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ORIGINAL PAPER

Geochemical implications of hydrocarbon exploitation on the soil around the crude oil-producing area of Uzere, Niger Delta region, Nigeria

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Abstract

The crude oil sector in Nigeria continues to be a significant source of income and foreign currency. However, operations related to oil exploration and production have the potential to seriously alter the environment, having an impact on ecosystems, water bodies, and human life. In many cases, pollution indices are viewed as a useful instrument for thoroughly evaluating contamination levels. Additionally, they may have a significant impact when evaluating soil quality and the forecast of long-term ecosystem viability, in the case of farmlands in particular. Atomic absorption spectrometry (AAS) was used to examine the heavy metal contents. Potential ecological risk index, geoaccumulation index, Nemerow pollution, pollution load index, contamination index (CI), and metal pollution index were the seven indicators employed in the study. The concentration of heavy metals such as manganese (Mn), iron (Fe), copper (Cu), zinc (Zn), nickel (Ni), lead (Pb), chromium (Cr), and arsenic (As) ranges from 11.9 to 184.1, 920 to 8870, 1.1 to 9.9, 9.7 to 60.4, 0.001 to 0.001, 2.4 to 34.7, 2.2 to 11.5, and 0.001 to 0.001 mg/kg, respectively. The correlation matrix showed that there were positive correlations between Mn and Ni, Fe and Cu, Zn, Pb, Cr, Cu and Cr, Zn and Pb, Cr, and Pb and Cr, while a negative correlation exists between Cu and Ar. PCA showed that 75% of the samples in PC1 have loadings; in PC2, 50% of the parameters have loadings; in PC3, 25% of the parameters have loadings; and in PC4, 12.5% of the entire parameter has loadings. Findings from the aforementioned indices revealed that the analyzed soil samples are polluted.

Keywords Crude oil · Spillage · Groundwater · Swamp · Delta · Nigeria

Introduction

Crude oil, as well as the exploration and production processes related to it, has the biggest effects on both the environment and world politics (Ogbeibu and Omoigberale 2005; Ogbeibu and Omoigberale, 2007; Omofonmwan and Odia 2009; Igwe et al. 2021; Omoigberale and Ogbeibu, 2010). A hamlet in the Niger Delta called Uzere is home to pipeline networks, flow stations, and oil fields (see Fig. 1). Drilling mud, generated water, drill cuttings, and hydrocarbons are just a few of the components that are released into the environment during the extraction of crude oil (Zheng et al. 2016). These materials have an impact on the water quality and aquatic flora and fauna (Ayotamuno et al. 2006; Eyankware and Obasi 2021; Allen et al. 2014). Excellent soil quality is an essential necessity for the sustainability of healthy environmental growth and development. According to Tubonimi et al. (2010) and Eyankware et al. (2020), analyses of the effects of oil exploration on soil and water quality have been conducted in the study region previously (Mogborukor, 2014; Eyankware et al., 2020; Arise et al., 2013). The assessment of groundwater quality often seems incomplete without a soil quality assessment because once the soil is contaminated, the groundwater is usually affected through natural exchange processes existing between the soil and the groundwater (Akinseye et al. 2023; Eyankware and Ephraim, 2021; Obasi et al. 2015; Akakuru et al. 2023).

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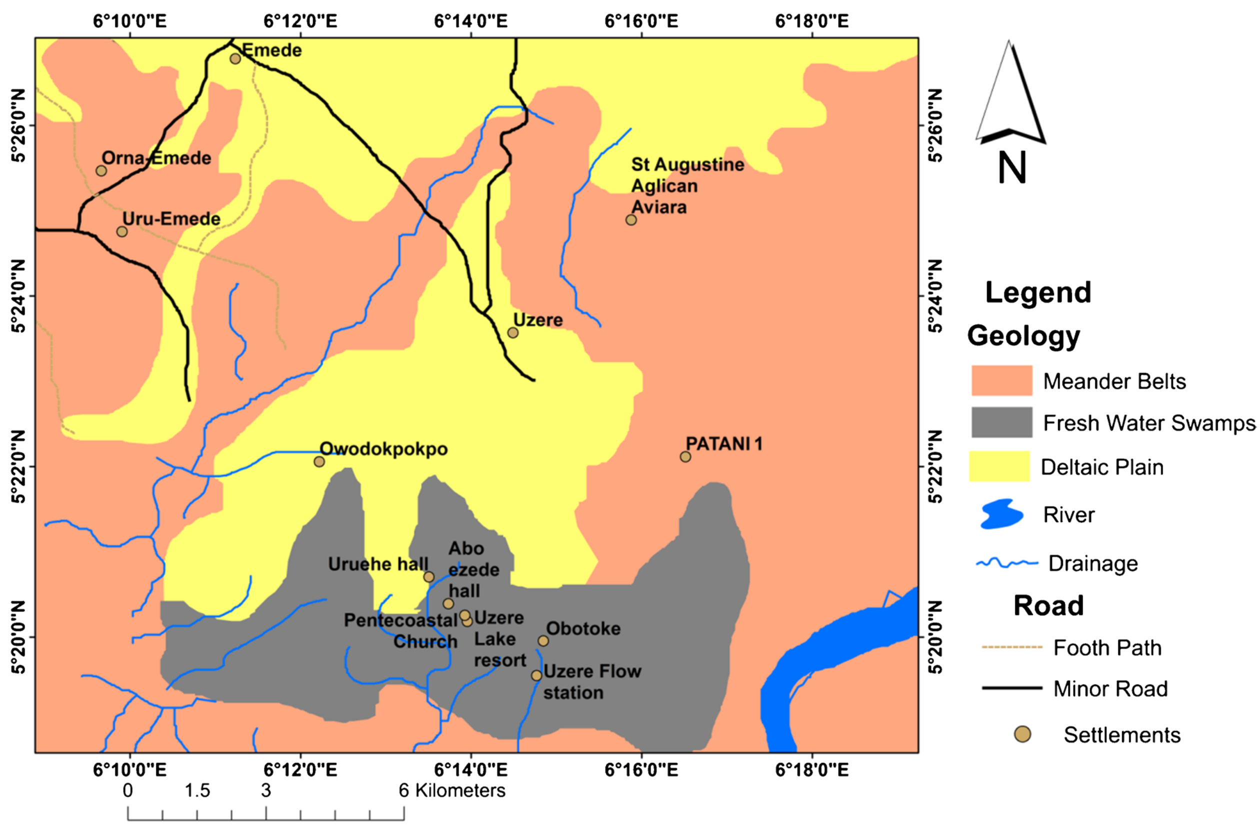

Fig. 1 Geology map of the study area showing soil sampling points

Routine monitoring and evaluation of soil quality in oil-producing towns have become crucial because of the escalating pace of oil exploration and production activities and environmental degradation in the Niger Delta region of Nigeria (Eyankware et al., 2022; Igwe et al. 2022; Eyankware and Obasi 2021; Akakuru et al. 2022; Opara et al. 2022). On the other hand, heavy metals can enter soil and river systems from either natural or anthropogenic sources (Eyankware and Obasi 2021; Reza and Singh, 2010; Eyankware et al., 2021; Esi, et al. 2025). Several researchers have studied heavy metal contamination in various rivers and soils with respect to industrial, municipal, and domestic pollution (Onwe et al. 2022; Eyankware, et al., 2024; Obasi et al. 2022; Igwe et al. 2022; Ogwah and Eyankware 2020; Opara et al., 2015). Nwilo and Badejo (2001) conducted a study on the management of oil spill issues in the Niger Delta. They found that 2,369,470 barrels of oil were spilled on the environment as a result of 4647 events between 1976 and 1996, which were brought on by pipeline corrosion and vandalism, human mistakes, equipment failure, and sabotage. Enegide and Chukwuma (2018) estimated the amount of oil spilled into the Niger Delta region from 1976 to 2014, as well as the resulting heavy metal exposures of the local population. According to their findings, the research area is always subjected to a higher rate of oil spills, with approximately 3.1 million barrels of crude oil enriched with heavy metals leaked in this region between 1976 and 2014. Chukwuemeka et al. (2019) investigated one of the Niger Delta regions to determine the concentrations, distribution, and human health risk of several heavy metals in soil samples from crude oil-damaged agricultural soil in Ogoniland, Nigeria. Large amounts of pollutants have leaked into the soil due to industrialization and population increases (Ulakpa and Eyankware 2021; Osisanya, et al. 2024; Eyankware and Obasi 2021). Heavy metals linked to crude oil spills are naturally present in soils (Ojanuga et al., 1996), but monitoring is necessary to understand metal load (Odu et al., 1988), as elevated accumulation has direct negative effects on people and the environment (Agbozu et al., 2007). Furthermore, the extent to which crude oil spills can be remedied depends on the type, efficacy, and cost of available remediation techniques (Ram et al., 1993; Odesa, et al., 2023; Chu and Cha, 2003; Urum et al., 2005; Eyankware and Akakuru 2022). Statistical hypothesis testing, regression models, and regional models, among other methods, were employed by scientists to look at soil pollution levels (Barbe et al.2014; Braşovulescu et al., 2021). Environmental factors and soil variables are precisely interpreted by it. Although anthropogenic sources of heavy metal deposition can significantly raise the concentration of these metals, natural ecosystems typically have modest concentrations of these metals (Klake et al. 2012). The primary point and non-point sources of heavy metal contamination in surface water systems include home wastewater, agricultural runoff, industrial effluents, and urban areas. These sources contribute significantly to the inorganic ion and heavy metal concentrations in surface water systems (Pandey and Singh 2017). Thus, a longstanding focus of environmental studies has been the examination of the causes and impacts of pollutant entry in surface water systems (Klavinš et al. 2000; Prasanna et al. 2012; Bhardwaj et al. 2017; Kumari and Sharma 2019; Mandal et al. 2019). The content of heavy metals in sediments was examined by Zhang et al. (2016). Furthermore, the assessment of ecological risk requires knowledge about overall heavy metal concentrations as well as the fractions that may be accessible to plants. To some extent, heavy metals can be stored and accumulated in the soil surrounding disposal sites. Grazing occurs all around the landfills; therefore, through the food chain, metals may move from the soil to grasses, grazing animals, and ultimately humans. Because of the possible risk that metal toxicity poses to environmental receptors, this condition is quite concerning to humans. The present study of soil was carried out to assess the concentration of heavy metals in soil within the study area, with a view to achieve the following objectives: to assess heavy metal pollution in soil, to investigate the degree of contamination and pollution using pollution indices as contamination factor (CF), contamination degree (CD), pollution load index (PLI), and geoaccumulation index (Igeo), and to identify the similar pollution sites using cluster analysis, and lastly the present study provides the first and useful data for the heavy metal in soil and contamination status within the study area.

Location, climate, and topography

The research area is located in the Uzere community, which is part of the Isoko metropolis in Delta State's south-south geopolitical zone. The Niger Delta region is a significant oil and gas producer. The Isoko metropolis is divided into the Isoko-South and Isoko-North major local governments, with headquarters in Oleh and Ozoro. It is located in Delta State between longitudes 06° 01′E and 06° 07′E and latitudes 05°14′N and 05°28′N (Fig. 1). Isoko -South L.G.A. is an Isoko indigene who lives in the southern part of Delta State. It has a total population of 235,147 people and covers an area of approximately 668 km^2 (258 sq mi). 115,980 females and 119,167 males are present, according to the Delta State population census from 2006. The study area covers a low-lying section of the larger Niger Delta Basin, interspersed with streams, canals and rivers. It is located in a region of deciduous and evergreen forests, with patches of mangrove forest, as well as a forest reserve along the Aviara clan area. Similarly, the research area is in the tropical rain forest area of the Niger Delta. The region experiences high rainfall and high humidity most of the year. The climate is equatorial and is marked by two distinct seasons: the dry and rainy seasons. The dry season lasts from about November to April and is significantly marked by the cool "harmarttan" dusty haze from the north-east winds. The rainy season spans May to October with a brief dry spell in August.

Materials and method

A total of thirteen (13) soil samples were collected within the study area as shown in Fig. 1, at intervals of 20 km. Towns such as Uzere, Patani, Uru-Emede, Orna-Emede, Aviara, and Owodokpokpo were used to collect control samples. Each sampling point yielded a minimum of three composite soil samples. A steel auger was used to collect soil samples from a depth of 0–15 cm into transparent plastic bags. In the laboratory, samples were air-dried for several days by spreading them out on transparent plastic on a bench. They were then sieved at 2 mm and repackaged in clear plastic bags until they could be analyzed. Twenty grams sieved air-dried soil samples were placed in 250 cm^3 conical flasks that had been thoroughly cleaned and 100 cm^3 of 0.5 M nitric acid was added. A mechanical shaker was used to mechanically shake the flasks for at least 30 min. The materials were filtered through ashless Whatman filter paper into 100-cm^3 plastic bottles. Before adding known amounts of manganese (Mn), iron (Fe), copper (Cu), zinc (Zn), nickel (Ni), lead (Pb), chromium (Cr), and arsenic (As) to some control samples, they were tested for background target analytes. This was done to see how well the extraction procedure worked. The differences between the baseline concentrations and the concentrations of the spiked samples were what determined the percent recoveries. In preparing the solutions used to spike the samples for cadmium, a general-purpose reagent containing cadmium nitrate with a minimum purity of 99% was utilized. An analytical grade of lead nitrate salt and analytical grade granules of copper and zinc were used to make the solutions that were spiked with lead, copper, and zinc. A reagent blank for each metal was likewise created and run through the whole process before being used in the sample determination. Analysis-grade metals and metal salts were used to create calibration curves. The amounts of cadmium, copper, lead, and zinc were found using a Varian Techtron AA6 atomic absorption spectrophotometer and metallic hollow cathode lamps that went with it. The fuel was acetylene gas, and the support was air. In every case, an oxidizing flame was used. The concentrations of four metals were calculated using calibration curves. To zero the instrument, a reagent blank was employed. The aspiration of standard solutions came next, followed by the aspiration of soil sample extracts.

Soil pollution indexes calculation

The occurrence of heavy metal in soil was computed using the following: potential ecological risk index, geoaccumulation index, contamination factor, and Nemerow pollution.

Data analysis

Data were examined using the SPSS statistics software to get Pearson correlation analysis and Principal component analysis (PCA).

Potential ecological risk index

The potential ecological risk index (PERI) is an assessment tool designed to evaluate the risks that heavy metals may pose to the environment, focusing primarily on soil and sediment (Hakanson, 1980). It analyzes the toxicity and concentration of various contaminants to gauge their potential impact on ecological systems. By considering factors like contamination levels and ecological sensitivity, PERI facilitates the identification of high-risk areas and the prioritization of remediation efforts.

$$RI = \sum_{i}^{n} E_r^i \tag{1}$$

The potential ecological risk index was first proposed by Hakanson (1980)

$$E_r^i = C_f^i * T_r^i = T_r^i * {}^{C_i}/_{C_b} \tag{2}$$

where E_r^i represents the ERI of metal i^{th}; T_r^i is ith metal response factor to toxic. The C_f^i is the contamination factor. Ci represents the metal concentration and Cb represents the background/target value.

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 are obtained from (Eq. 5). To quantitatively express E_r^i, five criteria grades were employed: $E_r^i < 40$, $40 \leq E_r^i < 80$, $80 \leq E_r^i < 160$, $160 \leq E_r^i < 320$, and ≥ 320 signifying low, moderate, considerable, high and very high risk, respectively (Hakanson 1980; Ogunkunle and Fatoba 2013; Riyad et al. 2015). The total of the individual potential ecological risk factors is used to calculate the potential ecological risk index for different heavy metals in soil. The vulnerability of various biological populations is represented, as are any threats posed by heavy metals. All of the detected heavy metals' potential ecological risk indices were calculated using (Eq. 6).

The geoaccumulation index (Igeo)

The geoaccumulation index (Igeo) serves as a quantitative tool for evaluating the level of heavy metal contamination in soils and sediments. It contrasts present metal concentrations with pre-industrial benchmarks to gauge the impact of human activities. By classifying pollution into different categories, from unpolluted to highly polluted, Igeo aids in assessing the seriousness of contamination and informs environmental management strategies. The calculation formula for Igeo is outlined in Eq. 3

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

As proposed by Muller, (1979), see Eq. 7.

Here, Bn is the geochemical background concentration (mg/kg) and Cn is the element n measured concentration (gg-1).

Nemerow pollution

The Nemerow pollution index serves as a comprehensive metric for evaluating the overall pollution levels within an environment by amalgamating various pollution indices. It considers both the average and peak pollution levels of different contaminants, thereby offering a thorough evaluation of environmental quality. This index is especially beneficial for pinpointing regions with serious pollution concerns and prioritizing them for remediation initiatives. The calculation of NP can be performed using Eq. 4.

$$NP = \sqrt{{}^{(p_{ave}^1 + p_{max}^2)}/_2} \tag{4}$$

As proposed by Ogundele et al. (2020).

ρ_{ave} and ρ_{max} are the average and maximum values of the single pollution index (SPI) for all heavy metals. The NP indices of each metal were calculated and classified into 5 grades: NPs < 0.7, 0.7 ≤ NP ≤ 1.0, 1.0 ≤ NPs ≤ 2.0, 2.0 ≤ NPs ≤ 3.0, and NPs > 3.0 indicating safety, precaution, slightly polluted, moderately polluted and seriously polluted domains, respectively (Cheng & Zhu 2007; Ogunkunle and Fatoba 2013).

Pollution load index

This was established by evaluating the following equation, which was described by Hakanson's (1980), Eyankware and Akakuru (2022) using the following expression:

$$PLI = \sqrt[n]{CF_1 \times CF_2 \times \ldots .CF_n} \tag{5}$$

If *n* is the total number of pollutants, CF is the computed contamination factor for each individual element, and PLI is the pollution load index.

The PLI index measures how frequently the concentrations of HMs in a given soil sample exceed the background levels of those elements. The process of comprehending and presenting the overall risk of HMs toxicity in soils may therefore be made simpler as a result.

Contamination factor (CF)

The contamination factor (C_deg) serves as a measurement tool to assess the level of contamination by contrasting the concentration of a specific pollutant in the environment with a baseline or reference value. It quantifies the level of contamination for individual substances, revealing the extent to which a pollutant surpasses its natural or pre-industrial concentration. Through the evaluation of C_deg, environmental scientists can pinpoint areas of significant contamination and evaluate the potential ecological and health risks linked to particular pollutants. The formula for C_deg is presented in Eq. 6.

$$CF = \frac{Cn}{Bn} \tag{6}$$

where Bn is the ambient concentration at the control site and Cn is the measured metal concentration. The classification scheme for CI is shown in Table 1.

component analysis

In the PCA, component loading involved dividing a sizable dataset of numerous variables into a smaller number of linear combinations in the component that accounted for a suitable portion of the overall data variance and made it simple to connect the variables to the sources or processes via Eq. (7).

$$\sigma^2 = \frac{1}{N}\sum_{i=1}^{N}(X_{N\_}N)^2 \tag{7}$$

pollution index (MPI)

MPI was evaluated using Caeiro et al. (2005) Eq. 6, which determined the collective influence of individual heavy metals on water quality (Horton, 1965; Mohan et al., 1996).

$$MPI = \sqrt[n]{M_1 \times M_2 \times M_{3\_\_\_\_\_\_\_\_}}Mn \tag{8}$$

where Mn = concentration of the metal.

Result and discussion

Table 1 outlines the concentrations of heavy metals, specifically Mn, Fe, Cu, Zn, Ni, Pb, Cr, and As, in mg/kg, detailing their minimum, maximum, and average values.

Potential ecological risks assessment

The Swedish scientist Hakanson created the potential ecological risk index in 1980; see Eqs. 1 and 2, respectively. The adverse effects of the contaminants on the environment and people have been evaluated using this indicator, which

Table 1 Results of heavy metals in soil

Sample code	Latitude	Longitude	Mn	Fe	Cu	Zn	Ni	Pb	Cr	As
SS1	5°20′00’’	6°12′25’’	27.6	2140	2	9.8	0.002	9.3	5.5	0.002
SS2	5°19′54’’	6°12′46’’	41.9	3240	1.1	15.5	0.001	10.2	10.4	0.001
SS4	5°19′33’’	6°13′07’’	39.8	3150	1.4	14.4	0.001	7.4	4.9	0.002
SS5	5°19′43’’	6°13′22’’	184.1	4900	6.2	12.1	0.002	6.5	3.3	0.001
SS6	5°19′27’’	6°13′33’’	56.1	3900	1.6	9.7	0.002	6.5	5.1	0.002
SS8	5°19′28’’	6°13′53’’	44.1	3570	2.4	12.6	0.001	5	2.2	0.001
SS10	5°18′57’’	6°14′10’’	26.7	8870	6.3	60.4	0.001	34.7	11.5	0.001
SS11	5°19′09’’	6°16′11’’	11.9	920	1.5	18.9	0.001	9.1	3.2	0.002
SS12	5°19′20’’	6°16′07’’	22.1	4641	9.9	13	0.002	2.4	9.8	0.001
SS13	5°22′46’’	6°13′29’’	29.6	8400	3.4	14.4	0.001	11.3	5.9	0.002
Min			11.9	920	1.1	9.7	0.001	2.4	2.2	0.001
Max			184.1	8870	9.9	60.4	0.002	34.7	11.5	0.002
Mean			48.39	4373.1	3.58	18.08	0.0014	10.24	6.18	0.0015
STDV			49.31688	2524.254	2.930226	15.11356	0.000516	8.98495	3.258766	0.000527
Variance			2432.154	6,371,861	8.586222	228.4196	2.67E-07	80.72933	10.61956	2.78E-07
Std. Err			15.59537	798.2393	0.926619	4.779326	0.000163	2.841291	1.030512	0.000167

Min minimum, *Max* maximum, *STDV* standard deviation, *Std. Err.* standard error reflects the toxicity and ecological sensitivity of the concentration of contaminants (Hakanson 1980; Weihua et al. 2010; Suresh et al. 2012). It was initially used as a technique to assess sediment pollution in aquatic environments. Success has been achieved in the risk evaluation of soils, dust, and air (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). Findings from Table 3 showed that 13 samples was collected throughout the study area, indicating that the soils present a very high ecological risk (see Tables 2 and 3). Because of the accelerated rise of industry and agriculture, the destabilization of natural ecosystems brought on by anthropogenic pressure from increasing human populations, and the danger that heavy metal soil contamination poses to the environment and food security (Sarwar et al., 2017), the usage of metal-containing chemicals in home and agricultural settings, industrial production, and mining are only a few examples of the anthropogenic activities that cause environmental pollution and human exposure to heavy metals (Tchounwou et al., 2012). The assessment of ecological risk requires knowledge about overall heavy metal concentrations as well as the fractions that may be accessible to plants. To some extent, heavy metals can be stored and accumulated in the soil surrounding disposal sites. Grazing occurs all around the landfills. Therefore, through the food chain, metals may move from the soil to grasses, grazing animals, and ultimately humans. Because of the possible risk that metal toxicity poses to environmental sensors, this condition is quite concerning to humans.

It was observed that the mean values of the ERI are higher than all the mean values of the PLI in all the sampled locations (Fig. 2).

Table 2 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	$80 \leq E_r^i < 160 or 300 \leq R_i < 600$	Considerable ecological risk
5	$160 \leq E_r^i < 320 or 600 \leq R_i$	Very high ecological risk

Petrographysic studies

The petrographic analysis of soil samples A and B, examined on different slides, indicates a fine sand composition with diverse grain textures. The grains are euhedral, subrounded, elongated, and subhedral, reflecting a range of crystal forms and degrees of weathering or transport. The presence of sutured and concavo-convex contact shapes suggests a degree of mechanical compaction or pressure-induced alterations in the grain boundaries. The samples were analyzed at a magnification of 120, which provided detailed insight into the mineral structure and grain interactions. The observation of monocrystalline quartz grains indicates that the sand is composed of well-formed, single crystal structures, contributing to the overall stability and strength of the sand matrix. The surrounding iron oxide cement not only binds the quartz grains together but also implies a degree of post-depositional mineral alteration or iron enrichment in the soil. The consistency in mineral composition, with quartz being the dominant mineral, highlights the sand's primary source material and its likely origin. The identification of iron oxide as a cementing agent points to potential geochemical processes involved

Table 3 Result of potential ecological risk index

PLI									ERI
Sample code	Mn	Fe	Cu	Zn	Ni	Pb	Cr	Ar	
SS1	0.325	5350	0.28	0.07	7.14E-05	0.47	0.06	0.002	53,501.19
SS2	0.493	8100	0.153	0.12	3.57E-05	0.51	0.11	0.001	81,001.37
SS4	0.469	78,750	0.195	0.11	3.57E-05	0.37	0.04	0.002	78,751.19
SS5	2.166	122,500	0.862	0.09	7.14E-05	0.36	0.04	0.001	122,503.5
SS6	0.66	97,500	0.23	0.07	7.14E-05	0.33	0.06	0.002	97,501.33
SS8	0.52	89,250	0.34	0.09	3.57E-05	0.25	0.03	0.001	89,251.22
SS10	0.32	221,750	0.88	0.44	3.57E-05	1.74	0.12	0.001	221,753.5
SS11	0.14	23,000	0.21	0.14	3.57E-05	0.46	0.03	0.002	23,000.97
SS12	0.26	116,025	1.38	0.09	7.14E-05	0.12	0.09	0.001	116,026.9
SS13	0.35	210,000	0.48	0.11	3.57E-05	0.57	0.06	0.002	210,001.5
MIN	**0.14**	**23,000**	**0.16**	**0.07**	**3.57E-05**	**0.12**	**0.02**	**0.001**	**23,000.9**
MAX	**2.17**	**221,750**	**1.38**	**0.43**	**7.14E-05**	**1.76**	**0.15**	**0.002**	**221,753.5**
MEAN	**0.57**	**109,327.5**	**0.49**	**0.13**	**5E-05**	**0.53**	**0.08**	**0.0015**	**109,329.3**
STDV	**0.59**	**63,106.36**	**0.41**	**0.11**	**1.84E-05**	**0.45**	**0.04**	**0.001**	**63,106.96**

Min minimum, *Max* maximum, *STDV* standard deviation

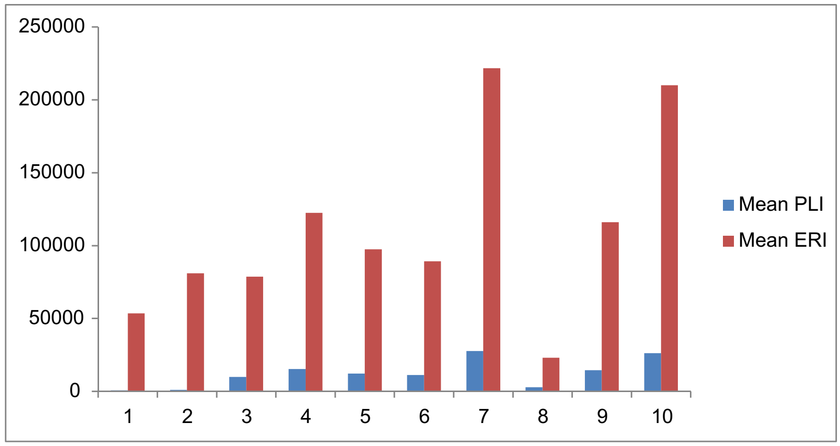

Fig. 2 The graph of the mean values of PLI and ERI

in the soil's formation or diagenesis. Soil samples C and D, being the same as A and B but examined on different slides, confirm the reproducibility of these observations, further validating the petrographic characteristics and providing a consistent understanding of the soil's mineralogical and textural properties; see Fig. 3a–d.

Geoaccumulation index

The geoaccumulation index (Igeo), developed by Muller in 1979, has been widely used to assess the degree of elements contamination in sediment, water, dust, and soil throughout the world (Hazzeman, et al., 2017); see Eq. 3. 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) (Wei and Yan 2010; Olujimi et al. 2014; Qing et al. 2015). According to the geoaccumulation index results (Table 4), all sample values were above 6, indicating that the samples are extremely highly polluted (see Table 5). This is similar to the potential ecological risk index's findings, which indicated that the soils are seriously polluted. Igeo generally showed that the majority of heavy metals had little to no effect on the soils in the study area. The possible ecological risk index result, which showed that the soils are heavily contaminated, is in conflict with this. Considering all things, the Igeo showed that the majority of heavy metals had no discernible impact on the soils in the research area (Table 6).

Contamination Factor (CF)

The contamination factor data showed that the soil samples were overly polluted. The results of the pollution index show that the research area's soil quality has completely decreased. In Table 5,

Pearson correlation matrix

To evaluate the relationships between two variables, utilize the correlation matrix. The correlation coefficient typically ranges from −1 to + 1. If the *r*-value is near to −1, the relationship is thought to be anti-correlated or to have a negative slope. When the value of r is close to + 1, the relationship is considered to have a positive slope or to be correlated. If the value is 0, the points are regarded as being uncorrelated (Srivastava et al., 2014). Table 7's correlation matrix revealed positive correlations between Mn and Ni, Fe and Cu, Zn, Pb, Cr, Cu and Cr, Zn and Pb, Cr, and Pb, whereas negative correlations existed between Cu and Ar and Cr and Ar. There is also proof that the parameters are directly correlated. This suggests that a change in one parameter's value will have a commensurate effect on the other parameter's value. When one parameter increases in response to another, the correlation is said to be positive; conversely, when one parameter increases in response to another, it is said to be negative (Akakuru et al. 2022). In other words, while one variable changed, the other changed as well, albeit in an unrelated direction. Additionally, it implies that human activity is the primary source of heavy metals in soils (Ugbome, et al., 2018; Anegbe et al. 2018).

Principal Component Analysis (PCA)

The PCA method of based classification seeks to explain the variance of numerous related variables (Osisanya et al. 2022; Akakuru et al., 2021a & b); see Eq. 7. It demonstrates how variables are related, which reduces the dataset's complexity. PCA uses the initial data's covariance matrix to extract eigenvalues and eigenvectors. Principal components (PCs) are the initially correlated variables multiplied by the eigenvectors to obtain the uncorrelated (orthogonal) variables (loadings). The eigenvalues of the PCs measure the variance of the scores, which are the transformed observations. The loadings show the involvement of the original variables

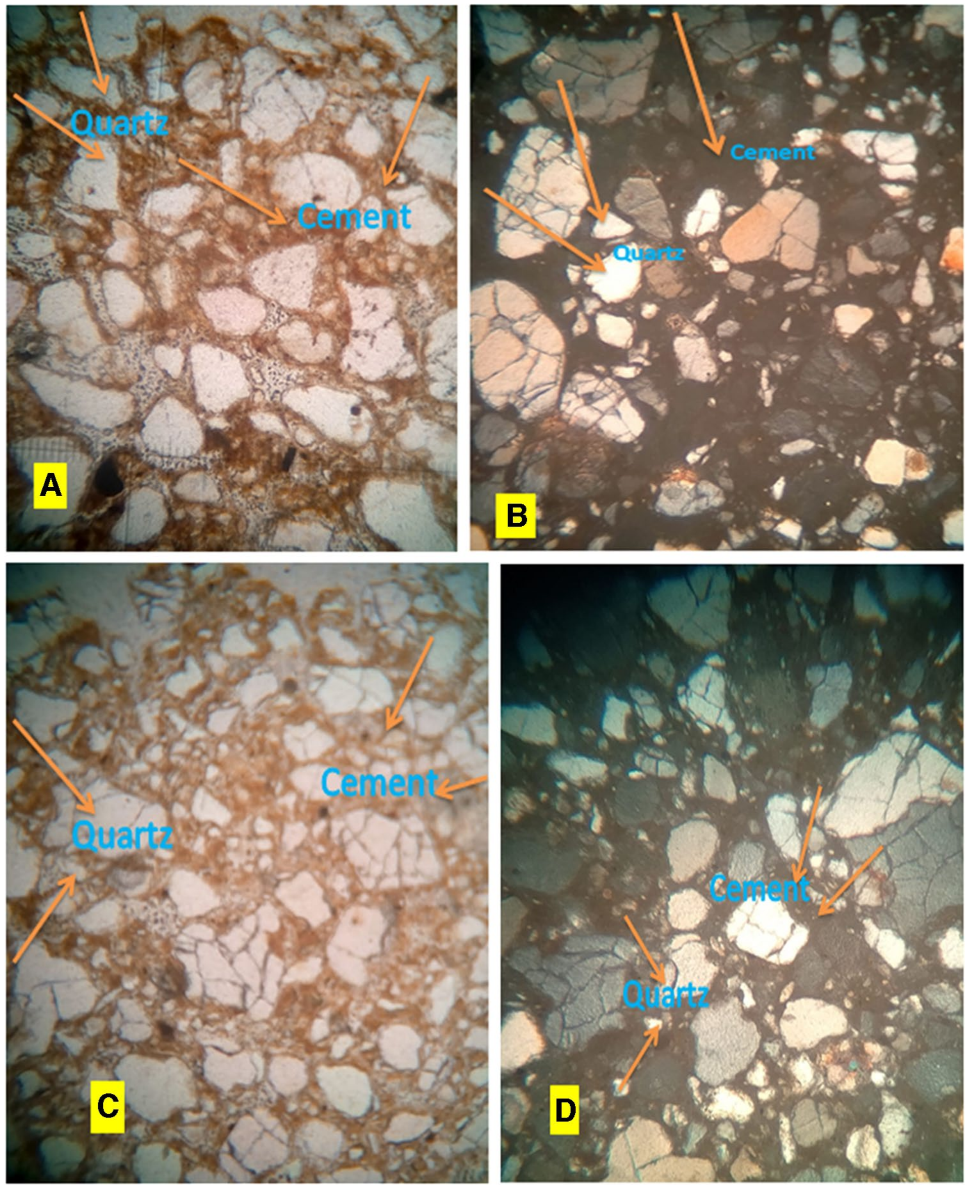

Fig. 3 a-d Microphotographs of soil in Uzere, Niger Delta region

in the PCs. From Table 8, the loadings of the parameters showed that 75% of the samples in PC1 have loadings, in PC2, they have 50% of the parameters having loadings, in PC3, 25% of the parameters had loading while in the PC4, 12.5% of the entire parameter has a loadings. Additionally, it is crucial to highlight that the majority of the parameters had extremely high loading values, indicating that they significantly contributed to the overall pollution load of the soil in the research area. The presence of the heavy metals that displayed notable loadings is a sign of the type of activity occurring in the study area. This implies that anthropogenic activity has had a significant impact on soil quality. Heavy metals are easily absorbed in the atmosphere due to their industrious and non-biodegradable composition. The enormous amount of poisons that are found in soil comes from several sources. As HMs disrupt the regular functioning of living systems, they pose a threat to human health when they surpass certain thresholds. Considering the natural estimates related to land treatment, the enormous volume of trash generated needs to be handled properly. According to Eyankware et al. (2021), Agidi et al. (2022), and Akakuru et al. (2022), the intensity of the provider's use and the characteristics of the soil determine the elevated levels of heavy metals in horticultural soils.

Contamination factor (Cf)

The contamination factor illustrates the pollution-related properties of the research region. It displays the degree of contamination from a single metal in a natural environment.

The contamination factor was calculated as the difference between the background concentration of the relevant metal and the concentration of the heavy metal (Ogundele et al. 2017) as shown in Eq. 6. The Cf of contamination may be classified based on the scale ranging from < 8 to > 32: 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 total number of samples of 10, as shown in Table 8's results for the degree of contamination, indicating that they had a low level of contamination except for Fe, which showed tremendous worrisome level of Cf.. The findings of this study agree with the geoaccumulation index of the samples collected in the area, but they disagree with the evaluation of the possible ecological risk index performed in the same area. Numerous rocks and minerals contain large amounts of iron, which can either be enriched or depleted as soils grow. When levels of potentially soluble iron minerals are high and in poorly drained soils, depletion frequently results in deficiency, while enrichment can result in toxicity. Iron concentrations up to 50,000 times the crop's yearly demand are possible, but their use is constrained by availability-related considerations. Iron-organic matter complexes and secondary oxides that are absorbed by or precipitate on soil mineral particles are the principal sources of iron in soils for plant usage (Agidi et al. 2022; Usman et al. 2022; Eyankware et al. 2022).

Pollution load index (PLI)

The pollution load index was created by Tomlinson et al. (1980) to measure the degree of soil contamination each metal causes at a specific location as shown in Eq. 5.The pollutant load index offers comparable instruments for assessing a site's state and, as a result, suggests any additional actions that could be necessary. A PLI value of > 1 signifies pollution, while a PLI value of < 1 indicates no pollution. The PLI values revealed that 64.8% of PLI was < 1 which implies no pollution. This is in line with study conducted by Anegbe et al. (2018) in Oghara, Delta state, while 35.2% showed PLI value > 1 which implies that pollution exists.

Nemerow pollution (NPI)

Another numerical index that unifies several factors into one is NPI (Nemerow, 1974); see Eq. 4. The combined level of water quality for all pollution parameters is represented by the NPI value, on the other hand. Instead of just looking at the concentrations of one or two specific contaminants, it is preferable from an empirical validity perspective to use an integrated soil quality index to assess an intrinsic soil risk assessment (Kowalska et al. 2018; Kong et al. 2019). The NPI determines how much pollution each parameter in a water sample contributes relative to another. This will help identify the parameter(s) in charge of the quality status.

NPI value of ≤ 0.7 indicates that the water is clean; NPI value of 0.7 < NPI ≤ 1.0 implies slightly clean, NPI value of 1.0 < NPI ≤ 2.0 implies slightly polluted, NPI value of 2.0 < NPI ≤ 3.0 implies moderately polluted, while NPI value of > 3.0 implies heavy pollution. From the results in Table 9, it shows that the soil is highly polluted; this could be attributed to human activities within the study area.

Spatial distribution of heavy metals in soil within the study area

Manganese (Mn)

Due to its role in numerous physiological processes, including photosynthesis, Mn is a mineral nutrient that is crucial for plants. The most prevalent occurrences of manganese shortage are in sandy soils, organic soils with a pH higher than 6, and extensively worn tropical soils (Eyankware and Obasi 2021). The range of Mn concentration in soil the used in this study is 11.9 to 184.1, with an average value of 48.39 mk/kg. According to Fig. 4a, the southwest (SW) portion of the research region contains higher concentrations of Mn than the other parts.

Iron (Fe)

In most soils, iron is a common metal (Zabowski et al. 2001). See Table 1 for the range of Fe concentrations in soil, which range from 920 to 8870 mk/kg on average. High levels of Fe were found in the research area's center and southeast (Uzerre flow station), as seen in Fig. 4b. This could be mostly due to Fe being deposited in soil as a result of human activity and being spread to surrounding soils and streams through weathering, leaching, and erosion processes (Marques et al., 2001; Lee et al., 2005; Lintnerova et al., 2008; Rodriguez et al., 2009).es et al. 2001; Lee et al. 2005; Lintnerova et al. 2008; Rodriguez et al. 2009).

Copper (Cu)

In the study region, the range of soil Cu concentrations is 1.1 to 9.9 mg/kg, with an average value of 3.9 mg/kg, as shown in Table 1. One of the rare metals that can be found in nature as a single mineral is copper. The parent rock, which is geological, is the most significant natural source of copper. When copper is introduced into the soil, it may not go very far because it may get very tightly bonded to the organic and geological components. The presence of excessive Cu may be sensed in the vicinity of sites where high levels of the metal have been detected, or it may be transferred to other areas by plant products that have absorbed excessive

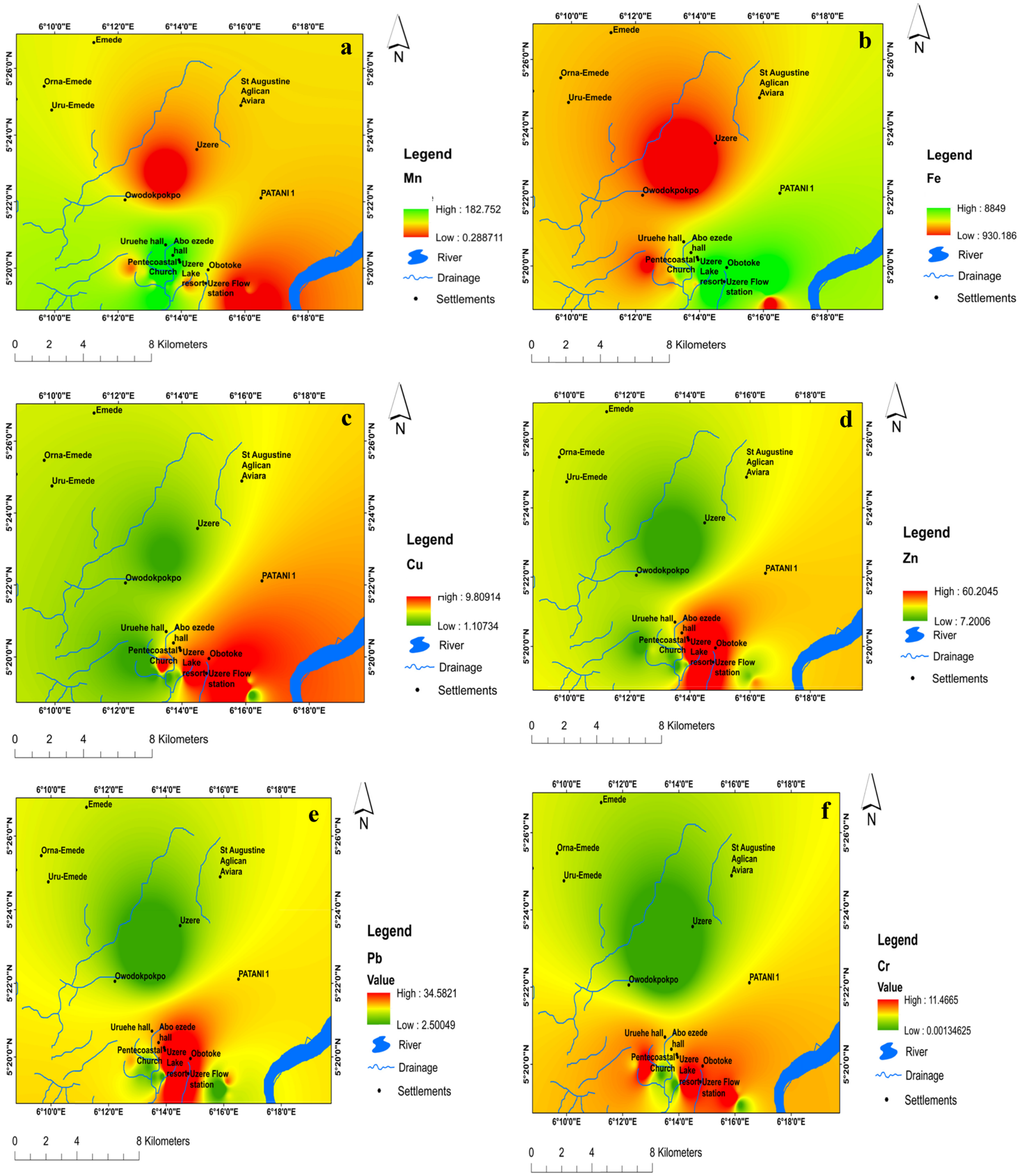

Fig. 4 a, b, c, d, e, and f Spatial distribution of Manganese (Mn), Iron (Fe), Copper (Cu), Zinc (Zn), Lead (Pb), and Chromium (Cr)

levels of the metal. According to the results from Fig. 4c, the SE section of the research region has a higher concentration of copper than the other parts. Cu in the soil can be connected to the mining and processing of copper ores, claim Zhuang et al. (2009). Cu has a considerable negative impact on ecosystem services and environmental quality because of its role in environmental contamination. Some metal pollutants, like Cu, could evade detection, though.

Table 4 Geoaccumulation index scale (Igwe, et al. 2021; 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	Moderate to unpolluted
0–2	1	Unpolluted
0 <	0	Background concentration

I*geo* geoaccumulation index

Table 5 Grading of soil according to contamination factor (CF) (Lacatusu, 2000)

S/No	Values	Interpretation
1	0.1	Very slight contamination
2	0.1–0.25	slight contamination
3	0.26 –0.5	moderate contamination
4	0.51 –0.75	severe contamination
5	0.76–1.0	Very severe contamination
6	1.1–2.0	Slight pollution
7	2.1–4.0	Moderate pollution
8	4.1 –8.0	Severe pollution
9	8.1–16	Very severe pollution
10	16	Excessive pollution

Zinc (Zn)

Zn concentrations in soil in the studied region range from 9.7 to 60.4 mg/kg, with an average value of 18.08 mg/kg (Table 1). According to Fig. 4d, the southeast portion of the research region contained the highest concentration of Zn. The Maximum Permissible Addition an(MPA) of Zinc in the study area is relatively high (Table 9) but low harmful, according to the Russian general toxicological standard (RGTS) (Table 10) and based on their standard for soil. Approximately 54% of the study area has MPA above the zinc limit. The geochemical makeup of the riverine region in the research area, along with the presence of abandoned waste, is thought to be the causes of the relatively high Zn concentrations in the aforementioned location (Oladoye and Adewuyi 2014).

Nickel (Ni)

Examples of Ni in soils include water-soluble, free-ion, or chelated metal complexes in soil solution, inorganic crystalline minerals or precipitates, adsorption of complex formation on organic cation surfaces or inorganic cation exchange surfaces, and inorganic crystalline minerals or precipitates. The research area's nickel concentrations are almost 50% higher than the MPA limit. Contrarily, nickel was deemed to be just moderately harmful (Oladoye and Adewuyi 2014). According to Table 1, the average Ni concentration in soil is 0.001 mk/kg, with values ranging from 0.001 to 0.002 mk/kg.

Table 6 Results of geoaccumulation index (Igeo)

Mn	Fe	Cu	Zn	Ni	Pb	Cr	As	Igeo	MPI	CF (contamination factor)
0.065	10,736.7	0.011	0.014	0.000	0.019	0.011	0.00	10,736.9	15.39	107,002.1
0.099	16,255.6	0.006	0.022	0.000	0.020	0.021	0.00	16,255.9	15.67	162,002.2
0.094	15,804.1	0.008	0.021	0.000	0.015	0.010	0.00	15,804.3	13.54	157,501.9
0.435	24,584.2	0.035	0.017	0.000	0.013	0.007	0.00	24,584.7	53.89	245,004.8
0.132	19,566.9	0.009	0.014	0.000	0.013	0.010	0.00	19,567.2	21.22	195,002
0.104	17,911.3	0.013	0.018	0.000	0.010	0.004	0.00	17,911.5	7.23	178,501.9
0.063	44,502.3	0.035	0.087	0.000	0.070	0.023	0.00	44,502.6	189.64	443,506.6
0.028	4615.8	0.008	0.027	0.000	0.018	0.006	0.00	4615.9	4.26	46,001.8
0.052	23,284.7	0.055	0.019	0.000	0.005	0.020	0.00	23,284.9	24.92	232,053.6
0.070	42,144.2	0.019	0.021	0.000	0.023	0.012	0.00	42,144.4	40.29	420,002.8
0.028	4615.8	0.006	0.014	0.000	0.005	0.004	0.00	4615.9	4.26	46,001.8
0.435	44,502.3	0.055	0.087	0.000	0.070	0.023	0.00	44,502.6	189.64	443,506.6
0.114	21,940.6	0.020	0.026	0.000	0.021	0.012	0.00	21,940.7	38.61	218,658
0.116	12,664.7	0.016	0.022	0.000	0.018	0.007	0.00	12,664.7	55.17	126,213.9

Fe iron, *Cu* copper, *Zn* zinc, *Ni* nickel, *Pb* lead, *Cr* chromium, *As* arsenic, *Igeo* geoaccumulation index, *MPI* metal pollution index

Table 7 Pearson correlation matrix

	Mn	Fe	Cu	Zn	Ni	Pb	Cr	Ar
Mn	1							
Fe	0.072606	1						
Cu	0.205414	**0.490492***	1					
Zn	−0.20532	**0.589556***	0.293184	1				
Ni	**0.420324***	−0.16293	0.395052	−0.39464	1			
Pb	−0.1937	**0.615923***	0.129681	**0.958063****	−0.38938	1		
Cr	−0.33249	**0.466656***	**0.422223***	**0.570486***	−0.06735	**0.548796***	1	
Ar	−0.32894	−0.28024	**−0.57557***	−0.32362	2.16E-17	−0.17832	**−0.40756***	1

Bold signifies correlation

*Weak correlation

**Strong correlation

Table 8 Result of PCA

	Communalities	Component			
		1	2	3	4
Mn	0.93	−0.17	**0.71**	**−0.62**	0.08
Fe	0.78	**0.77**	0.15	−0.19	0.35
Cu	0.85	**0.51**	**0.72**	0.26	0.05
Zn	0.90	**0.91**	−0.21	−0.15	0.07
Ni	0.90	−0.31	**0.73**	0.33	0.40
Pb	0.92	**0.87**	−0.30	−0.20	0.21
Cr	0.85	**0.77**	0.04	**0.49**	−0.11
Ar	0.98	**−0.50**	**−0.57**	0.12	**0.62**
Eigenvalue	7.10	2.84	1.28	0.04	1.66
Variance (%)	0.39	34.28	26.19	13.22	5.56
Cumm. variance (%)	0.39	34.67	60.86	74.08	79.63

Bold signifies loading

Lead (Pb)

Lead is a hazardous non-essential element, and its effects have been studied more thoroughly than those of other trace metals (Raikwar et al. 2008; Igwe et al. 2021; SON 2015; Egbueri and Mgbenu, 2020; Eyankware et al. 2022). To learn more about how easily accessible Pb is in soil, the pH of each soil sample whose Pb content was examined was assessed. At pH 6–8 (near-neutral soils), Pb is strongly bound to soil particles and may not be available for plant absorption. The average Pb content for this study, as indicated in Table 1, was 10.24 mg/kg, with a range of 2.4 to 34.7 mg/kg. The study's greatest Pb concentrations were found in the southeast and southwest. See Fig. 4e.

Table 9 Results of CF, PLI, and Nemerow's pollution index

	Contamination factor								PLI	NPI
Sample code	Mn	Fe	Cu	Zn	Ni	Pb	Cr	As		
SS1	0.325	5350	0.055	0.07	1.42857E-05	0.093	0.055	0.0004	4.44364E-05	1431
SS2	0.492	8100	0.031	0.111	7.14286E-06	0.102	0.104	0.0002	4.52433E-05	3280
SS4	0.469	7875	0.039	0.102	7.14286E-06	0.074	0.049	0.0004	3.90901E-05	3100
SS5	2.166	12,250	0.173	0.086	1.42857E-05	0.065	0.033	0.0002	0.000155574	7503
SS6	0.66	9750	0.045	0.069	1.42857E-05	0.065	0.051	0.0004	6.12671E-05	4753
SS8	0.519	89,250	0.067	0.090	7.14286E-06	0.05	0.022	0.0002	2.08947E-05	3982
SS10	0.313	2217	0.175	0.431	7.14286E-06	0.347	0.115	0.0002	0.00054754	24,589
SS11	0.140	2300	0.042	0.135	7.14286E-06	0.091	0.032	0.0004	1.22758E-05	2645
SS12	0.260	1160	0.275	0.092	1.42857E-05	0.024	0.098	0.0002	7.19484E-05	6730
SS13	0.349	2100	0.095	0.102	7.14286E-06	0.113	0.059	0.0004	0.000116328	22,050
MIN	0.140	2300	0.031	0.069	7.14286E-06	0.024	0.022	0.0002	2.26758E-06	2645
MAX	2.166	2217	0.275	0.431	1.42857E-05	0.347	0.115	0.0004	0.003604663	24,586
MEAN	0.569	1093	0.099	0.129	0.00001	0.103	0.0618	0.0003	0.000123187	77,683
STDV	0.580	63,106.3	0.082	0.107	3.68856E-06	0.089	0.0326	0.0001	1.9138E-05	84,969

Min minimum, *Max* maximum, *STDV* standard deviation, *CF* contamination factor, *PLI* pollution load index

Table 10 Maximum permitted addition (MPA) in mg/kg of heavy metals and metalloids according to Dutch ecologists' data Li et al. (2015)

Metal/metalloid	MPA
Beryllium (Be)	0.0061
Selenium (Se)	0.11
Thallium (Tl)	0.25
Antimony (Sb)	0.53
Cadmium (Cd)	0.76
Vanadium (V)	1.1
Mercury (Hg)	1.9
Nickel (Ni)	2.6
Copper (Cu)	3.5
Chromium (Cr)	3.8
Arsenic (As)	4.5
Barium (Ba)	9.0
Zinc (Zn)	16
Cobalt (Co)	24
Tin (Sn)	34
Lead (Pb)	55
Molybdenum (Mo)	253

Not determined is denoted by a dash

Chromium (Cr)

The makeup of the original geological materials from which the soil was created affects the amount of Cr in soil, which varies substantially (Jankiewicz and Ptaszyski 2005). Pb concentrations for this study vary from 2.2 to 11.5 mg/kg, with an average value of 6.18 mg/kg, as indicated in Table 1. It was noted in Fig. 4f that the southwest (SW) and southeast (SE) regions of the contain large amounts of copper. In addition, human activities like mining, especially in areas close to operational mines, may considerably raise soil Cr concentrations. Human consumption of plants that have absorbed this heavy metal from the soil can result in kidney and liver illness (Harendra et al. 2017) (Table 11).

Arsenic (As)

As is a naturally occurring substance discovered all through the earth's crust. As is a highly toxic metalloid that is broadly disseminated on the Earth's surface and in its hydrosphere (Igwe, et al., 2022; Emilie et al., 2017). Skin conditions including blackening and swelling of the palms and toes can result from prolonged exposure (Mahimairaja et al. 2005). The potential for negative human impacts has made excessive arsenic concentrations in the natural geochemical environment a serious worry in recent years (Eyankware and Ephraim, 2021).That is a well poison, and even a limited percentage of arsenic trioxide, such as 0.1 g, can be hazardous to the environment. Although occupational arsenic poisoning is well-known, high arsenic toxicity is now uncommon (WHO, 1981). Arsenic has been known to cause cancer in humans in high quantities for more than a century, and it is now generally acknowledged that ingesting inorganic arsenic can result in skin, lung, and leukemia cancer while inhaling it can result in respiratory tract cancer (Jarup, 1992; Kotoky et al., 2008). As concentration during the study ranged from 0.001 to 0.002 mg/kg with an average value of 0.0015 mg/kg, as indicated in Table 1.

Conclusion

This study has presented a comprehensive analysis of the geochemical implications of hydrocarbon exploitation on the soil in the crude oil-producing area of Uzere, located in the Niger Delta region of Nigeria. The assessment focused on the spatial characteristics and levels of heavy metal contamination in the soil, comparing them to a control site to understand the impact of anthropogenic factors on soil quality. Several soil quality models were used to figure out how polluted and poor the soil was. These models included the Nemerow integrated pollution index (NPI), the contamination factor (Cf), the pollution load index (PLI), and the geo-accumulation index (Igeo). The results consistently indicated severe pollution, with extremely high levels of heavy metal contamination in the soil. The study also employed principal component analysis (PCA) and correlation matrix analysis to identify relationships between different heavy metals. The findings revealed significant correlations, such as those between Mn and Ni, Fe and Cu, Zn, Pb, Cr, Cu and Cr, Zn and Pb, Cr, Pb and Cr, and Cr and Ar. These correlations were further elucidated by loadings in different principal components, providing insights into the complex interplay of

Table 11 Hazards of metals/metalloids according to the Dutch soil standards and the Russian general toxicological standard (quoted after Li et al. 2015)

Hazard class	Russia	The Dutch MPA for soils
1. Highly hazardous	0As, Cd, Hg, Se, Pb, Zn	< 1: Be, Se, Tl, Sb, Cd
2. Moderately hazardous	Co, Ni, Mo, Cu, Sb, Cr	1e10: V, Hg, Ni, Cu, Cr, As, Ba
3. Low hazardous	Ba, V, W, Mn, Sr00	> 10: Zn, Co, Sn, Ce, Pb, Mo00

Note: For the numbers, the dimension is in mg/kg heavy metals in the soil. Spatial distribution maps of heavy metals demonstrated that the southwest and middle parts of the study area exhibited higher traces of heavy metals compared to other regions. This spatial analysis contributes valuable information to our understanding of the degree of heavy metal contamination and potential sources in various locations within Uzere. In light of the study's findings, it is imperative to emphasize the need for international regulations governing the assessment of soil pollution and quality. The severity of heavy metal pollution highlighted in this research underscores the urgency for enhanced soil management, remediation strategies, and effective soil contamination control measures. The study's comprehensive and up-to-date insights can serve as a foundation for informed decision-making and sustainable practices in addressing the environmental challenges associated with hydrocarbon exploitation in the Niger Delta region.

Author contribution The research work was conducted by Ibitoye Abel Taiwo and Osisanya Olajuwon Wasiu, while Osisanya Olajuwon Wasiu wrote the manuscript, Imasuen Okpeseyi Isaac and Ibitoye Abel Taiwo read and approved the final manuscript.

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Data availability The datasets generated during and/or analyzed during the current study are available from the corresponding author upon reasonable request.

Declarations

Ethics approval All authors have read, understood, and have complied as applicable with the statement on "Ethical responsibilities of Authors" as found in the Instructions for Authors and are aware that with minor exceptions, no changes can be made to authorship once the paper is submitted.

Competing interest The authors declare no competing interests.

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