). The potential ecological risk index related to various heavy metals (Table 1, and 2) present in the soil is determined by aggregating the individual potential ecological risk factors. This index serves to illustrate the susceptibility of various biological communities and the associated risks introduced by heavy metals. The computation of the potential ecological risk index for all evaluated heavy metals was conducted through the application of (Equation 2).

$$RI = \sum_{i}^{n} E_r^i \qquad 2$$

Geo-accumulation index (Igeo): As proposed by Muller, (1979) see equation 3

$$I_{geo} = log_2 \left({}^{C_n}/_{kB_n} \right) \quad (3)$$

In this context, Cn represents the quantified concentration (μg g^{-1}) of element n, while Bn indicates the geochemical background concentration (mg/kg).

Contamination factor (C_{deg})*;* As proposed by Devanesan, *et al.,* (2017); Ogundele, *et al.,* (2020) as shown in equation 4.

$$C_{deg} = \sum_{i=1}^{n} C_f^i \qquad 4$$

Nemerow pollution; As proposed by Ogundele, *et al.,* (2020) in equation 5.

$$NP = \sqrt{(p_{ave}^1 + p_{max}^2)/_2} \qquad 5$$

Pave and Pmax are the average and maximum values of single pollution index (SPI) for all heavy metals. The NP indices of each metal was calculated and classified into 5 grades: NPs < .7, 0.7 ≤ NP ≤ 1.0, 1.0 ≤ NPs ≤ 2.0, 2.0 ≤ NPs ≤ 3.0 and NPs > 3.0 indicating safety, precaution, slightly polluted, moderate polluted and serious polluted domain, respectively (Cheng and Zhu 2007; Ogunkunle and Fatoba, 2013) as shown in equation 5.

Principal component analysis (PCA): In principal component analysis (PCA), the component loading procedure entails the reduction of a large dataset containing multiple variables into a more simplified collection of linear combinations. These linear combinations account for a considerable share of the total variance in the data and enable a clear correlation between the variables and their corresponding sources or processes, as demonstrated in equation (6).

$$\sigma^2 = \frac{1}{N}\sum_{i=1}^{N}(X_{N-} N)^2 \qquad 6$$

RESULT AND DISCUSSION

Potential Ecological Risks Assessment (ERI: Developed by Swedish researcher Hakanson in 1980, the potential ecological risk index functions as a tool for evaluating the adverse effects of pollutants on both environmental integrity and human health. This index reflects the levels of toxicity and the ecological vulnerability linked to different concentrations of contaminants (Hakanson, 1980; Weihua *et al.,* 2010; Suresh *et al.,* 2012). It was originally intended to assess pollution in sediments of aquatic environments. However, over time, its applicability has expanded, demonstrating its utility in performing risk assessments pertaining to soils, airborne dust, and air quality (Qingjie *et al.,* 2008; Sun et al. 2010; Suresh *et al.,* 2012; Ogunkunle and Fatoba 2013; Iqbal and Shah 2014; Riyad *et al.,* 2015; Osipova *et al.,* 2016). .

Table 1: Concentration (mg/kg) of heavy metals in soil samples within the study area

Sample site	Zn (mg/kg)	Cr (mg/kg)	Cu (mg/kg)	Pb (mg/kg)	Cd (mg/kg)	Co (mg/kg)	Ni (mg/kg)	As (mg/kg)
FS/01	29.44	14.87	12.38	5.40	1.84	8.81	3.73	ND
FS/02	15.04	20.76	10.19	2.96	0.74	12.37	2.28	0.001
FS/03	11.08	10.81	11.44	5.03	4.83	8.53	1.81	BDL
FS/04	17.76	14.34	5.05	6.46	0.93	14.93	3.52	0.0001
FS/05	18.79	7.56	7.39	4.59	0.83	11.85	3.94	0.000
FS/06	15.97	21.48	14.26	6.29	1.83	9.48	1.43	0.002
FS/07	10.86	7.83	10.35	2.52	0.64	8.26	2.84	BDL
FS/08	27.65	21.48	7.37	7.48	2.38	5.16	2.94	BDL
FS/09	30.75	24.22	5.20	5.49	2.74	8.47	1.84	0.0002
FS/10	15.86	10.38	8.36	3.532	0.93	10.46	3.85	0.020
FS/11	16.87	13.23	7.84	3.28	0.88	9.47	2.02	BDL
FS/12	19.08	6.34	21.84	5.59	1.37	7.15	3.64	0.0001
FS/13	10.76	8.32	9.75	4.85	1.51	10.45	5.02	0.0002
FS/14	16.97	10.32	8.39	2.04	5.63	10.11	5.39	BDL
FS/15	25.97	14.24	12.82	4.85	1.43	6.32	3.94	0.0001
Min	10.76	6.34	5.05	2.04	0.64	5.16	1.43	0
Max	30.75	24.22	21.84	7.48	5.63	14.93	5.39	0.02
Aver	**19.08**	**13.92**	**10.56**	**4.69**	**2.045**	**9.524**	**3.23**	**0.003**
STDVE.S	**9.193706**	**6.222007**	**4.95451**	**1.986412**	**1.855909**	**4.494157**	**1.360949**	**NIL**

Where ND: Not detected, BDL: Below detection limit

According to the information shown in Table 3, and 4, every sample gathered from the research area surpasses the threshold of 600, indicating a notable ecological risk related to the soil conditions see Table 4. The presence of heavy metal contamination in the soil presents a serious danger to environmental integrity and food safety. This issue is exacerbated by the rapid growth of industrial and agricultural practices, along with the disturbances to natural ecosystems caused by human pressures stemming from increasing population densities (Sarwar *et al.,* 2017). The environmental pollution and the resulting exposure of humans to heavy metals can be linked to a variety of human activities, such as mining, industrial production, and the use of metal-infused substances in domestic and agricultural settings (Tchounwou *et al.,* 2012).

Table 2: The value of control site.

Control sites	**Zn**	**Cr**	**Cu**	**Pb**	**Cd**	**Co**	**Ni**	**As**
TA-1	5.41	8.48	5.97	0.48	0.75	5.87	1.83	0.0001
TA-2	8.29	10.57	8.85	1.94	1.86	3.85	0.98	BDL
Min	5.41	8.48	5.97	0.48	0.75	3.85	0.98	0.0001
Max	8.29	10.57	8.85	1.94	81.86	5.87	1.83	0.0001
Aver	6.85	9.52	7.41	1.21	1.30	4.86	1.40	0.0001

BDL means Below Detection Limit

Table 3: Ecological risk index set limit in soil (Hakason, 1980).

S/No	Range	Remarks
1	$R_i\ or\ E_r^i$	Ecological Pollution Degree
2	$E_r^i < 40\ or R_i < 150$	Low Ecological Risk
3	$40 \leq E_r^i < 80\ or 150 \leq R_i < 300$	Moderate Ecological Risk
4	$80 \leq E_r^i < 600\ or 300 \leq R_i < 600$	Considerable Ecological Risk
5	$160 \leq E_r^i < 320\ or\ 600 \leq R_i$	Very high Ecological Risk

Table 4: Results of potential ecological risk index

Ti*PI								
Zn	Cr	Cu	Pb	Cd	Co	Ni	As	**∑ Ti*PI**
0	19.3833	1672.321	785.858	135455.5	7543.861	237.644	0	146637.09
4.64E-05	15.59494	1937.96	394.959	38765.87	4875.753	135.85	0.09766	47687.8
0	6.94903	1094.658	705.494	614454.9	28654	79.654	0	67554.5
4.73E-06	10.73771	749.013	395.976	79976	5865.465	458.86	0.08759	70654.13
0	4.05893	504.644	504.765	146569	9464.754	483.669	0	165445.8
8.47E-05	9.37538	1964.85	1374.44	339865	14657	81.59847	0.099764	357558.7
0	5.05360	1214.064	255.972	28484.8	1776.578	124.7657	0	24656
0	22.917609	1094.65	598.930	46554.9	79765.87	146.986	0	47887.9
0.000043	26.49493	1363.843	328.94	487768	18653.3	176.132	0.17786	575486.9
0.000593	8.38491	1054.536	297.949	68765.87	6788.987	219.4194	1.308571	63833.44
0	6.39173	1132.865	403.210	55665.17	4767.976	89.02653	0	58433..1
2.94E-06	2.63630	1356.57	403.228	59876	6859.592	279.2051	0.011686	53737.28
4.93E-06	4.774641	865.765	503.811	187876.4	13560.97	393.8857	0.0366	194747.1
0	7.46494	1765.976	238.436	498787.4	36549.98	382.5867	0	427637.5
2.19E-05	15.39947	2076.065	782.934	176669.8	6584.393	142.3143	0.0136	153563.5

*Index of Geoaccumulation (Igeo);*In 1979, Muller established the Igeo index as a method for assessing the degree of contamination in elemental concentrations present in sediments, water, dust, and soil. Since its inception, this index has been widely adopted around the world to evaluate pollution levels in these various environmental matrices (Hazzeman *et al.,* 2017).

The classifications of (Igeo) and their respective interpretations are Igeo ≤ 0 (practically unpolluted), 0 < Igeo ≤ 1 (unpolluted to moderately polluted), 1 < Igeo ≤ 2 (moderately polluted), 2 < Igeo ≤ 3 (moderately to strongly polluted), 3 < Igeo ≤ 4 (strongly polluted), 4 < Igeo ≤ 5 (strongly to extremely polluted), and Igeo ≥ 5 (extremely polluted) see Table 5, (Wei, and Yan 2010; Olujimi, *et al.*, 2014; Qing *et al.*, 2015). The results detailed in the Igeo (see Table 6) reveal that all sampled values lie between 0 and 2, which implies that the samples exhibit no signs of pollution.

This finding is in sharp contrast to the results obtained from the potential ecological risk index, indicating a significant level of soil contamination. In summary, the Igeo analysis indicates that most heavy metals have not notably affected the soil quality in the area under investigation.

Table 5: Igeo scale (Igwe, *et al.*, 2020; Igwe, *et al.*, 2022; Hazzeman, *et al.*, 2017).

I_{geo} value	I_{geo} Class	Designation of sediment quality
>5	6	Very highly polluted
4-5	5	Highly populated
>3-4	4	Moderate to highly polluted
2-3	3	Moderately polluted
>1-2	2	Moderated to unpolluted
0-2	1	Unpolluted
0<	0	Background concentration

Table 6: Results of Geoaccumulation Index (Igeo)

Zn	Cr	Cu	Pb	Cd	Co	Ni	As	(Igeo)
0.05272	0.02564	0.18281	0.004737	0.194743	0.052725	0.004624	0	0.595854
0.04637	0.04748	0.05337	0.00324	0.19363	0.053634	0.001736	1.1E-05	0.483383
0.039389	0.019939	0.118837	0.01847	1.07473	0.043635	0.002615	0	1.59987
0.07383	0.02633	0.04002	0.010373	0.04452	0.06373	0.018464	5.01E-07	0.35565
0.03673	0.020484	0.068821	0.01383	0.28462	0.04351	0.002745	0	0.664747
0.047383	0.02094	0.14930	0.01838	0.417531	0.05273	0.004361	1.73E-05	0.785362
19.47833	0.04843	0.10474	0.01449	0.07453	0.027353	0.002544	0	0.216439
0.06737	0.03847	0.05941	0.014345	0.23534	0.02987	0.018374	0	0.753925
0.08938	0.04939	0.04993	0.011639	0.436634	0.042725	0.019465	1.54E-05	1.257532
0.03672	0.027474	0.064473	0.00425	0.19748	0.041735	0.001746	0.00114	0.36436
0.02049	0.047731	0.064747	0.00535	0.164654	0.057253	0.001653	0	0.275438
0.01939	0.029494	0.18832	0.003366	0.265451	0.043634	0.006153	5.05E-07	0.63853
0.02643	0.023252	0.08353	0.01572	0.481648	0.063531	0.004163	1.74E-06	0.135757
0.02877	0.019484	0.046727	0.004373	1.474936	0.045462	0.005441	0	1.624287
0.042622	0.02929	0.047428	0.02626	0.322421	0.043351	0.004637	1.4E-06	0.619744

Degree of contamination(C_{deg})*:*The contamination factor (C_f), serves to illustrate the pollution attributes of the area under investigation. It represents a specific pollution index pertaining to a particular metal within an environmental medium. This factor is determined by calculating the ratio of the concentration of heavy metals to the background concentration of the respective metal (Ogundele, *et al.,* 2017). The C_{deg} of contamination may be classified based the scale ranging from <8 to >32: < 8, 8–16, 16–32 and > 32 indicates low degree, moderate, considerate and very high degree of contamination, respectively (Chen, *et al.,*. 2012; Ogundele, *et al.,* 2017; Devanesan *et al.,* 2017). The results concerning the extent of contamination, presented in Table 7, indicate that every sample received a score of less than 8, which reflects a minimal level of contamination see Fig.3 This data is consistent with the geoaccumulation index results for the regional samples; nevertheless, it diverges from the assessment of potential ecological risk carried out in the area.

Nemerow pollution (PNI): PNI, developed by Nemerow in 1974, serves as a numerical measure that amalgamates several factors into a single metric. Conversely, the NPI value signifies the overall water quality level derived from various pollution indicators. From the standpoint of empirical validity, it is more advantageous to utilize a comprehensive water quality index for assessing intrinsic groundwater risk rather than focusing solely on the concentrations of one or two specific pollutants (Kowalska, *et al.,* 2018; Kong *et al.,* 2019). The PNI evaluates the relative contribution of each pollution parameter within a water sample, thereby identifying the factors that influence the quality status.

PNI value of ≤ 0.7 indicates that the water is clean, PNI value of 0.7< PNI ≤ 1.0 implies slightly clean, PNI value of 1.0< PNI≤ 2.0 implies slightly polluted, PNI value of 2.0< PNI≤ 3.0 implies moderately polluted, while PNI v2alue of > 3.0 implies heavy pollution (Table 7).

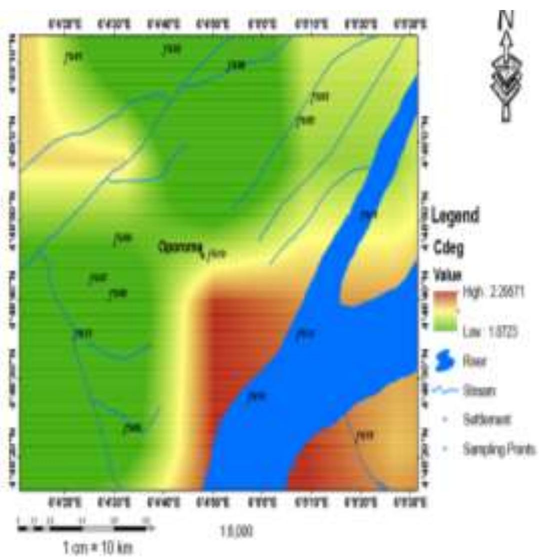

Fig. 3: Spatial distribution of Cdeg of the study area.

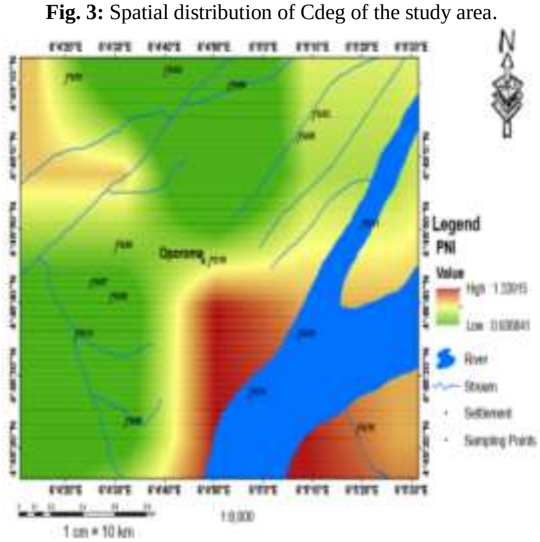

Fig. 4: Spatial distribution of PNI within the study.

Table 7: Results of contamination factor, pollution load index and nemerow pollution

Zn	Cr	Cu	Pb	Cd	Co	Ni	As	**Cdeg**	**PNI**	**PNI**
0.232	0.1243	0.396538	0.0407	0.925	0.265	0.017643	0	1.663433	0	0.70075
0.117643	0.1709	0.300769	0.0197	0.475	0.325588	0.007357	0.00004	1.37373	2.075E-06	0.27562
0.093643	0.0837	0.348846	0.0428	4.25	0.199412	0.008429	0	4.8644	0	3.07549
0.139071	0.1103	0.168462	0.0402	0.475	0.410588	0.022214	0.000002	1.26775	7.96E-07	0.256457
0.159714	0.0493	0.245769	0.0348	1.175	0.298529	0.021714	0	1.473450	0	0.754479
0.125786	0.1001	0.515385	0.0528	1.9125	0.237353	0.007071	0.00006	2.588548	7.55E-06	1.37858
0.081286	0.0848	0.357308	0.0177	0.3375	0.179706	0.013	0	1.08634	0	0.284574
0.220571	0.1509	0.206923	0.0631	2.0125	0.128824	0.019357	0	2.131568	0	1.38546
0.167643	0.2149	0.173462	0.042	3.0875	0.213824	0.009714	0.00006	2.114647	1.54E-05	2.15336
0.123857	0.0913	0.283462	0.0254	0.775	0.276176	0.016357	0.0004	1.175689	1.04E-05	0.13667
0.102	0.1077	0.242692	0.0299	0.5875	0.231176	0.007929	0	1.154567	0	0.36438
0.092357	0.0426	0.741923	0.0138	1.2875	0.196765	0.029214	0.000002	2.08749	6.45E-07	0.843606
0.067643	0.0733	0.321923	0.0344	1.6	0.265882	0.0305	0.000006	2.14245	1.02E-06	1.096443
0.104429	0.0915	0.277308	0.0193	5.0125	0.275	0.028643	0	4.473437	0	3.58549
0.202714	0.1248	0.437308	0.0334	1.4125	0.172353	0.017	0.000004	2.07452	2.36E-06	1.01125

From the results in Fig. 4, and Table 7, it shows that 36.4% of the entire sample are had a value <0.7, indicating that the samples are clean, 18.2% of the entire sample have had a value <1, indicating that the sample is slightly clean, 27.3% of the entire samples had values <3, implying that the samples are moderately polluted, while 13.6% of the samples are >3, implying that the samples are heavily polluted. Human activities may be accountable for the elevated pollution levels observed in this research. Such a conclusion stands in opposition to the findings of a study carried out in Nigeria by Egbueri, *et al.,* (2020) and Eyankware, *et al.,* (2022).

Pearson correlation matrix: The correlation matrix serves as a valuable instrument for evaluating the relationships between two variables. Typically, the correlation coefficient falls within the range of -1 to +1. A relationship is deemed to exhibit a negative slope or anti-correlation if the r-value approaches -1. Conversely, when the r-value is near +1, the relationship is characterized as having a positive slope or correlation. If the value is zero, the variables are regarded as uncorrelated (Srivastava *et al.*, 2014). According to the correlation matrix (Table 8), there are positive correlations observed between Zn and Cr (0.560), as well as between Zn and Pb (0.491).Table 8 reveals a minimal correlation among the elements, with the majority exhibiting no correlation whatsoever, which implies a lack of relationship between the two variables. In other words, when one variable varies in a specific direction, the other typically fluctuates in a completely independent fashion. Furthermore, this finding suggests that anthropogenic activities are the main sources of heavy metals in soil (Ugbome, *et al.,* 2018; Anegbe, *et al.,* 2018).

Table 8: Pearson correlation matrix

	Zn	Cr	Cu	Pb	Cd	Co	Ni	As
Zn	1							
Fe	0.01678							
Cr	0.354*	1						
Cu	-0.9526	-0.28474	1					
Pb	0.576*	0.257371	-0.28943	1				
Cd	0.019944	-0.00183	0.197433	0.17393	1			
Co	-0.42820	-0.198363	-0.18330	-0.16948	-0.18304	1		
Ni	-0.07964	-0.49272	0.504832	-0.29841	0.14849	0.10636	1	
As	0.018648	0.079373	-0.13828	-0.06939	-0.13847	0.039743	-0.16855	1

** Moderate Correlation*

Principal Component Analysis (PCA): PCA is a classification technique that aims to elucidate the variations among a multitude of interrelated variables (Eyankware and Akakuru, 2022c; Akakuru *et al.*, 2021aandb). This method illustrates the interconnections between variables, thereby simplifying the complexity of the dataset. PCA derives eigenvalues and eigenvectors from the covariance matrix of the initial data. The resulting principal components (PCs) are uncorrelated (orthogonal) variables formed by the multiplication of the original correlated variables with the eigenvectors (loadings). The eigenvalues associated with the PCs evaluate the variance they represent, while the loadings reflect the contribution of the original variables to the PCs, with the transformed observations being known as scores. In PC1, 62.5% of the variables in the components have loadings, they include Zn (0.718), Cr (0.777), Cu (0.570), Pb (0.697), and Ni (0.620). PC2 has a loading of 37.5%

among variables Cu (0.579), Cd (0.697) and Co (0.615). For PC3. 12.5% of the variables have loading As (0.671). The findings from this PCA corroborate earlier studies and additionally indicate that ongoing human activities in the region have significantly impacted the local soil (Akpoveta, *et al.*, 2010; Osakwe, 2014; Osakwe, *et al.*, 2012). The contamination of soil with heavy metals raises serious concerns due to their harmful effects on living organisms. These heavy metals are known for their persistent and non-biodegradable nature, allowing them to accumulate in the environment. Agricultural lands are subjected to considerable amounts of pollutants from diverse sources. When levels surpass established thresholds, heavy metals can pose a considerable risk to human health by interfering with the normal operations of biological systems. It is essential to manage the large quantities of waste generated with care, taking into account the environmental implications associated with land application.

The elevated levels of heavy metals within agricultural soils are influenced by the soil's inherent characteristics as well as the supplier's application rate in comparison to the soil's baseline concentration (Eyankware *et al.*, 2021; Agidi *et al.*, 2022; Akakuru *et al.*, 2022).

.**Table 9:** Table PCA

		Component		
	Communalities	1	2	3
Zn	.585	**.698**	.274	.142
Cr	.604	**.659**	.015	.114
Cu	.593	**-.495**	**.499**	-.067
Pb	.694	**.503**	.182	.018
Cd	.603	-.015	**.597**	-.118
Co	.493	-.302	**-.615**	.043
Ni	.584	**-.612**	.274	.287
As	.528	.98	-.183	**-.617**
	Eigenvalues	.683	1.183	-.183
	Variance (%)	32.0628	18.6362	7.83732
	Cumulative var. (%)	25.737	46.837	61.383

Spatial Distribution of heavy metals in soil within the study area: Zinc (Zn): In the research area, soil Zn concentrations vary between 10.76 to 30.75 mg/kg, yielding an average concentration and standard deviation of 19.08 mg/kg and 9.194mg/kg respectivey. The most significant levels of Zn were detected in the northwestern and northeastern sections of the study region, as illustrated in Fig. 5. Elevated levels of zinc (Zn) in soil may arise from a combination of natural and anthropogenic factors. Natural contributors encompass geological formations and the weathering of minerals. In contrast, human-related sources comprise industrial operations such as mining and smelting, agricultural methods involving fertilizers and manure, as well as the management of industrial and municipal waste (Esi, *et al.*, 2025; Eyankware, *et al.*, 2018).

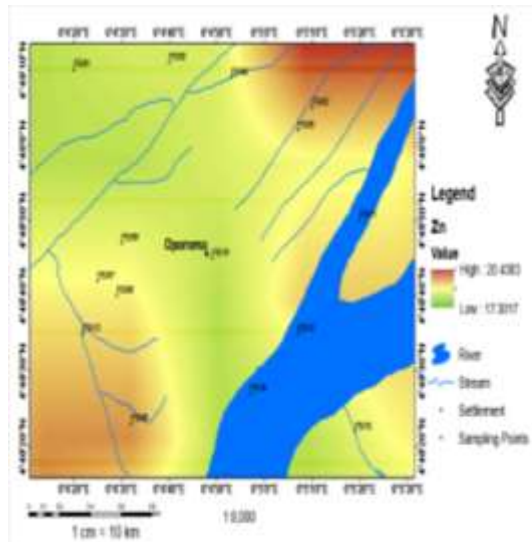

Fig. 5: Spatial distribution of Zn of the study area

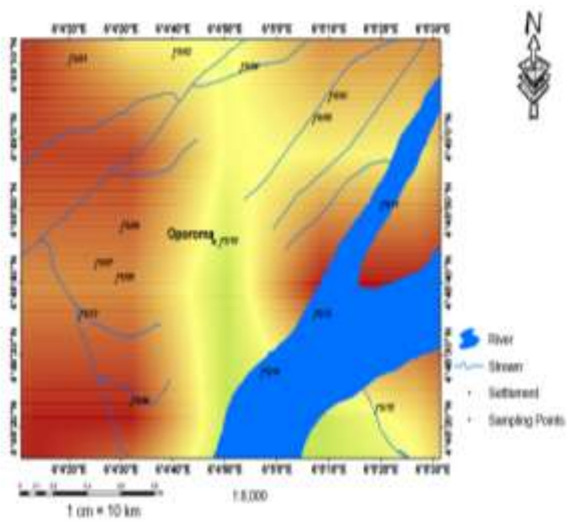

Fig. 6: Spatial distribution map of Cr within the study.

Chromium (Cr): In the study area, Cr concentrations in soil vary between 6.34 to 24.22 mg/kg, with an average concentration and standard deviation of 13.92 mg/kg and 6.222mg/kg respectivey (refer to Fig.8, and Table 1). As illustrated in Fig. 6, elevated levels of Cr are predominantly found along the southwestern and southeastern axes of the region. Further deductions from Fig.8, suggested that Cr values increases towards the NW, and SW parts of the study area, Jankiewicz and Ptaszyski (2005) indicated that the variability in soil Cr concentrations is significantly influenced by the characteristics of the geological parent materials from which the soil originates. Additionally, human activities, particularly mining operations in proximity to active sites, can lead to substantial increases in soil Cr levels. The absorption of heavy metals by plants can result in health issues such as kidney and liver damage in humans (Harendra *et al.,* 2017).

Copper (Cu): In the study area, the concentrations of Cu in the soil range from 5.05 to 21.84 mg/kg, yielding an average concentration and standard deviation of 10.56 mg/kg and 4.955mg/kg respectively (refer to Table 1). Analysis of Table 1 and Fig. 7 indicates that elevated levels of Cu were detected at sampling sites DO/06, 12, 19, 20, and 21, located to the southwest and southeast. This phenomenon may be linked to the geological parent material, which serves as a primary natural source of Cu within the soil. Moreover, Cu is unique among metals as it can exist in nature in an uncombined mineral form. Conversely, when Cu is added to the soil, it tends to bond strongly with organic and geological substances, complicating its dispersal. The impact of excess Cu can be observed in areas with elevated Cu concentrations, as well as in plant products that have absorbed significant amounts of Cu and are subsequently transported to different regions. The presence of Cu in soil is associated with the mining and processing of Cu ores, as noted by Igwe *et al.,* (2021) and Zhuang *et al.,* (2009). Cu significantly contributes to environmental pollution, adversely influencing environmental quality and ecosystem resources. Certain metal pollutants, including Cu, may be released during the mining or processing of ores and can be dispersed over extensive distances, leading to degradation of soil sediment quality (Eyankware *et al.,* 2022).

Lead (Pb): Pb is a hazardous non-essential element that has been extensively researched compared to other trace metals (Raikwar *et al.,* 2008; Igwe, *et al.,* 2021; SON 2015; Eyankware, *et al.,* 2022). In order to assess the availability of lead (Pb) in soil, the pH levels of all soil samples analyzed for their Pb content were recorded. At a pH range of 6–8, which corresponds to near-neutral soils, Pb tends to adhere strongly to soil particles, making it less accessible for absorption by plants. The Pb concentrations identified in this study varied from 2.04 to 7.48 mk/kg, with an average concentration and standard deviation of 4.69 mg/kg and 1.99mg/kg respectively, as presented in Table 1. Furthermore, as illustrated in Fig. 7, it was noted that in the NW, SE, and certain areas of SW, elevated levels of lead (pb) in soil can arise from both natural and anthropogenic sources. Natural origins encompass the weathering of rocks and minerals that contain lead, whereas human activities—such as industrial operations, mining activities, and the previous use of leaded gasoline—have the potential to considerably enhance the concentration of lead in the soil (Eyankware, *et al.,* 2024; Odesa, *et al.,* 2025).

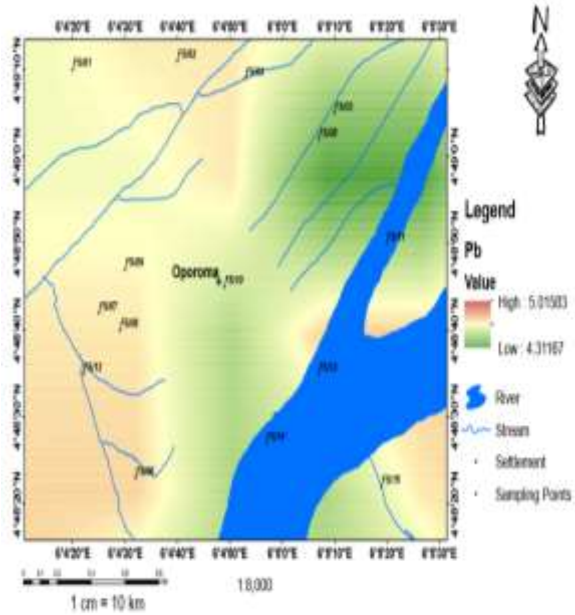

Fig. 7: Spatial distribution map of Pb within the study.

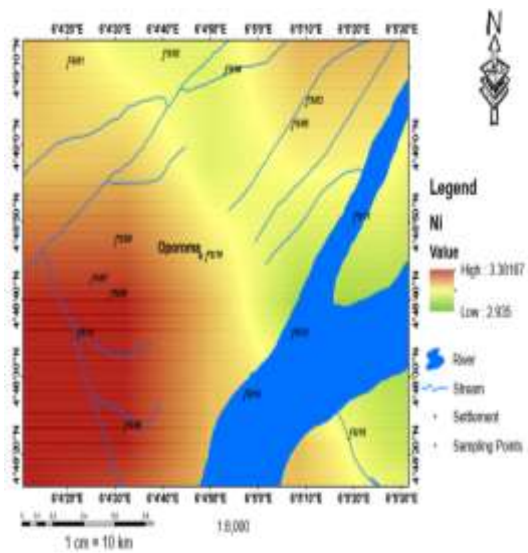

Fig. 8: Spatial distribution map of Ni within the study.

Nickel (Ni): In the study area, Ni concentrations in soil vary from 1.43 to 5.39 mg/kg, yielding an average concentration and standard deviation of 3.23 mg/kg and 1.36mg/kg respectively (refer to Fig. 8, and Table 1). The most elevated levels of Ni were detected in the southeastern (SE) and southwestern (SW) regions, as well as in certain areas of the northeastern (NE) section, as illustrated in Fig. 8. Nickel exists in the soil in multiple forms, such as the adsorption and complex formation on the surfaces of organic cations or those involved in inorganic cation exchange, along with inorganic crystalline minerals or precipitates, soluble forms in water, free ions, or chelated metal complexes present in the soil solution, in addition to inorganic crystalline minerals *or precipitates (Eyankware, et al., 2025a).*

rsenic (As): In this study, the concentration of AS ranges from **0** to 0.02 mk/kg, with an average concentration of 0.003 mk/kg (See Fig.9, and Table 1 which corresponds to a naturally occurring element present throughout the Earth's crust. This metalloid, known for its high toxicity, is widely distributed across the Earth's surface and in its aquatic systems (Igwe *et al.,* 2022; Eyankware, *et al.,* 2024). As trioxide is widely acknowledged as a powerful toxin, with even a small dose, roughly 0.1 g, capable of causing considerable environmental hazards. Although chronic arsenic poisoning resulting from workplace exposure is extensively documented, cases of acute arsenic toxicity have become increasingly uncommon (WHO, 1981). For more than a hundred years, arsenic has been identified as a carcinogen in humans when present in high concentrations. Current understanding asserts that consuming inorganic As can result in skin cancers, lung cancers, and leukemia, while inhalation is associated with cancers affecting the respiratory system (Esi, *et al.,* 2025). As is an element that naturally exists in various forms within the Earth's crust. This extremely hazardous metalloid is widely found on the Earth's surface and within its aquatic ecosystems (Igwe, *et al.,* 2022; Esi, *et al.,* 2025). Known for its potent toxicity, even a tiny amount of arsenic trioxide, roughly 0.1 g, can present considerable environmental dangers. Although chronic arsenic poisoning from occupational exposure is well-established, cases of acute arsenic toxicity have become infrequent (WHO, 1981). For over a hundred years, arsenic has been recognized as a human carcinogen when present in high doses, and it is now clearly understood that the consumption of inorganic As can result in skin cancer, lung cancer, and leukemia, while its inhalation is associated with respiratory tract cancers (Jarup, 1992; Kotoky, *et al.,* 2008).

Cobalt (Co): Co is a naturally occurring element that exhibits properties akin to those of iron and nickel. It can be found in trace amounts within the soil (Igwe, *et al.,* 2021). The concentrations of Co in the examined region vary from 5.16 to 14.98 mg/kg, with an average concentration and standard deviation of 9.524 mg/kg and 4.49mg/kg respectively (see Table 1). Igwe, *et al.,* (2021) indicate that heavy metals, such as Co, which are discharged during lead-zinc mining processes under certain conditions, have the capacity to mobilize, transfer, and accumulate in different environments, including soil, thus influencing plants, animals, and humans in both direct and indirect manners.

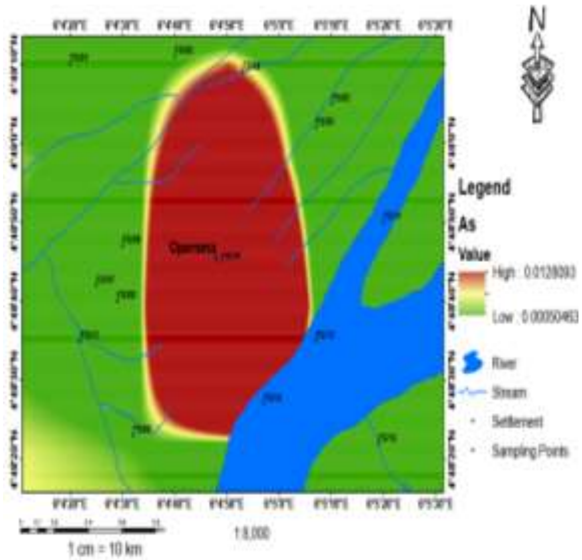

Fig. 9: Spatial distribution map of As within the study.

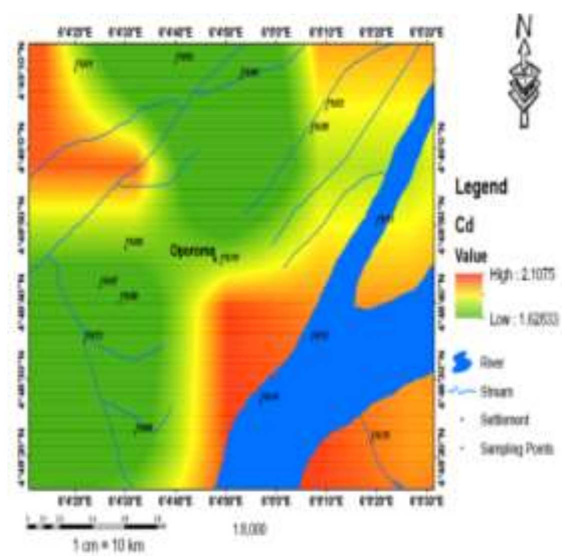

Fig. 10: Spatial distribution map of Cd within the study.

Cadmium (Cd): Cd is a naturally occurring element, is present in mineral soils (Esi, *et al.,* 2025; Igwe, *et al.,* 2022). Cd levels in soil vary between 0.64 and 5.63 mk/kg, with an average concentration and standard deviation of 2.045 mk/kg and 1.8556mg/kg, as shown in Fig. 10 and, Table 1. The elevated Cd levels around selected parts of SE, NE, and NW can be linked to geogenic sources. Research by Eyankware and Ephraim, (2022) and Li *et al.,* (2015) indicates that the concentration of Cd is influenced by the geological parent materials. However, it is noteworthy that soil cadmium concentrations typically remain below 1 mg/kg, aligning with the permissible limit of 0.8 mg/kg set by the World Health Organization (WHO).

Conclusion: The presence and degradation of heavy metal pollutants in soils are largely linked to human activities such as industrialization, mining, agriculture, and waste management, posing serious ecological and health risks. This study analyzed heavy metal concentrations using PCA, Pearson correlation, and indices including ERI, Igeo, Cdeg, and PNI. The ERI values exceeded 600, indicating very high ecological risk, while Igeo and Cdeg analyses classified the soils as unpolluted to low contamination levels. PNI results showed 33.3% clean, 28.3% slightly clean, and 13.7% moderately polluted soils. The correlation analysis confirmed that anthropogenic activities significantly influence heavy metal distribution. Overall, the findings highlight the urgent need for effective control measures to prevent metal accumulation, safeguard soil quality, and protect human and ecosystem health.

DECLARATION

Ethical Approval: This study did not involve human participants or animal experimentation and therefore did not require formal ethical approval. All procedures involving data handling and analysis were conducted responsibly and in accordance with standard academic and institutional guidelines.

Disclaimer (Artificial Intelligence): Authors hereby declare that no generative *Artificial Intelligence* (AI) technologies such as Large Language Models (ChatGPT, COPILOT, XLNet, Ernie 3.0 Titan etc) and text-to-image generators have been used during writing or editing of this manuscript.

Declaration of Conflict of Interest: The authors declare that no known conflict of interest or personal relationships that have influenced the work reported in this paper.

Declaration of Data Availability: Data sharing is not applicable to this article as no datasets were generated or analyzed.

REFERENCES

Adesuyi, AA; Njoku, KL, Akinola, MO (2015). Assessment of Heavy metals pollution in soils and vegetation around selected Industries in Lagos, South western Nigeria. *J. Geos. Envir. Protectn*, 3:11-19.

Adesuyi, AA; Njoku, KL; Akinola, MO; Jolaoso, AO (2018). Biomonitoring of heavy metals level in wetland plants of Lagos Lagoon, Nigeria. *J. Appl. Sci. Environ. Manage*., 22(9): 1489–1498

Adesuyi, AA (2020). Integrating remote sensing with bioassessment of selected part of Lagos lagoon wetlands [Ph.D. Dissertation]. University of Lagos, pp335

Ajibola, MO; Adewale, BA; Ijasan, KC (2012). Effects of Urbanisation on Lagos Wetlands. *International J. Busin. Soc. Sci*., 3(17): 310-318

Baruah SG, Ahmed I, Das B, Ingtipi B, Boruah H, Gupta SK, Chabukdhara M.(2021). Heavy metal (loid)s contamination and health risk assessment of soil-rice system in rural and peri-urban areas of lower Brahmaputra valley, Northeast India. Chemosphere. 2021;266:129150. https://doi.org/10.1016/j.chemosphere.2020.129150

Esi, EO; Odedede PO; Eyankware, MO; (2025). Integration of geophysical and radiological assessment of solid waste diposal impact on groundwater and human health in southern Nigeria, *Geosyst. Geoenviron*., doi: https://doi.org/10.1016/j.geogeo.2025.100425

Eyankware, MO; Akakuru, OC; Osisanya, WO; (2023). Assessment of heavy metal pollution on ground water quality in the Niger Delta Region of Nigeria. *Sustain. Wtr. Resources Manage*., 9, 189. https:// doi.org/10.1007/s40899-023-00955-7

Eyankware, MO; Ephraim, BE; (2021). A comprehensive review of water quality monitoring and assessment in Delta State, Southern Part of Nigeria. *J. Environ. Earth Sci*., 3(1), 16–28. https://doi.org/ 10.30564/jees.v3i1.2900

Eyankware, MO; Eyankware, OE; Ulkapa, ROE. (2016). Assessment of impact of leachate on soil phys icochemical parameters in the vicinity of Eliozu Dump site, Port Harcourt, Nigeria. *Basic Res. J. Soil Environ. Sci.,* , 4(2), 15–25.

Eyankware, MO; Obasi, PN. (2021). A holistic review of heavy metals in water and soil in Ebonyi SE. Nigeria; with emphasis on its effects on human, aquatic organisms and plants. *Wld. New. Natural Sci.*, 38, 1–19.

Eyankware, MO; Akakuru, OC; Igwe, EO; Olajuwon, WO; Ukor. KP. (2024). Pollution Indices, Potential Ecological Risks and Spatial distribution of Heavy Metals in soils around Delta State, Nigeria. *Wtr, air, soil Pollutn*. https://doi.org/10.1007/s11270-024-07209-yI.

Onwe, IM; Obasi, IA; Eyankware, MO; Uchenna, OL (2024). An integration of hydrochemical data and stable isotopes in groundwater evaluation in Ngboejogu, Southern Benue Trough, Nigeria. *Modelg. Earth Sys. Environ*. https://doi.org/10.1007/s40808-024-02166-1

Njoku, KL; Akinola, MO; Zinghadina TO (2013) A study on the spatial distribution of heavy metals in industrial area of Ikorodu, Lagos State Nigeria. *J. Research in Environ. Sci. Techn*., 2(3): 64-70.

Obiefuna, JN; Nwilo, PC; Atagbaza, AO., Okolie, CJ (2013) Spatial Changes in the Wetlands of Lagos/Lekki Lagoons of Lagos, Nigeria. *J. Sustain. Dev*., 6(7): 123-133.

Odesa, GE; Elozona, OE; Eyankware, MO. (2024a). A Review Study on Ecological Equity and Modern Remediation Techniques in Management of Soil. *J. Pure. Appl. Sci.24*

Odesa, GE; Ozulu, GU; Eyankware, MO; Mba-Otike, MN; Okudibie, EJ. (2024b). A holistic review three-decade oil spillage across the Niger Delta Region, with emphasis on its impact on soil and water. *Wld New. Sci.. 190(2); 119-139.*

Odesa, GE; Okanigbuan, PN; Eyankware, MO; Ngozi-Chika, CS; Efetobo, O. (2025).Health risk assessment of water resources within the lignite series of Obomkpa and environs, southern Nigeria. *J. Contamint. Hydrology*. https://doi.org/10.1016/j.jconhyd.2025.104665.

Omene, ME; Chokor, JU; Eyankware, MO. (2015). The effects of land use on soil physiochemical properties in Ughelli and its environs, Nigeria. *Interntl. J. Rsrch. Review, India*. 2(11): 656-671

Singh, BP; Choudhury, M; Samanta, P; Gaur, M; Kumar, M. (2021). Ecological risk assessment of heavy metals in adjoining sediment of river ecosystem. Sustainability. 2021;13(18):10330. https://doi.org/10.3390/su131810330

Sánchez-Castro, I; Molina, L; Prieto-Fernández, MÁ; Segura, A.(2023). Past, present and future trends in the remediation of heavy-metal contaminated soil-Remediation techniques applied in real soil-contamination events. Heliyon. 9: e16692. https://doi.org/10.1016/j.heliyon.2023.e16692.

Paul, S; Choudhury, H; Deb, U; Pegu, R; Das, S; Bhattacharya, SS; (2019). Assessing the ecological impacts of ageing on hazard potential of solid waste landfills: a green approach through vermitechnology. *J Clean Prod*. 2019;236: 117643. https://doi.org/10.1016/j.jclepro.2019.117643

Choudhury, M; Jyethi, DS; Dutta, J; Purkayastha, SP; Deb D, Das R, Bhattacharyya KG. (2021). Investigation of groundwater and soil quality near to a municipal waste disposal site in Silchar, Assam. India *Int J Energy Water Res. 2021*. https://doi.org/10.1007/s42108-021-00117-5.

Golui, D; Mazumder, DG; Sanyal, SK; Datta, SP; Ray, P; Patra, PK; Bhattacharya, K.(2017). Safe limit of arsenic in soil in relation to dietary exposure of arsenicosis patients from Malda district, West Bengal-a case study. *Ecotoxicol Environ Saf*. 2017;144:227–35. https://doi.org/10.1016/j.ecoenv.2017.06.027

Huang, Y; Chen, Q; Deng, M; Japenga, J; Li, T; Yang, X; He, Z; (2018). Heavy metal pollution and health risk assessment of agricultural soils in a typical peri-urban area in southeast China. *J Environ Manag*. 2018;207:159–68. https://doi.org/10.1016/j.jenvman.2017.10.072.

Jiang, X; Lu, WX; Zhao, HQ; Yang, QC; Yang, ZP. (2014). Potential ecological risk assessment and prediction of soil heavy-metal pollution around coal gangue dump. *Nat Hazards Earth Syst Sci*. ;14:1599–610. https://doi.org/10.5194/nhess-14-1599-2014.

Sánchez-Castro, I; Molina, L; Prieto-Fernández, MÁ; Segura, A. (2023). Past, present and future trends in the remediation of heavy-metal contaminated soil-Remediation techniques applied in real soil-contamination events. *Heliyon.* 2023;9: e16692. https://doi.org/10.1016/j.heliyon.2023.e16692.

Xiao, P; Zhou, Y; Li, X; Xu, J; Zhao, C. (2021). Assessment of heavy metals in agricultural land: A literature review based on bibliometric analysis.Sustainability.;13(8):4559. https://doi.org/10.3390/su13084559.

Zhuang, Z; Mu, HY; Fu, PN; Wan, YN; Yu, Y; Wang, Q; Li, HF (2020). Accumulation of potentially toxic elements in agricultural soil and scenario analysis of cadmium inputs by fertilization: a case study in Quzhou county. *J Environ Manage*. 2020;269:110797. https://doi.org/10.1016/j.jenvm