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Concentrations Pollution Indices of Heavy Metals in Soil around Okerenkoko and Benikrukru, Delta State Nigeria

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ABSTRACT: Heavy metal contamination in soils of Niger Delta region, Nigeria driven by oil spills and illegal refining, poses serious ecological and human health risks. This study evaluated subsurface soil pollution in Okerenkoko and Benikrukru communities by determining concentrations of seven heavy metals and associated risks. Eight composite surface soil samples (0–15 cm) were digested and analyzed by atomic absorption spectrophotometry. Mean concentrations were Zn 8.65 ± 4.34 , Cu 6.06 ± 3.06 , Pb 1.36 ± 0.69 , Cr 2.43 ± 1.18 , Cd 12.1 ± 5.19 , Ni 7.8 ± 1.8 , and Hg 1.10 ± 1.36 mg/kg; Zn, Cr, Cd, Ni, and Hg exceeded WHO permissible limits. Pollution indices (CF, PLI, mCd, Igeo) confirmed moderate to very high contamination, while potential ecological risk was dominated by Cd (mean PER 92.27) and Cu (50.77). Human health risk assessment revealed unacceptable non-carcinogenic risk to children (THI 8.08) and elevated lifetime cancer risk (children 9.56×10^{-4} ; adults 5.21×10^{-4}), mainly through ingestion. The study confirms severe anthropogenic pollution from petroleum activities, with children most vulnerable. Urgent regulatory enforcement, continuous monitoring, and targeted remediation (phytoremediation) are recommended. This work provides critical baseline data and integrated risk quantification for understudied oil-impacted within the Niger Delta communities.

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Controlling the current environment is crucial since contemporary industrialization and population growth have degraded the natural state of soil and hastened the use of environmental resources. This is especially the case when it comes to the problem of soil heavy metal (HM) pollution, which is harmful and results from soil HM stimulation at an excessive level. (Nagajyoti *et al.*, 2023). Although, heavy metal continues to be extremely toxic and difficult to break

down, they are a major global concern. This is because when they enter the environment due to their tendency to spread and accumulate, it disrupts natural ecosystems, and negatively impact human health at various stages of food chain (Ali *et al.*, 2019). Soil HMs primarily come from humans and nature, with the latter generally being associated to oil well extraction, metal mining operations, metal smelting, and manufacturing, as well as automotive emission

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standards (Maio *et al.*, 2022; Nagajyoti *et al.*, 2023). A dearth of comprehensive studies evaluating the hazards of HM pollution in soil has been identified, according to research near crude oil processing facilities. This is mainly due to the fact that petroleum contains various HMs, which can leak and accumulate in the soil surrounding oil processing sites during the various stages of production and transportation (Fu *et al.*, 2014; Kahlid *et al.*, 2020; Hosam *et al.*, 2022). A danger to human and environmental health might arise when HM concentrations in the soil go beyond what is considered safe. Additionally, the evaluation of the potential risks and the toxicological impact of HMs, their accumulation over time, and the combined effects of each HM were evaluated through utilization of Contamination Factors (CF), Pollution Load Index (PLI), Modified Contamination Degree (mCd), Geo-accumulation factor (Igeo), and Ecological Risk (ERI). Researchers thoroughly assessed the biological risk of HMs using the level of heavy metal contamination in soil particles. Researchers thoroughly assessed the biological risk of HMs using the toxicity response coefficient and the associated environmental background value (Jang *et al.*, 2021; Luo *et al.*, 2022). This method is frequently employed to determine the level of heavy metal contamination in soil particles. However, the hazards to people of all ages were assessed using the USA Environmental Protection Agency's (EPA) human health risk (HHR) technique (Cai *et al.*, 2019; Lu *et al.*, 2022). Through the utilization of the HHR model, created by Proshad *et al.*, (2022); Sun *et al.*, (2022); Xiao *et al.*, (2022) the non-carcinogenic and cancer-causing risks of HMs in individuals across all age groups were determined. Three routes of exposure to HMs are determined by the HHR model: ingestion, inhalation, and skin contact. By identifying the critical variables that impact both cancer risk and risk that is not cancerous, the HHR model highlights the potential health risks associated with each HM, through emphasizing their significance to an individual's well-being (Safiur *et al.*, 2019; Rinklebe *et al.*, 2019). To effectively reduce the risks to human health from elevated levels of heavy metals in soil, it is crucial to prioritize the management and oversight of activities that contribute significantly to this accumulation, such as metal processing, manufacturing, agriculture, vehicle emissions, oil and gas extraction, and other similar processes (Baltas *et al.*, 2020; Jiang *et al.*, 2021). Consequently, the objective of this paper is to evaluate the concentrations and pollution indices of heavy metals in soil around Okerenkoko and Benikrukru, Delta State Nigeria.

MATERIALS AND METHOD

Description of the study area: The research areas of Okerenkoko and Benikrukru are situated in the heart of Nigeria's traditional crude oil processing sector, located in the Niger Delta. These study sites span between longitudes 5°23'0" and 5°17'0". The coordinates 5°37'0" and 5°40'0" North, as depicted in Fig. 1a and b. Both the wet and dry winter months (November–March) and the stormy season (April–October) have significant impacts on the areas. On average, the area receives around 3000 mm of rainfall annually. Okerenkoko and Benikrukru are situated along the coastlines and are characterized by shallow coastlines that are primarily part of the mangrove ecosystem swamp forest. Unfortunately, much of the forest has been significantly impacted by human activities through oil spill (Ulakpa *et al.*, 2023). The climate in these areas is generally warm, with temperatures ranging from 26 to 28°C. Along the Niger Delta's shores, wind speeds typically range from calm to moderate.

Along the Niger Delta's shores, the wind speed typically ranges from 0 to 3 m/s on a monthly basis, with varying intensity observed in the late afternoon and evening, as reported by (Eyankware *et al.*, 2020). Located in the research area is coastal scenery within the Niger Delta Basin, where the majority of the shoreline is made up of brackish or salty mangrove forests set back from the water by dunes of sand. The study site is located on flat, reasonably level terrain that is about 18 meters above sea level on average, and lacks imposing hills that are characteristic of the recent geological formation of the Niger Delta. The landscape is characterized by low-lying features that contribute to Inundation following precipitation (Eyankware *et al.*, 2021). Many winding creeks traverse the study region, with some of them eventually emptying into the Atlantic Ocean.

Geologically, the mineral deposits of Agbada, Benin, and Akata split the sedimentary pattern into three subgroups. The pattern is primarily formed of sand, shale, and clay. Numerous water reservoirs in the delta are formed by the Benin Formation, which is primarily composed of huge, exceedingly permeable sands and narrow, sparsely spaced gravels distributed shale and clay interbeds (Oteri and Atolagbe, 2003). In the delta, there are two main areas that can be classified according to the location of the first saltwater sands in the Benin Formation's closed aquifers. One area has saltwater sands on an ongoing basis beneath both freshwater and saltwater beaches at superficial levels. The other area has freshwater sands beneath saltwater sands at superficial levels.

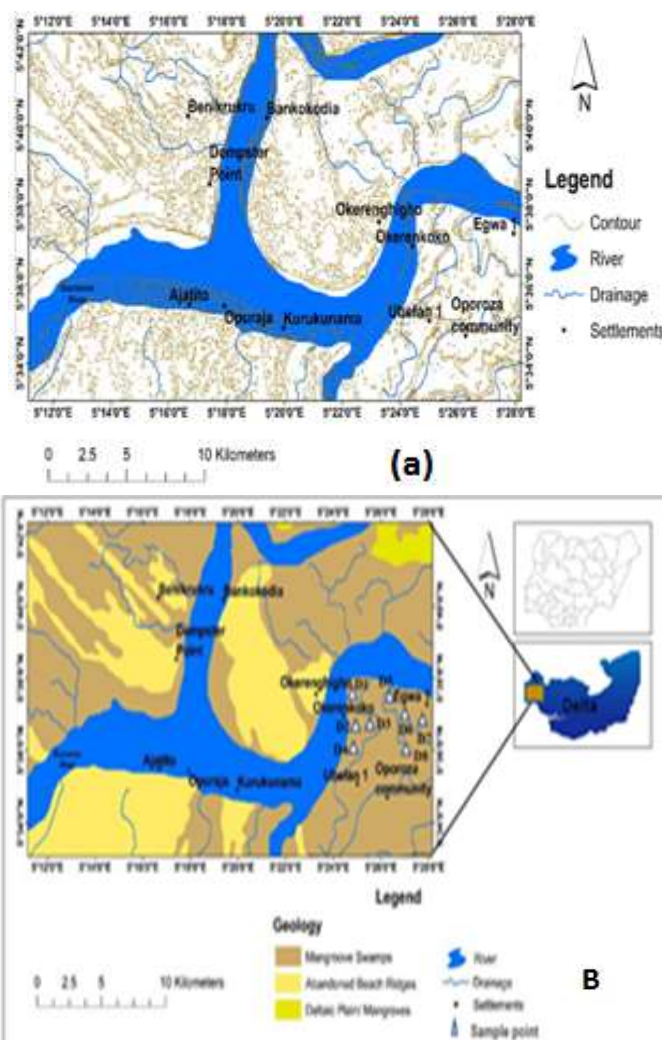


Fig.1(a): Geographical depiction of the study area, **(b)** geological chart depicting the research

Sample collection and treatment: In the investigated area, eight subsurface soil samples (0 to 15 cm deep) were taken in May 2022 as shown in Fig. 1. The decision to sample soil at a depth of 0 to 15 cm when assessing soil quality was made based on various factors. This specific range is commonly chosen in environmental research related to HM contamination because it represents the top layer of soil where most biological activity and root growth take place. Moreover, this shallow depth is particularly vulnerable to contamination from human activities, such as industrial processes like oil production, highlighting its importance in evaluating heavy metal pollution. By concentrating on the 0 to 15 cm depth range, the researcher observed the immediate effects of HM deposition on soil quality and having a clearer picture of the possible health risks and ecological risks in these areas. This depth range also allows for a more focused and efficient sampling strategy,

through providing a representative sample of surface soil conditions in the research area. Relatively, to create a mixed sample, 4 subsamples from each sampling location were gathered. Afterwards, the sample was promptly transported to the laboratory in a polyethylene zip-bag.

Sample analysis methodologies: A concentrated acid mixture of HNO_3 - HF-HClO_4 was used to break down soil samples (each weighing 0.1 g) after they had been oven pulverized, sieved through a 1 mm stainless steel mesh, and dried. All digested solutions underwent filtration and had their compositions adjusted with ultrapure water for instrumental examination. Zinc, copper, lead, cadmium, nickel, and mercury were identified using a nuclear ingestion spectrophotometer (AAS) with a rapid sequential (FS) (Varian 240 AA) mode of analysis. Selection of 7 soils HMs was made based on their known

environmental impact and potential health hazards. These selected HMs, were specifically chosen due to their common presence in the soil of the region and their connection to oil production activities. Each of these HMs possesses distinct characteristics that make them worrisome from the standpoint of potential harm to human health and soil contamination. Furthermore, it enables a thorough and detailed assessment of soil quality in the study area, aiding in informed decision-making and promoting sustainable development practices.

Statistical Data Analysis: Throughout the investigation, subsurface soil samples within the research region were analyzed for certain HMs characteristics (Pb, Hg, Cu, Cr, Cd, Ni, and Zn). The primary goal of this research was to use principal component analysis to examine, predict, and localize the origins of likely soil contamination at the sites under scrutiny. In conjunction with analytically recording the present condition of soil samples for comparability in the future, will be helpful to personnel in charge of soil quality improvements, oversight, exploitation, and degradation.

An examination of the Pearson correlation coefficient can be done to determine the direction and strength of a linear relationship between two continuous variables. In the field of soil quality assessment, this method is valuable for analyzing the connections between different soil parameters and indicators of soil health. By conducting Pearson correlation coefficient analysis, researchers are able to gain insights into the relationships in variables. Through calculating these coefficients, it becomes possible to assess the degree and direction of associations between them and if a strong linear correlation exists between the variables under investigation.

Contamination Assessment: Various ecological indices were utilized for the purpose of determining the concentrations of HM pollutants in soil.

Contamination Factor (CF): The benchmark CF for contamination, is divided into four levels to evaluate the contamination of a particular metal over time, was presented as the ratio of the concentration observed to the actual quantity of a given metal as shown in (Eqn. 1). The four groups are as follows: low ($CF < 1$), moderate ($1 \leq CF < 3$), considerable ($3 \leq CF < 6$), and extremely high ($CF \geq 6$)

$$F = \frac{C_n (\text{Sample})}{B_n (\text{background})} \quad (1)$$

Where C_n is the background value (Akakuru *et al.*, 2023b)

Pollution Load Index (PLI): Is calculated as the n th root of the contamination factor of the target HMs (CF), multiplied by itself. It has been used to evaluate the sample's overall level of toxicity and the contribution of the seven metals as indicated in (Eqn. 2). According to Akakuru *et al.* (2023b), the PLI is an additional assessment technique which includes single factor index and a thorough assessment. Jorfi *et al.* (2017); Afolabi and Eludoyin, (2021) estimated the PLI of the seven HMs' integrated methodologies, a value of 0 indicates pristine soil, a value of 1 indicates the presence of just a little amount of contaminants, and a value greater than 1 indicates a progressive decline in soil quality.

It is as in equation 1:

$$\sqrt[n]{CF_1 * CF_2 * CF_3 * \dots * CF_n} \quad (2)$$

Contamination factor (CF) and pollution load index (PLI) are equivalent, with n being the element number. PLI values above 1 suggest contamination, whereas PLI values below 1 signify absence of it.

Modified Degree of Contamination: The mCd, developed by Akakuru *et al.* (2023b), was used as a standard for evaluating the rate of contaminants from HMs in subsurface soil. The mCd was divided into four categories: A level of pollution is considered very low when $mCd < 1.5$, low when $1.5 \leq mCd < 2$, average when $2 \leq mCd < 4$, and extremely high when $4 \leq mCd < 8$ (very polluted environment), and $8 \leq mCd < 16$ (very significant amount of pollution). Severe contamination; $16 \leq mCd < 32$ indicates severe contamination, and $mCd \geq 32$ is deemed to have an ultra-high level of contamination. The criteria for determining the broader standards for contamination at a certain sample location are as follows according to (Jorfi *et al.*, 2017). The total amount of contaminants for a specific system of estuarine pollutants divided by the total amount of contamination under investigation is the level of tainting; ii). The average concentration of a toxin that hasn't completely subsided from three cases; and iii) the amended equation is used to determine the gauge fixations. Common place earthly stuff. (Eqn. 3) is a modified criterion for measuring tainting using a long cycle.

$$mCd = \sum_{i=1}^n (Cf_i) \quad (3)$$

Where the number of items being examined is n , and C_f stands for contamination factor. The analysis can include multiple metals as it takes since there is no maximum number because the mCd is determined using this complex and broad equation.

Geo-accumulation Index Method (Igeo): Igeo is a popular tool for determining the level of heavy metal contamination in sediment. It was originally developed for use in soil pollution assessments. To determine the extent to which HMs pollute, one can utilize the geo-accumulation index (Igeo). It seems that the geo-accumulation index is used extensively for analyzing substrate pollution. The following are the categories into which Igeo values were categorized according to Cui *et al.*, (2021): unpolluted ($Igeo \leq 0$), slightly polluted ($Igeo \leq 1$), slightly more polluted ($Igeo \leq 2$), strongly polluted ($Igeo \leq 3$), strongly polluted ($Igeo \leq 4$), highly polluted ($Igeo \leq 5$), and exceedingly polluted ($Igeo < 5$). The following calculation method is provided by Ma *et al.*, (2022) for this approach, which uses the soil's geochemical baseline value as a reference point.

The calculation formula for this technique, which takes the soil's geochemical baseline value as the reference, is shown in Eqn. 4

$$Igeo = \log_2 \left(\frac{C_n}{1.5 B_n} \right) \quad (4)$$

Where 1.5 is the possibility factor, B_n is a baseline of the dangerous metal n , and C_n is its quantity in the environment.

Potential Ecological Risk Index (PERI): An ecological risk assessment for a given system can be expressed using the potential ecological risk index which is adding up all of the PER values. These categories apply to PER values: The degrees of the environmental threat are determined by the RI index values acquired, and these are the following: Indicators of minimal environmental hazard include RI values below 150 and values between 150 and 300 indicates slight environmental threat; and include 300 RI and less indicates medium to elevated ecological threat (Ferati *et al.*, 2015). In this investigation, the environmental threat index was derived by the following formula, which had been first suggested by (Hakanson, 1980) as indicated in Eqn. 5 and 6.

$$PER = \sum Ti * PI \quad (5)$$

$$PI = \frac{Cs}{Cb} \quad (6)$$

Where C_b represents the ambient value and C_s the quantity present.

In this instance, PER and Ti stood for a single environmental threat and a harmful reaction factor for HMs. According to the toxicological coefficients of the Hakanson categorization criteria was developed. Cd, Pb, Cu, Hg, Zn, Cr, and Ni have toxicological reactivity factors of 2, 5, 2, 10, 30, and 2 correspondingly.

The environmental threat categorization criteria were altered in this investigation with the goal of enhancing the precision of the PER evaluation findings. Eir and PER are categorized using the Hakanson potential ecological risk technique the maximum toxicity coefficient in conjunction with the accumulation toxicity coefficient of 7 HMs. First, $PER_u = 150/133 = 1.13$ was the categorization measurement for the unit toxicity coefficient, where 150 represented principal categorization threshold of ERI and 133 was the overall safety factor for the eight contaminants when first published. In this investigation, Cd (30) had the most elevated toxicity coefficient for ERI.

Human Health Risk: Both non-carcinogenic as well as cancer-causing dangers to the safety of humans were associated with soil (Canpolat *et al.*, 2022; Guo *et al.*, 2022). People's involvement with metals by ingestion, inhalation, and dermal absorption was taken into consideration in the determination of both carcinogenic and non-carcinogenic risks. Additionally, the typical per day dosage value (ADD) in all forms was determined employing Eqn. 7-9. According to Jiang *et al.*, (2021); Akakuru *et al.*, (2023b) a typical day contact for each of the above three pathways were computed as follows:

$$ADD_{jk_{ing}} = \frac{C_{jk} \times IngR \times EF \times ED}{BW \times AT} 10^{-6} \quad (7)$$

$$ADD_{jk_{inh}} = \frac{C_{jk} \times IngR \times EF \times ED}{PEF \times BW \times AT} \quad (8)$$

$$ADD_{jk_{der}} = \frac{C_{jk} \times SA \times SL \times ABF \times EF \times ED}{BW \times AT} 10^{-6} \quad (9)$$

In this case, in sample j , C_{jk} was the quantity of HMs k . The total amount of the quotients of ADD of every HM and the accompanying reference dosage were used to construct HQ_i , which was utilized to represent the non-carcinogenic risk of HMs under

multiple environmental pathways. Eqn.10 calculates the total hazard quotient (THQ):

$$HQ_i = \sum = \frac{ADD_i}{R_f D_i} \quad (10)$$

The terms "HQ_i" and "ADD_i" stand for "non-cancer hazard quotient" and "average daily dose measurement of metal consumption by swallowing, inhaling, and skin exposure" respectively. "R_fD_i" stands for "reference everyday intake," which is a rough measure of the everyday consumption that determines the maximum risk list toxic substances in list metals used in people of every ages regardless of age.

$$CR = + \sum ADD j k_i * SF \quad (11)$$

$$TCRI = ECRA \quad (12)$$

The outcome of each heavy metals ADD and its related slope factor was used to determine the CR, which was then utilized to evaluate the carcinogenic danger of persons subjected to heavy metals. As shown in Eqn. (11) and (12), which is the TCRI was displayed.

RESULTS AND DISCUSSION

Heavy Metal Attribute: Table 1 displays data regarding the analysis of HMs values on the ground in the research region. Zn values between 3.76 to 15.36 mg/L were recorded, with average of 8.65 and a SD of 4.34. It was noted that the levels of Zn in the soil impacted by oil contamination surpassed the recommended standard set by the WHO. This implies that this could harm the soil's ecology and have an impact on crop development. When measured against the soil and the ecological condition criteria of (WHO, 2017). For an ideal body, zinc is a crucial necessity. In comparison to a previous study Guo *et al.*, (2022), discovered that soil samples collected in the Tianjin area had zinc concentrations ranging from 16.4 to 123.0 mg/L, with an average of 94.7 mg/L. According to their findings, the presence of Zn poisoning in soil could indicate underlying pollution issues. They also pointed out that the hydrophobic properties of zinc can make it difficult to be detected in soil unless it has been exposed to high levels of oxygen. Despite this, zinc is crucial for the development of plants and overall health of humans. (Ikezam *et al.*, 2021; Pedron *et al.*, 2022). According to the soil's samples collected in the designated area displayed a range of Cu (copper) values from 2.59 to 10.0, with an average value of 6.06 and a SD of 3.06. It is worth mentioning that the WHO has established

a standard limit of 10 for Cu in soil. Lead (Pb) levels in the area were affected by the oil spill, with results showing a range of 0.46 to 2.04 mg/L, with an average of 1.36 mg/L and an SD of 0.69 mg/L. The WHO standard for Pb in soil is 2 mg/L. In this context, it was observed that the Cu are in agreement with the WHO set standard, as the highest value recorded for Cu is 10.0 and Pb is 2 respectively, it is essential to maintain ongoing monitoring soil concentrations of Cu and Pb particularly in regions where such values are closer or reach the upper limit of the standard. Exceeding this limit, as indicated by Antoniadis *et al.*, (2019); Adnan *et al.*, (2022) gastrointestinal distress, renal illness, liver disease, and anaemia are some of the negative health outcomes that may result from their research. Figure 2 shows the prevalence of HMs concentrations in the study region. Differences in chromium (Cr) concentrations (mg/L) were 1.66 to 4.05, with an average of 2.43 and a SD of 1.18. Table 1 presentation of the level of Cr demonstrates that of Cr found in the soil samples in this situation are well above the recommended limit set by the WHO of 0.1 mg/L. This indicates that significant levels of Cr contamination in the soil may pose environmental risks and potentially carcinogenic effects on human health. Related research by Jiang *et al.*, (2021), Kang *et al.*, (2022); Fatoba *et al.*, (2016) highlighted that Cr presents considerable hazards. HM that can have negative effects on living organisms when it is present in high levels. Hence, it is important to take action quickly to address this heightened level of Cr contamination in the soil by implementing appropriate remediation techniques in an effort to lower the possible hazards to the environment and public health. The concentrations of cadmium (Cd) in the samples varied between 6.34 and 20.3 mg/L, with a mean value of 12.1 and a standard deviation of 5.19. Nickel (Ni) levels ranged from 5.75 to 10.23 mg/L, averaging 7.8 with a standard deviation of 1.8. Mercury (Hg) concentrations spanned from 0.00 to 2.06 mg/L, with a mean of 1.10 and a standard deviation of 1.36, as presented in Table 1. The levels of Cd, Ni, and Hg detected in the soil are much higher than the recommended limits set by the (WHO, 2017), which are 0.03, 0.05, and 1.36 respectively. This indicates a significant contamination level which is attributed to anthropogenic activities. In accordance with research conducted by Baltas *et al.*, (2020) reveals that the increased concentrations of Cd, Ni, and Hg in the soil present significant risks to human health and the ecosystem. Hence, these toxic HMs can cause harmful effects on organisms when present in high concentrations. Thus, it is crucial to promptly address and remediate these contaminated levels in the soil to

address the possible environmental and health hazards linked to these contaminants.

Table 1: Concentration of heavy metals in the subsurface soil of the researched area

	Latitude	Longitude	Zn (mg/L)	Cu (mg/L)	Pb (mg/L)	Cr (mg/L)	Cd (mg/L)	Ni (mg/L)	Hg (mg/L)
Okerenkoko									
D1	5° 36'N 45"	5° 25'E 18"	10.74	2.59	1.02	0.86	8.92	9.65	2.06
D2	5° 36'N 17"	5° 26'E 10"	10.83	3.80	1.04	1.66	15.22	6.34	3.3
D3	5° 37'N 02"	5° 25'E 11"	9.8	5.15	1.00	3.06	20.3	8.02	1.45
D4	5° 37'N 10"	5° 25'E 09"	15.36	4.08	1.08	4.05	18.97	7.7	1.78
Benikrukru									
D5	5° 37'N 11"	5° 26'E 29"	5.75	10.0	0.46	1.97	16.39	5.75	0.21
D6	5° 37'N 05"	5° 27'N 34"	3.76	7.22	2.32	3.41	8.34	8.55	0.00
D7	5° 36'N 22"	5° 26'E 10"	5.19	5.77	1.23	2.30	6.34	10.23	0.00
D8	5° 37'N 14"	5° 28'E 08"	7.77	9.57	2.04	2.09	10.4	6.15	0.01
Average			8.65	6.06	1.36	2.43	12.1	7.8	1.10
Min			3.76	2.59	0.46	0.86	6.34	5.75	0.00
Max			15.36	10.33	2.32	4.05	15.22	10.23	3.3
Std			4.34	3.06	0.69	1.18	5.19	1.8	1.36
WHO			0.8	10	2	0.1	0.003	0.05	-0.08

Figure 2a depicts the spatial distribution of Cd in coastal soils near Okerenkoko and Benikrukru, Nigeria. The color gradient, ranging from blue to red, identifies severe contamination hotspots exceeding 20 mg/kg. These elevated concentrations cluster along riverine areas, suggesting pollution from petroleum-related runoff. The map corroborates a mean Cd level of 12.1 mg/kg, which far surpasses WHO standards. This spatial pattern confirms Cd dominance in ecological and human health risks, particularly for children through ingestion. The findings align with Eyankware *et al.*, (2024); Rakiya *et al.*, (2024); Joseph *et al.* (2025) broader regional studies on anthropogenic heavy metal pollution in the Niger Delta. The visualization underscores the urgent need for targeted remediation and integrated risk management. Figure 2b illustrates the spatial distribution of Pb concentrations in the study area, ranging from lower levels (blue, ~0.54 mg/kg) to higher concentrations (red, 2.26 mg/kg). Elevated Pb values cluster near settlements such as Okerenkoko and Benikrukru, indicating localized anthropogenic hotspots likely linked to riverbanks or drainage lines. This pattern underscores Pb as a key contaminant from activities like oil exploration and waste disposal. The findings correlate with regional studies carried out by Owamah *et al.*, (2023); Ahmed *et al.*, (2024) noting low-to-moderate pollution indices and specific anthropogenic sources for Pb, without indicating severe ecological risk. Overall, the map reveals uneven pollution influenced by human proximity and hydrological pathways. Figure 2c displays the spatial pattern of Cu contamination, with CF values between 3.07 and 9.80. These levels signify a transition from moderate to considerable pollution, with the highest concentrations localized in the northeastern sector. The uneven distribution forms distinct hotspots, frequently associated with

documented oil spill locations. This correlation supports the established link between petroleum industry operations and increased heavy metal concentrations in Niger Delta soils. The mapped contamination, is consistent with Esther *et al.*, (2022); Okoye *et al.*, (2022); Akinkpelumi *et al.*, (2025); Benjamin *et al.*, (2025) studies that focused primarily on anthropogenic impact. Furthermore, the proximity of elevated values to river networks suggests hydrology plays a key role in pollutant dispersion within the study sites. The results confirm a continuing ecological threat, emphasizing the need for focused intervention and monitoring. Figure 2d depicts Hg concentrations in coastal soils near Okerenkoko and Benikrukru. A color gradient from blue (0.03599 mg/kg) to red (2.068 mg/kg) reveals elevated Hg hotspots clustered along rivers, particularly around Okerenkoko. Benikrukru lies near both low and high contamination zones, with high levels attributed to petroleum-related activities like spills and flaring. The mean concentrations were revealed to be significantly above typical background values (<0.1 mg/kg). Key hotspots exceed common international guidelines for agricultural soils (0.1–1 mg/kg), indicating potential ecological and health risks through bioaccumulation. This distribution pattern aligns with previous findings from Niger Delta studies carried out by (Fatoba *et al.*, 2016; Anyanwu *et al.*, 2023 Chris and Anyanwu, 2023).

Figure 2e shows distinct contamination gradients, with red hotspots in the northwest and southwest of the study area. These zones, particularly along rivers and near settlements such as Okerenkoko and Benikrukru, indicate zinc concentrations exceeding 13 mg/kg. The elevated Zn levels are primarily linked to petroleum-related runoff from oil extraction in the Niger Delta, augmented by anthropogenic sources

like artisanal refining and industrial effluent. Notably, the average Zn concentration of 9.1 mg/kg surpasses the WHO soil safety guidelines, indicating widespread pollution. This poses significant ecological risks through bioaccumulation in food webs. The spatial distribution underscores Zn's major role in human health risks such as developmental problems in children from soil ingestion and dermal exposure and in broader ecosystem damage, including diminished soil fertility and biodiversity decline.

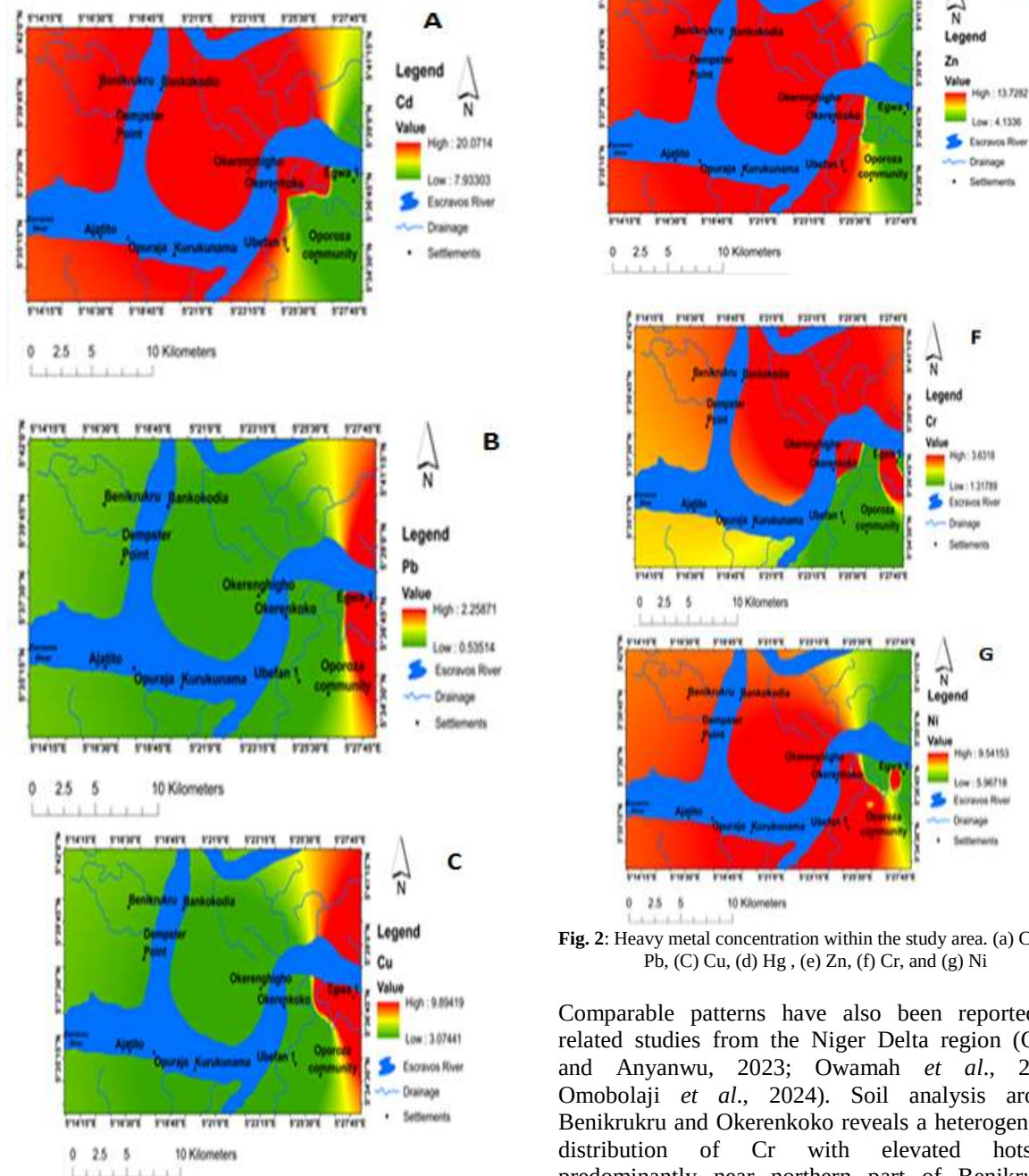


Fig. 2: Heavy metal concentration within the study area. (a) Cd, (b) Pb, (c) Cu, (d) Hg, (e) Zn, (f) Cr, and (g) Ni

Comparable patterns have also been reported in related studies from the Niger Delta region (Chris and Anyanwu, 2023; Owamah *et al.*, 2023; Omobolaji *et al.*, 2024). Soil analysis around Benikrukru and Okerenkoko reveals a heterogeneous distribution of Cr with elevated hotspots predominantly near northern part of Benikrukru. While the lower values (blue/green) appear along

southern river sections and some eastern areas as shown in figure 2f. Measured values range from 1.32 to 6.33, shows concentrations that frequently surpass regional background levels. This spatial pattern indicates hydrological transport via the Escravos River and drainage networks, facilitating Cr deposition across the flood-prone delta. The elevated soil concentrations align with Olawoyin *et al.*, (2012); Fatoba *et al.*, (2016); Omobolaji and Olufemi (2022); Anyanwu *et al.*, (2023) studies which reveals contamination to anthropogenic petroleum-related activities within the study area. Figure 2g illustrates variable Ni concentrations in soil, ranging from 5.07 mg/kg to 5.95 mg/kg. As indicated it was found that higher levels are found within the northwest and southwest part of the study area suggesting localized human sources linked to the Escravos River. This pattern indicates Ni pollution from petroleum activities and waste management in the oil-producing region. Similar studies conducted by Chris and Anyanwu, (2023); Duru *et al.*, (2024); Omobolaji *et al.*, (2024); Ale, (2025) report mild to moderate contamination from anthropogenic inputs, without critical environmental threats. The distribution pattern as well as that of Cd, Hg, Zn, Cr, and Ni revealed shared industrial pollution drivers and comparable, severe, ecological impacts for both heavy metals.

Identification of Heavy Metals Sources: The Pearson correlation matrix for seven heavy metals Zn, Cu, Pb, Cd, Ni, and Hg is presented in the Table 2 below. It was observed that Zn and Cu exhibit a strong positive correlation ($r = 0.674$), indicating that these metals tend to vary together in contaminated soils. Zinc and copper are likely sourced from crude oil contaminants or additives used in the refining process in the region under investigation. Their close

proximity may indicate that they both adsorb organic matter in soils polluted by oil, which would increase the combined toxicity (by, for example, preventing soil microorganisms' enzyme function). These two might be indicators of moderate oil pollution. Although not highlighted for significance, the value indicates that Pb and Cd have a strong positive connection ($r = 0.656$), which is likely at $p < 0.05$ or higher. Petroleum products are thought to contain a lot of lead and cadmium, particularly from older spills involving leaded fuels or industrial oils. Both metals tend to build in topsoil, which increases the likelihood of groundwater leaching or plant uptake, and this association suggests that they may have a common anthropogenic source, such oil leaking. A somewhat favorable and statistically significant relationship exists between Ni and Hg ($r = 0.469$). In contrast to Hg, which can either bind to oil or evaporate from spills, Ni appears to be a well-known indicator of oil contamination (e.g., from vanadyl porphyrins in crude). Though mercury can either evaporate from spills or attach to oil's sulfur constituents. Because of their connection, it is possible that Ni-Hg couples release harmful substances into ecosystems simultaneously following spills, especially during transitions from the marine to the terrestrial (such as coastal oil spills). Human activities appear to be the principal cause of HMs detected on soil. This finding provides more evidence that oil-polluted soils exhibit clustered metal tendencies. Results from other studies Fu *et al.*, (2014); Fatoba *et al.*, (2016); Canpolat *et al.*, (2021) did not corroborate with the current studies. These associations warrant additional study because they may shed light on the soil's HM contamination problem, including its distribution, origins, and potential dangers.

Table 2: Pearson correlation coefficient of heavy metals concentration in Okerenkoko and Benikrukru

	Zn	Cu	Pb	Cr	Cd	Ni	Hg
Zn	1.000						
Cu	0.674*	1.000					
Pb	-0.580*	-0.324	1.000				
Cr	0.170	0.373	0.353	1.000			
Cd	-0.445*	-0.427*	0.656	0.164	1.000		
Ni	0.103	0.054	0.167	0.002	-0.546*	1.000	
Hg	0.387	0.185	-0.617*	-0.496*	-0.836**	0.469*	1.000

Denotes ** statistical significance at the 0.05 probability threshold and * signifies statistical significance at the 0.01 probability threshold. Suggests ** a robust or strong relationship

Contamination Factor (CF): The results of the contamination factor (CF) assessment in the researched area as shown in table 3, indicate that only 1.0% of the samples have CF values below 1, signifying a low level of pollution. However, there is an exception with Ni at sample site D8, where a

severe level of pollution was observed. Approximately 67.9% of the samples have a contamination factor (CF) between 1 and 3, indicating moderate pollution levels, except for Ni. A small percentage (4.4%) of samples has CF values between 3 and less than 6, indicating a considerable

level of pollution. Interestingly, 26.7% of the samples exhibit CF values higher than 6, pointing towards a very substantial level of pollution.

Pollution Load Index: Table 3 displays the PLI results, which show that all samples, with the exception of those from sampling sites D1 and D2, were within the range of 1. Since most of the samples were of good quality, this indicates that there are only minute quantities of contaminants here because of human activity. With a median of 7.9E-09 and a range of 9.11E-07 to 3.22E-08, it is possible to estimate the degree of pollution from the predicted PLI values, which are affected by the possible contributions of different compounds in a given location. In ecological matrix analysis, PLI is used as a versatile technique to determine the degree of pollutant load index (Ma *et al.*, 2022; Eyankware *et al.*, 2022a).

Modified Degree of Contamination (mCd): Table 3 presents the findings of the study, indicating that the majority of subsurface samples in the researched area had mCd values below the 1.5 threshold. With the exception of subsurface sample site D8, which recorded levels above 4 due to the oil spill effect of anthropogenic activities, the region appears to be mostly free of pollution. The data suggests that there is a high level of pollution in the area. Hoque *et al.*, (2023) identified heavy metal contamination in the soil of subtropical river basins, which supports these

findings. In addition, further examination of the mCd plot showed that the middle value was 0.81, with the extremes being 5.22 and 0.55. This conclusion aligns with the results of the PLI analysis conducted in this study.

Geo-accumulation Index (Igeo): Table 3 shows the Igeo results, which supported the hypothesis that half of the sample (50.0% to be exact) had contamination levels between zero and one, according to the study's conclusions. Furthermore, 10% were found within the 2 range, indicating moderate contamination; 10% were found within the 4 range, indicating low contamination; and 30% were found within the 5 range, indicating significant contamination. Pollution in the region may have been caused by human activities, like oil refinery leaks that have damaged the soil and reduced agricultural yields. With a maximum of 5.78 and a minimum of 0.34, the Igeo values presented by Hoque *et al.*, (2023) indicated a median value of 2.58 throughout the study region. Soil Cd levels are rising, which indicates soil toxicity is increasing and, consequently, Igeo levels are rising, even if the CF and PLI results are principles on a regional level. While earlier research by Royer *et al.*, (2023) found higher Igeo values, the current study's findings show varying degrees of contamination in the affected soils, which corresponds with the findings of (Adnan *et al.*, 2022; Ma *et al.*, 2022; Mahvi *et al.*, 2022).

Table 3: Results of CF, PLI, mCd, Igeo, and PER

	CF							PLI	mCd	Igeo
	Zn	Cu	Pb	Cr	Cd	Ni	Hg			
Okerenkoko										
D1	0.6935	0.5697	7.9E-03	0.0917	2.8909	0.6310	0.5698	9.83E-07	0.61	1.43
D2	0.8782	0.9035	1.9E-03	0.9810	0.8083	0.5497	0.5451	3.22E-08	0.55	1.51
D3	0.6822	1.0301	0.2506	0.6228	0.7625	0.9561	0.4870	6.28E-08	0.61	5.78
D4	1.0134	0.9583	0.6559	0.6941	2.4158	0.9561	0.5217	9.11E-07	0.96	1.03
Benikrukru										
D5	0.8547	0.8785	0.3994	0.5500	1.6858	0.4152	0.5294	6.7E-08	0.67	4.13
D6	0.7020	4.4422	0.7558	0.7917	0.9333	0.8576		6.91E-07	1.41	2.23
D7	0.2304	0.4175	0.8402	2.1471	1.7626	0.8136		7.93E-08	1.04	5.52
D8	0.9527	0.9583	0.6086	1.0693	0.8494	26.6957	1.0000	4.49E-08	5.23	0.34

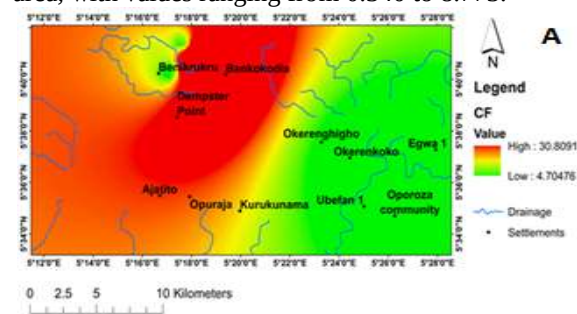
Analysis of the Contamination Factor (CF) in Table 3 shows a clear spatial gradient in pollution levels across the sampling sites. Site D8 registers the most severe contamination with a CF of 33, establishing it as a primary area of concern. Conversely, sites D2, D3, and D5 present the lowest CF readings (around or below 5), reflecting negligible contamination. The CF values for sites D4, D6, through D7 fall within 6 to 9. This non-uniform distribution suggests localized contamination sources, with D8 and D7 likely influenced by significant anthropogenic activity; the low levels at D2, D3, and D5 may indicate

background conditions or effective natural attenuation. The substantial range in CF values highlights significant site-to-site heterogeneity, a finding consistent with other regional contamination studies. The composite plot for mCd shows a clear spatial decline across the eight monitored locations. A pronounced pollution hotspot is evident at site D8, which records the maximum mCd value near 6.0 and also demonstrates a substantially high mCd level above 5.0. Conversely, the lowest degrees of integrated pollution are observed at sites D1, D2, D3, D4, and D5, where mCd values fall at or below 1.0.

Sampling point D6 present intermediate mCd scores, spanning from approximately 1.5. This spatial configuration indicates a non-homogenous distribution of contaminants, with a significant contamination apparently centered on the D6-D8 area. The severely elevated mCd at these proximal sites implies a synergistic impact from several pollutants, potentially originating from concentrated human activities like manufacturing, or wastewater discharge in their vicinity. The minimal mCd readings at the opposite end of the sampling transect likely correspond to baseline environmental conditions or zones shielded from major pollution sources. The broad spectrum of mCd results, extending from near-background to critically high levels, confirms considerable spatial disparity in cumulative soil pollution. This observed heterogeneity is consistent with prior research on regional soil quality, including studies by (Mahvi *et al.*, 2022). Sites D3 and D7 exhibited the highest Igeo values, reaching approximately 6, which indicates a classification of extreme geoaccumulation. In contrast, the lowest values were recorded at sites D4 and D8 (approximately 1 and below 1, respectively), corresponding to conditions ranging from uncontaminated to background levels. Sites D5 and D6 displayed intermediate values, between 2.3 and 4, while D1 and D2 registered lower to moderate accumulation levels, around 1.5. This spatial distribution implies that D3 and D7 represent core zones of significant anthropogenic impact. This likely result from their proximity to emission sources. The near-background Igeo levels at D4 and D8 denote areas with minimal human-derived contamination, suggesting limited influence from contributing factors. The moderate and variable accumulation observed at D1, D2, D5, and D7 reflects a contamination gradient commonly documented in environmental media such as sediments or soils. Such gradients typically arise from differences in distance from sources, as well as variations in transport dynamics, dispersion, and geochemical attenuation processes across the study area. For PER sites D1 and D4 recorded the most elevated PER levels, identifying them as zones of peak concentration. Conversely, locations D2, D3, D6, and D8 returned the lowest readings, signifying negligible presence. Intermediate values were documented for sites D5 and D7. This spatial pattern suggests that D1 and D4 are likely focal points of influence, potentially due to proximate emission sources or localized environmental conditions. The minimal levels observed at D2, D3 through D8 indicate regions with reduced exposure to contributing factors. Such a distribution of PER is consistent with established environmental gradients, where disparities in source

strength, dispersion, or attenuation processes create measurable site-to-site differences. The CF distribution map in Figure 3a shows that the western part of the research area exhibits a greater concentration of CF cases. The CF values range from 0.41 to 26.7, with 1.0 being the midpoint. Most variables have lower values, indicating relatively lower pollution levels in those areas. This outcome reflects research conducted by Bankole *et al.*, (2024) in Nigeria which indicates that the surroundings of the oil spill locations may be responsible for the similarities in the findings. Furthermore, petroleum plant site's proximity to an area that is heavily anthropogenically influenced adversely affects soil quality, plant growth, and the mechanisms that allow oil to escape into the surface and subterranean soil.

Figure 3b shows the spatial spread of PLI summarizing combined heavy metal pollution in soils near Okerenkoko and Benikrukru, Delta State. The map shows a sharp pollution gradient, with PLI values ranging from 5.12 to 8.63. The highest level was recorded in the North-west marking a severe multi-metal hotspot attributed to nearby oil-related and artisanal refining activities in the Niger Delta. Such contamination degrades soil, hinders plant growth, and allows toxins to enter water systems, threatening ecosystem and human health through food and water. Based on the mCd distribution in Figure 3c, the western part of the study area exhibits higher overall heavy metal contamination, as indicated by elevated mCd values. These increased concentrations are primarily attributed to anthropogenic activities at the sites. Regional mCd values range from 0.556 to 5.017. When assessed against the critical threshold of 1.5, which signifies a shift from very low to low-moderate contamination, the data reveal that the eastern zones consistently show lower readings. This pattern indicates a comparatively reduced aggregate level of heavy metal pollution in the eastern sections. Figure 3d shows the spatial spread of Igeo which reveals a distinct gradient of soil contamination in the study area, with values ranging from 0.340 to 8.773.



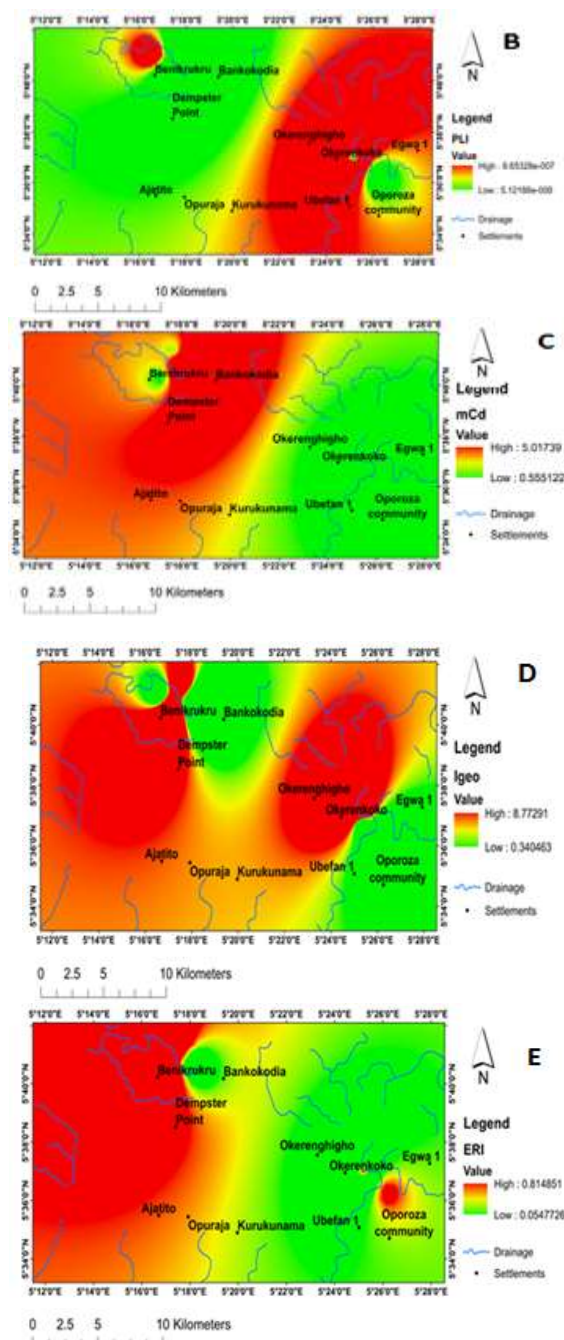


Fig. 3: Spatial patterns of; (a) CF, (b) PLI, (c) mCd, (d), Igeo, and (e) ERI

The most intensely polluted multi-metal hotspots are however located in the North-western zone, this severe accumulation is linked to prolonged oil-related activities, including spills and artisanal refining. Such contamination degrades soil quality, stunts plant growth, and enables harmful metals to infiltrate water systems. Figure 3e displays a distinct spatial gradient of the ERI. The Northwestern zones exhibit the highest potential ecological risk, with a maximum

value of 0.814851, marking them as areas of significant environmental concern primarily due to intensive local anthropogenic pressures. Conversely, the central and eastern sections of the study area consistently show lower ERI readings, with a minimum value of 0.0547726. This contrast indicates a comparatively reduced aggregate ecological risk from heavy metals in the eastern regions.

Potential Ecological Risk Index (PERI): Using a specific methodology and modifying the minimum threshold, the oil refinery facilities' ecological risk assessment was carried out.

Table 4 shows the results, which detail the distinct ecological hazards that may be linked to each HM. In order of average Ecological Impact Rating (Eir) values revealed the presence of the following heavy metals (HMs): Cd, Cu, Ni, Pb, Cr, Hg, and Zn. With ERI values of 92.27 for Cd and 50.77 for Cu, these elements indicate a moderate to elevated ecological risk in the study area. Concentrations of these two metals were much higher than those of the others; they were also much more able to dissolve in soil and shown a strong poisonous effect. The health of humans could be affected if this is swallowed or breathed in massive amounts. Before this study, Mahvi *et al.*, (2022) similarly found that Hg presented a notable ecological hazard, while Cd was determined to have a moderate soil ecological risk in Kerman, Iran, caused by a variety of land uses. Though consistent with PLI, CF, and Igeo findings in the same field, the current study's findings contradict earlier findings. There was little contamination, according to Wang *et al.*, (2021), and these findings are in the conclusions with those of Kuber *et al.*, (2019). The research area's PER spatial distribution is shown in Figure 3a, while the composite plot of PER values across the region is shown in Figure 3e. These graphics show the PER values in the region clearly; they go from 0.9 to 12.79, with 6.8 being the median, and there are no abnormalities.

Human Health Risk Assessment: Table 5 provides a comprehensive overview of the human health risks associated with heavy metal (HM) exposure in contaminated soils from selected communities in the oil-producing regions of the Niger Delta, Nigeria. The HQ values represent the potential for non-cancer health effects from individual HMs, with a threshold of 1 indicating acceptable risk (i.e., no anticipated adverse effects). Values exceeding 1 suggest a likelihood of harmful outcomes over prolonged exposure. The THI aggregates these across all metals and pathways, providing an overall risk profile. For children

The THI of 8.08E+00 (8.08) far exceeds 1, signaling substantial non-carcinogenic risks. This group appears most vulnerable, primarily through oral ingestion and respiratory inhalation. For instance; Cd (HQ oral: 5.56E-01, dermal: 4.79E-01), can be linked to kidney damage and developmental issues. Pb (HQ oral: 4.48E-01, inhalation: 6.65E-01), can be associated with neurological impairments, Ni (HQ oral: 4.52E-01) and Cu (HQ oral: 3.60E-01, inhalation: 3.48E-01), which can cause respiratory

and gastrointestinal problems respectively (Jiang *et al.*, 2021; Canpolat *et al.*, 2022).

However, dermal contact plays a lesser but notable role for Cd and Cu. The elevated totals for certain metals (e.g., Cu at 6.32E+00) align with behavioral factors, supporting calls for targeted protections in similar polluted subtropical basins (Hoque *et al.*, 2023).

Table 4: Potential ecological risk posed by heavy metal contamination in the soil of the research area

Sample	Ti*Pi						PER	
	Zn	Cu	Pb	Cr	Cd	Ni	Hg	
Okerenkoko								
D1	0.69	2.85	0.04	0.18	16.73	3.15	2.79	116.43
D2	0.87	4.52	0.01	1.96	14.25	2.75	2.81	56.17
D3	0.68	5.15	1.25	1.25	6.88	4.78	3.48	55.47
D4	1.01	4.79	3.28	1.39	7.48	4.71	1.87	108.53
Benikrukru								
D5	0.85	4.39	1.20	1.10	10.57	2.08	1.18	81.37
D6	0.70	22.2	3.78	1.58	8.00	4.29	–	60.55
D7	0.23	2.08	4.20	4.29	12.88	4.07	–	67.75
D8	0.95	4.79	3.04	2.14	15.48	13.48	–	49.88
Mean	5.98	50.77	16.8	13.89	92.27	39.31	12.13	

Table 5: Non-cancer and cancer risk assessment of adults and children under different exposure routes.

	Oral ingestion		Respiratory inhalation		Dermal contact			
	Children	Adult	Children	Adult	Children	Adult	Children	Adult
Hazard quotient of each HMs							HQ	
Zn	2.94E-02	4.16E-03	8.15E-03	4.42E-03	2.04E-03	1.16E-03	3.96E-02	4.53E-01
Cu	3.60E-01	5.04E-02	3.48E-01	1.88E-01	1.06E-01	6.02E-04	6.32E+00	2.39E-01
Pb	4.48E-01	6.29E-02	6.65E-01	7.08E-01	3.50E-02	6.15E-02	1.58E-01	6.14E-01
Cr	9.09E-02	2.05E-02	2.64E-10	1.43E-10	9.38E-07	5.34E-02	9.09E-02	5.55E-02
Cd	5.56E-01	8.14E-02	1.60E-09	8.69E-10	4.79E-01	2.73E-01	3.50E-02	3.54E-01
Ni	4.52E-01	6.33E-02	1.21E-01	6.56E-02	3.45E-03	1.97E-03	1.76E+00	1.32E-01
Hg	2.60E-03	4.09E-01	8.06E-04	4.37E-02	3.01E-04	1.72E-04	3.71E-03	9.74E-03
THI	–	–	–	–	–	–	8.08E+00	8.57E-01
Cancer risk of each HMs							CR	
Zn	–	8.32E-04	5.32E-06	–	–	–	8.32E-04	5.32E-06
Cu	3.54E-05	2.39E-06	2.34E-08	5.47E-06	7.30E-05	4.16E-08	1.08E-04	2.94E-05
Pb	–	–	2.10E-09	1.13E-07	–	–	2.10E-09	1.13E-07
Cd	1.37E-06	1.44E-05	1.32E-05	7.71E-07	–	–	1.46E-05	1.52E-05
Ni	1.33E-06	3.54E-08	3.54E-10	9.83E-07	–	–	1.33E-06	1.02E-06
TCR							9.56E-04	5.21E-04

In contrast, for adult the THI of 8.57E-01 is below 1, indicating generally acceptable non-carcinogenic risks. However, specific pathways show elevated HQs, such as Pb via inhalation (7.08E-01) and Cd via dermal contact (2.73E-01). This suggests occupational or daily exposures through farming or soil handling but could still pose localized concerns; though overall lower than for children due to reduced intake rates and body weight differences. These results is in line with the result obtained from soil quality indices, which indicated moderate to high HM pollution (e.g., CF values of 1–3 for most samples, with Ni as a key outlier contributing to higher contamination in western areas). The PER analysis earlier in the study highlighted moderate to high ecological risks from Cd (92.27) and Cu (50.77),

which correlates with the high HQs observed here, implying that ecosystem degradation translates directly to human health threats. Anthropogenic sources, such as oil spills and illicit refining, are implicated as primary drivers, consistent with spatial patterns showing higher risks in industrialized zones. These results align with the study's soil quality indices, which indicated moderate to high HM pollution (e.g., CF values of 1–3 for most samples, with Ni as a key outlier contributing to higher contamination in western areas). The PER analysis earlier in the study highlighted moderate to high ecological risks from Cd (92.27) and Cu (50.77), which correlates with the high HQs observed here, implying that ecosystem degradation translates directly to human health threats. Anthropogenic

sources, such as oil spills and illegal refining, are implicated as primary drivers, consistent with spatial patterns showing higher risks in industrialized zones.

However, this runs counter to the findings of a research by Li *et al.*, (2022) on soil contamination and health hazards, which indicated that there were few non-carcinogenic dangers for adults.

TCR for cumulative exposure, with acceptable levels in the study typically ranges from $1\text{E}-06$ to $1\text{E}-04$ (i.e., 1 in 1,000,000 to 1 in 10,000 lifetime cancer cases). Such values above $1\text{E}-04$ warrant concern and potential intervention. For instance, the cancer risk index in children of $9.56\text{E}-04$ (9.56×10^{-4}) exceeds the upper threshold, indicating an unacceptably high cancer risk. Major contributors include Zn (total CR: $8.32\text{E}-04$, primarily oral), Cu ($1.08\text{E}-04$ across routes), and Cd ($1.46\text{E}-05$). Oral and dermal pathways dominate, reflecting soil-to-mouth transfer in contaminated play areas. In adults the TCR of $5.21\text{E}-04$ (5.21×10^{-4}) is also elevated, though slightly lower than for children. Zn ($8.32\text{E}-04$ oral) and Cu ($2.94\text{E}-05$) are prominent, with inhalation adding minor contributions from Pb and Cd. The carcinogenic profile reinforces the non-carcinogenic findings, with metals like Cd, Ni, and Pb known carcinogen showing risks tied to long-term exposure. This echoes the Igeo and mCd results, which predicted significant contamination shifting west to east, and the PER emphasizing Hg and Cd as high-risk elements. The study's correlation matrix (e.g., strong Zn-Cu association, $r = 0.674$) suggests co-occurrence from shared pollution sources, also amplifying combined risks. In addition, these children's higher risks align with behavioral factors, supporting calls for targeted protections in similar polluted subtropical basins (Hoque *et al.*, 2023). The dominance of ingestion as an exposure route corroborates findings from Jiang *et al.*, (2021) and Canpolat *et al.*, (2022), where oral intake drove risks in HM-contaminated sites. These outcomes are also consistent with regional studies, such as Mahvi *et al.*, (2022) in Iran and Adnan *et al.*, (2022), which reported elevated contamination in industrial soils, and Kuber *et al.*, (2019) on ecological hazards from Hg and Cd.

Conclusion: This research establishes essential baseline information on heavy metal pollution in surface soils of lesser-studied, oil-affected communities in the Niger Delta, confirming strong evidence of human-induced contamination linked mainly to oil-related operations. It advances scientific understanding through the combined application of various pollution indices and risk evaluation frameworks, revealing contamination ranging from moderate to extremely high, where cadmium and

copper stand out as primary contributors to ecological and human health threats. The findings underscore the greater susceptibility of children to non-carcinogenic and carcinogenic effects, predominantly through soil ingestion. Major accomplishments involve pinpointing spatial contamination hotspots and metal source relationships, thereby aiding effective environmental decision-making. Immediate suggestions encompass enhanced regulatory oversight, ongoing surveillance, and the adoption of specific remediation approaches like phytoremediation to reduce persistent hazards and rehabilitate soil health.

DECLARATIONS

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): Author(s) 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 influence the work reported in this paper.

Declaration of Data Availability Statement: Data are available upon request from the first Author.

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