Journal of Environmental Protection, 2024, 15, 415-438
https://www.scirp.org/journal/jep
ISSN Online: 2152-2219
ISSN Print: 2152-2197

Heavy Metal Levels and Ecological Risk in Crude Oil-Contaminated Soils from Okpare-Olomu, Niger Delta, Nigeria

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How to cite this paper: Bankole, A.O., Ogunkeyede, A.O., Agboro, H., Ekhorutomwen, P.A., Otuomagie, O.I., Isimekhai, K.A., Fadairo, E.A. and Isukuru, E.J. (2024) Heavy Metal Levels and Ecological Risk in Crude Oil-Contaminated Soils from Okpare-Olomu, Niger Delta, Nigeria. *Journal of Environmental Protection*, **15**, 415-438.
https://doi.org/10.4236/jep.2024.154024

Received: February 8, 2024
Accepted: April 21, 2024
Published: April 24, 2024

Abstract

Crude oil spills have inflicted extensive disruption upon the Niger Delta ecosystem, resulting in crop loss and severe environmental damage. Such spills exacerbate heavy metal concentration within soil due to the presence of metallic ions. The Okpare-Olomu community has borne the brunt of crude oil pollution from illicit bunkering, sabotage, and equipment malfunction. This study targets an evaluation of ecological hazards linked to heavy metals (HMs) in crude oil impacted agriculturally soils within Okpare-Olomu in Ughelli South LGA of Delta State. In this study, 24 topsoil samples were obtained from areas affected by crude oil pollution; the heavy metal content was evaluated through atomic absorption spectrometry. The concentration ranges for HMs (mg/kg) in soil were: 24.1 - 23,174 (Cu); 0.54 - 37.1 (Cd); 9.05 - 54 (Cr); 12 - 174 (Ni); 18.5 - 8611 (Pb); and 148 - 9078 (Zn) at a soil depth of 0 - 15 cm. Notably, metal concentrations were recorded to be above permissible World Health Organization limits. Predominantly, Zn and Pb recorded higher heavy metal concentration when compared to other heavy metals analysed, notably at sampling points PT7 through PT24. Zinc and Pb contamination exhibited highly significant contamination factors, and contamination severity was evidenced across all sample points, signifying a grave risk level. Pollution load indices indicated pervasive extreme pollution levels. Geoaccumula-

tion indices signaled moderate to strong pollution, mainly by Pb and Zn. Ecological risk assessments revealed variable levels of heavy metal contamination, from low to very high, with potential ecological risk reflecting markedly elevated levels. This study underscores the imperative for soil remediation to rectify ecological imbalances in agriculturally affected soil constituents.

Keywords

Heavy Metals, Crude Oil, Pollution, Degree of Contamination, Potential Risk Index

1. Introduction

Crude oil exploration and production provide job opportunities and promote the economic status of a nation. Its production and related activities tend to introduce pollutants into the immediate environment, disrupting the ecosystem where such pollution occurs. Activities such as sabotage of production, transportation or storage facilities, illegal bunkering, and tanker accidents were major culprits responsible for the introduction of crude oil into the environment [1] [2] [3] [4] [5]. Although oil and gas have enormously contributed to societal development, their exploration, exploitation, and trade have also played a role in the current environmental challenges experienced in the world and the Niger Delta today [6].

Crude oil pollution has led to the proliferation of heavy metal concentrations in soil and water systems in the Niger Delta. Heavy metal persistence and toxicity in environmental systems pose a devastating environmental problem today, with specific consequences including soil contamination [7], water pollution [8], air pollution [9], bioaccumulation and biomagnification [10], and ecosystem degradation [11], leading to profound impacts on human health and ecosystem integrity. Heavy metals are amassed in our environment due to natural and anthropogenic activities from crude oil exploration, production, refining, or storage. Studies have shown the increased concentration of heavy metals due to crude oil pollution [9] [12] [13]. Heavy metals such as Ni and V have been discovered to be present in crude oil [14] [15] [16], and oil pollution (spills of petroleum hydrocarbons) can have a significant impact on heavy metal distribution in the soil [17] [18] [19] [20].

Heavy metals in the soil can be absorbed by plant roots, especially in contaminated areas [21]. Metals accumulate not only in some plants' roots but are also translocated from the roots to the leaves or shoots. Chlorosis, weak plant growth, yield reduction, reduced nutrient uptake, plant metabolism disorders, and a reduced ability to fix molecular nitrogen in leguminous plants are all caused by heavy metals entering plant roots [22] [23]. Plants' uptake and accumulation of these heavy metals endanger animal and human health [24] [25]. Heavy metals found in crude oil, particularly Cadmium, may have significant toxic and hazardous effects on human health [26]. Heavy metal pollution has a worldwide

impact on the biosphere [27] [28] [29]. Toxic metal pollution of waters and soils is a major environmental issue, and most traditional remediation methods are ineffective [30].

In the occurrence of crude oil pollution, it is important to study the effect on soil ecology. This is critical in evaluating the site and deciding the best soil management approach. Soil pollution indices, such as enrichment factor (E.F.), geoaccumulation index (Igeo), and pollution load index (P.L.I.), provide information on soil quality and contamination levels for each sample based on individual metals [31]-[38]. The potential ecological risk index (PERI) can be used to estimate the risk posed by individual metals on the soil ecology of the impacted agricultural land in Okpare-Olomu [39] [40] [41]. The main objectives of this study are to evaluate the heavy metal contamination in the soil and estimate potential ecological risks in crude oil-impacted soils of the Okpare-Olomu area.

2. Materials and Methods

2.1. Study Area and Sampling

Okpare-Olomu community in the Niger Delta is located precisely in Ughelli South Local Government Area of Delta State, Nigeria. It lies within latitudes 050, 270N and 050, 330N and longitude 050, 530E and 060, 040E of the Niger Delta, Nigeria. The people of Okpare-Olomu are predominantly farmers and fishermen and housed in their community is a Shell flow station. Agricultural lands in the community have suffered from crude oil pollution due to the years of crude oil bunkering, illegal refining of crude products, and crude oil pollution. Sampling points are presented in **Table 1**.

2.2. Soil Sample Collection and Storage

Soil samples were randomly collected from crude oil-polluted agricultural soils in Okpare-Olomu community in Ughelli South LGA, of Delta State, Nigeria. The coordinates of the areas where soil samples were collected are shown in **Table 1**. Sampling was done in nine different points in the community, with multiple samples collected from areas with dense pollution which made the samples collected accumulate to 24 in total. The collected soil samples were marked P1, P2, P3 up to P24. A control soil sample was picked at coordinates 050, 320N, 050, and 55˚E. Soil collection was done with a hollow stem soil auger at 0 - 15 cm depth. To prevent cross-contamination between samples, the soil auger was meticulously cleaned after each collection using a 0.1 M hydrochloric acid solution followed by neutralization with a sodium bicarbonate solution to ensure minimal impact on soil pH. The samples were placed in Aluminium foils, properly labelled, and transported to the laboratory in an ice chest at −4˚C. It was later air-dried before digestion and analysis.

2.3. Laboratory Analysis

The modified procedure of [42] was used in the digestion and analysis of heavy

Table 1. Sample collection coordinates.

Points	Coordinates
P1	N 05 27.608
	E 05 53.847
P2	N 05 27.619
	E 05 53.848
P3	N 05 27.630
	E 005 53.849
P4	N 05 27.560
	E 005 53 851
P5	N 05 27 551
	E 005 53 855
P6	N 05 27.658
	E 005 54 237
P7	N 05 27.665
	E 005 54 237
P8	N 05 27.657
	E 005 54 235
P9	N 05 27.642
	E 005 54 230
P10	N 05 27.631
	E 005 54.222
CONTROL	N 05 32.296
	E 005 55.356

metals in collected soil samples. Soil samples were air-dried, crushed into powdered form, and passed through a 2 mm sieve to remove litter and debris. Acid digestion of the soil samples was performed before analysis. The sieved soil sample was weighed (0.5 g) and transferred into a 100 mL beaker with 10 mL of concentrated nitric acid (HNO_3; d = 1.4 g/cm^3) and concentrated Hydrochloric acid (HCl; d = 1.18 g/cm^3) in ratio 3:1 v/v, was added and the mixture was placed on a hot plate under fume cupboard and heated to near dryness until its colour turned white. This residue was allowed to cool and then dissolved with 20 % nitric acid (5 mL). The mixture was then filtered and made up to 20 cm^3 with distilled water. A flame atomic absorption spectrometer (A.A.S.) (Buck Scientific, 210 VGP) equipped with the proper hollow-cathode discharge lamps was used to detect heavy metal concentrations (Cr, Cd, Pb, V, Ni, Zn, and Cu). Throughout, deuterium background correction was utilized. Each heavy metal's working standard solution was created by diluting stock solutions (1000 mg/L; Merck KGaA, Darmstadt, Germany).

2.4. Quality Assurance/Quality Control

To assess the analytical performance of our laboratory procedures, we employed a robust procedure involving certified reference materials (CRMs). This procedure incorporated the analysis of NIST SRM 2711a, a well-characterized Montana II soil from the National Institute of Standards and Technology (N.I.S.T.). By analyzing this CRM alongside our actual samples, we were able to evaluate the accuracy, precision, and bias of our analytical methods against established reference values. This multi-faceted approach ensured reliable and verifiable results, strengthening confidence in our data and findings. The sample preparation procedure was validated using the recovery study. The minimum detection limits (MDL) for the studied metals were Cr: 1.3 mg/kg; Cd: 0.4 mg/kg; Pb: 2.1 mg/kg; Ni: 1.5 mg/kg; Zn: 0.07 mg/kg; Cu: 0.6 mg/kg. The following mean recoveries (mean ± standard deviation) were obtained: Cr: 104 ± 3.1%; Cd: 91 ± 3.2%; Pb: 93 ± 2.9%; Ni: 95 ± 2.4%; Zn: 98 ± 2.1%; Cu: 97 ± 2.5%. All calibration lines were linear, with a correlation coefficient higher than 0.99. The A.A.S. sequence included a Q.C. sample and a blank after 10 soil samples. All sample analysis, including blanks and controls, were performed in replicates to ensure data accuracy and reproducibility. Descriptive analysis (mean and standard deviation) and pollution indices (EF, Igeo, P.L.I., RI) were performed in Microsoft excel (2016). Principal component analysis (P.C.A.) was conducted using X.L.S.T.A.T., an add-in to excel.

2.5. Ecological Risk Assessment

The soil indices and their equations for risk assessment methods are presented in Table 2.

2.5.1. Contamination Factor and Degree of Contamination

Contamination factors (C.F.) for soil samples were assessed to quantify the impact of each metal on the agricultural soils of the crude oil-polluted community [25] [47]. This was calculated by dividing the soil's analyzed heavy metal concentration by the background value [49], as shown in Equation (1).

The contamination factor is given as:

$$\text{Contamination factor}\left(\text{Cf}\right) = \frac{\text{Mean of concentration of metals in contaminated environment}}{\text{Baseline concentration of metals from control site}} \quad (1)$$

Values obtained after evaluation are classed either as; Cf < 1 (low contamination), 1 < Cf < 3 (moderate contamination), 3 < Cf < 6 (considerable contamination) and Cf > 6 (very high contamination).

Meanwhile, the degree of contamination (DoC) is calculated using the formula shown in Equation (2).

$$\text{Degree of contamination}\left(\text{DoC}\right) = \sum \text{Cf}_{\text{Ni}} + \text{Cf}_{\text{Cr}} + \text{Cf}_{\text{Cd}} + \text{Cf}_{\text{Pb}} + \text{Cf}_{\text{Zn}} + \text{Cf}_{\text{Cu}} \quad (2)$$

The DoC is classed as DoC < 8 (low risk), 8 < DoC < 16 (moderate risk), 16 < DoC < 32 (considerable risk) and DoC > 32 (very high risk).

Table 2. Benchmarks for soil grouping using pollution indices.

Index Values	Equation/Class	References
Geoaccumulation index	Igeo = log2[Cn/(1.5 × Bn)]	[43]
Igeo < 0	Unpolluted	[44]
0 < Igeo < 1	Unpolluted to moderately polluted	[45]
1 < Igeo < 2	Moderately polluted	[35]
2 < Igeo < 3	Moderately to strongly polluted	[32]
3 < Igeo < 4	Strongly polluted	[34]
4 < Igeo < 5	Strongly polluted to extremely polluted	
Igeo > 5	Extremely polluted	
Pollution load index	PLI=	[44]
P.L.I. < 1	Unpolluted	[45]
1 < P.L.I. < 2	Moderately polluted	[46]
2 < P.L.I. < 10	Strongly polluted	[34]
P.L.I. > 10	Extremely polluted	[35]
Risk Index		[47]
RI < 150	Low ecological risk	[31]
150 < RI < 300	Moderate ecological risk	[48]
300 < RI < 600	Significant ecological risk	[35]
RI > 600	Very high ecological risk	[27]

Note: C_x is the measured concentration of individual metal in the soil, C_n is the concentration of the reference element in the unpolluted soil, Bn is the background concentration or reference value of the metal n, N is the number of metals tested, Ti_r denotes the toxic response factor of heavy metals. These factors for Pb; Cd; Zn; Cr; Ni; and Cu have values: of 5; 30; 1; 2; 5; and five, respectively [27] [31] [35] [47] [48].

2.5.2. Geoaccumulation Index (Igeo)

The geoacumulation index (Igeo) was applied to assess the contaminant contents in agricultural lands in Okpare-Olomu due to crude oil pollution [50]. The geoaccumulation index (Igeo) was used to assess the contaminant concentration in sediments and soils [50]. The geoaccumulation index (Igeo) was calculated using Equation (3).

$$\text{Igeo} = \log\left(\frac{C_n}{1.5 \times \text{Bg}}\right) \tag{3}$$

C_n is the concentration of heavy metal in soil. Bg is the reference value for each metal expressed here as concentrations of heavy metals in the control soil. 1.5 is constantly used for the possible variations of the background data due to the lithogenic effects [51].

2.5.3. Pollution Load Index (P.L.I.)

The pollution load index (P.L.I.) of each metal analyzed was evaluated using

Equation (4).

$$PLI = \left(CF_1 \times CF_2 \times \cdots \times CF_n\right)^{1/n} \quad (4)$$

The factor C.F. is the calculated contamination factor, and n is the number of heavy metals (six in the case of this study) [44]. Classification of the P.L.I. of each metal is shown in **Table 1**.

2.5.4. Potential Ecological Risk Index (PERI)

The potential ecological risk index (PERI) was computed to assess the cumulative pollution effects of multiple metals on the soil. The PERI was evaluated using the formula developed by [47], as shown in Equations (5) and (6).

$$PERI = \sum E_i \quad (5)$$

$$E_i = T_i \times CF_i \quad (6)$$

E_i is the single ecological risk index, Ti is the toxic response factor for a given metal, I (e.g. Cd = 30, Zn = 1, Pb = Ni = Cu = 5, and Cr = 2) [52]. CF_i is the calculated contamination factor for the metal of interest, $E_i < 40$ indicates low contamination, whereas $40 \leq E_i < 80$, $80 \leq E_i < 160$, $160 \leq E_i < 320$, and $E_i \geq 320$ shows a moderate, considerable, high, or significantly high risk, respectively and Cf_i indicates a low ($CF_i < 1$), moderate ($1 \leq CF_i < 3$), considerable ($3 \leq CF_i < 6$), or very high contamination ($CF_i \geq 6$) [47].

3. Results and Discussion

3.1. Heavy Metal Concentrations in Crude Oil-Polluted Agricultural Lands in Okpare-Olomu

Six (6) heavy metals were identified in high concentrations in crude oil-impacted agricultural soils in Okpare-Olomu: Cu, Pb, Ni, Cd, Cr, and Zn. The results of the analysis of heavy metal concentrations in crude oil-polluted soil from Okpare-Olomu are shown in **Figures 1-6**. The average concentration of heavy metal concentration increased in the order of Cd > Cr > Ni > Pb > Zn > Cu. Particularly, the oil-contaminated agricultural lands showed higher concentrations of heavy metals when compared to the control samples or sites. Concentration of heavy metals (mg/kg) across 24 sampling points and control ranged as follows: 0.54 - 37.1, 12 - 158, 24.1 - 7567, 147.6 - 9078, 9.05 - 28.8 and 18.5 - 8611 mg/kg for Cd, Ni, Cu, Zn, Cr, and Pb respectively. **Table 3** contains permissible levels of heavy metals in soils in different countries and Nigeria, with which concentrations of determined heavy metals were compared. The oil-contaminated soil areas showed high amounts of heavy metals compared to the control points.

According to [53], high amounts of Cd in soil have been revealed to trigger the synthesis of reactive oxygen species (R.O.C.), which tend to hinder the utilization, uptake and transport of essential nutrients and water. Thus, causing possible death of plant tissues. Cadmium showed elevated metal concentration,

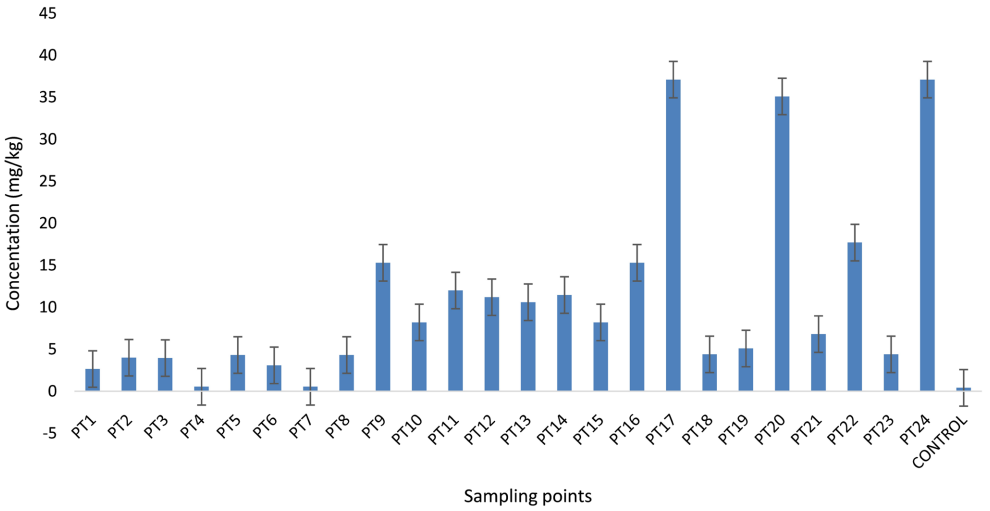

Figure 1. Concentration of Cd in crude oil-polluted soil in Okpare-Olomu community.

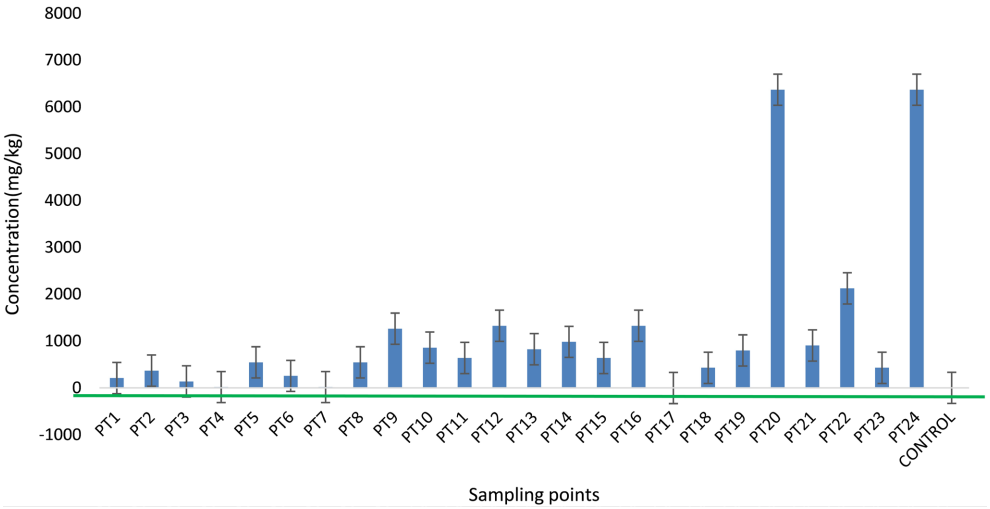

Figure 2. Concentration of Pb in crude oil-polluted soil in Okpare-Olomu community.

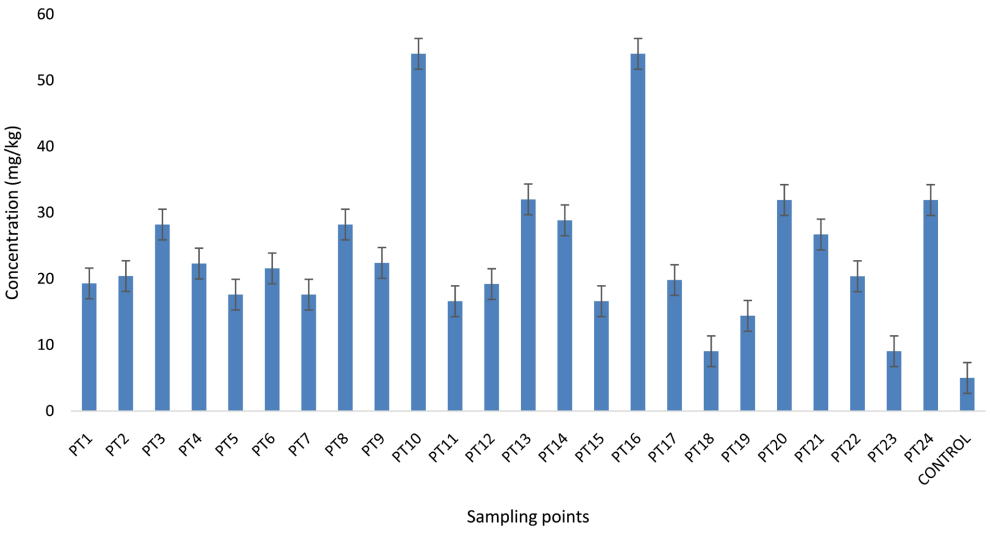

Figure 3. Concentration of Cr in crude oil-polluted soil in Okpare-Olomu community.

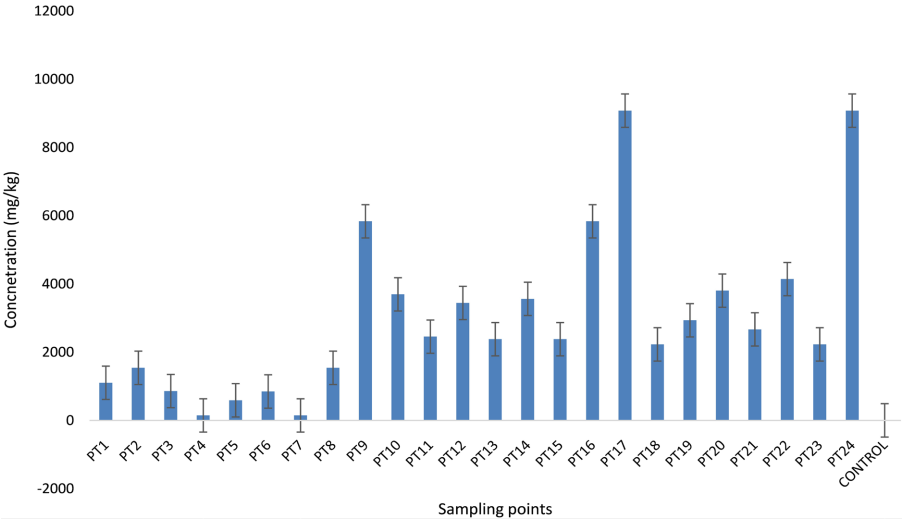

Figure 4. Concentration of Zn in crude oil-polluted soil in Okpare-Olomu community.

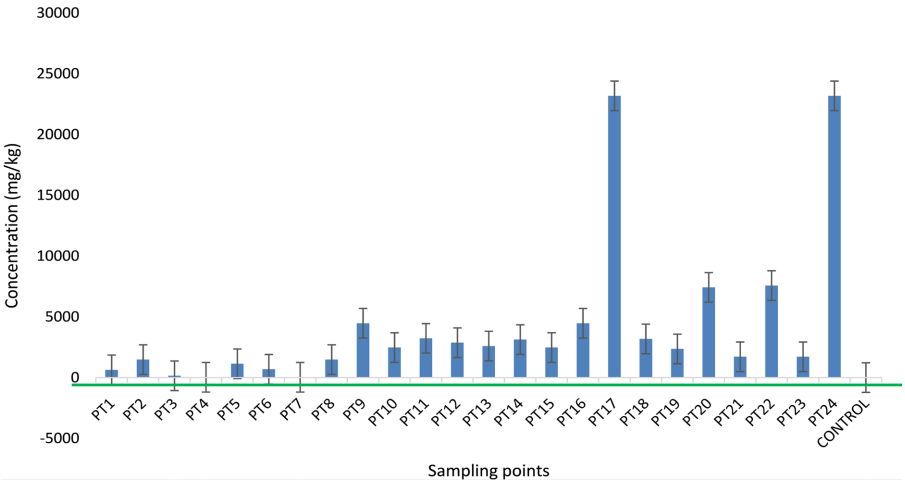

Figure 5. Concentration of Cu in crude oil-polluted soil in Okpare-Olomu community.

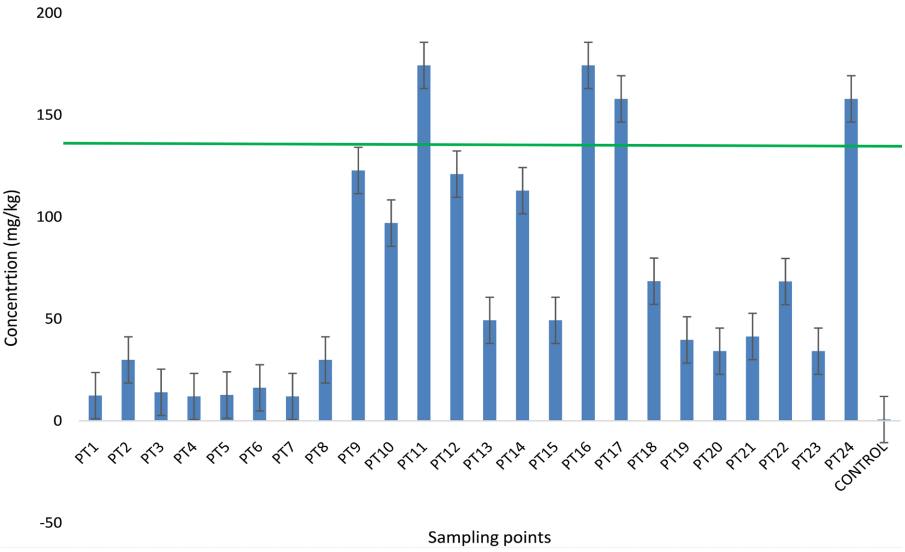

Figure 6. Concentration of Ni in crude oil-polluted soil in Okpare-Olomu community.

Table 3. Permissible allowable limits of heavy metals in soil in different countries (mg/kg).

Country	Pb	Cd	Cr	Cu	Zn	Ni
Germany	70	1	60	40	150	50
Poland	100	3	100	100	300	100
UK	450	10	130	-	-	130
Australia	300	3	50	100	200	60
Taiwan	300	5	250	200	600	200
Bulgaria	26	-	65	34	88	46
Canada	200	3	250	150	500	100
China	80	1	200	100	250	50
Tanzania	200	1	100	200	150	100
FAO/WHO	100	3	100	100	300	50
E.U. Guidelines	300	3	150	140	300	75
South Africa	20	8	7	16	240	91
Nigeria (D.P.R.)	35	100	20	-	-	140
This study	18.5 - 8611	2.7 - 37.1	9.1 - 28.8	24.1 - 23174	148 - 9078	12 - 157.9

mainly as sampling was carried up higher down the agricultural land. All points sampled recorded higher concentration values than the WHO permissible limits except PT4, PT7, and the control points, with values of 0.54 and 0.42 mg/kg, respectively (**Figure 2**). The contribution of phosphate fertilizers in the community's agricultural lands might be a factor in the high concentration of Cadmium in agricultural soils in the study area [54]. The mean Cd concentration was higher in this study when compared to Cd concentration in crude oil polluted arable land in Isikwuato, Abia state (0.76 mg. kg), crude oil polluted lands in Owerri, Okigwe, and Orlu zones in Imo State, Nigeria [55] [56].

The concentration of Pb in crude oil polluted soils from Okpare-Olomu is shown in **Figure 2**.

Analysis of Pb from crude oil polluted sites in Okpare-Olomu (**Figure 3**) revealed that only PT4, PT7, and the control points were below the permissible limit of WHO. All other sampled points were well above the permissible limits. Pb concentration in this study is higher when compared to concentrations detected in soils in the industrial area of Ho Chi Minh City in Vietnam [57]. Sewage disposal, disposal of wastes, use of fertilizers and pesticides and the exhaust of automobiles have been implicated to be other anthropogenic sources of Pb in the environment [58]. These activities are regularly being carried out in the research area, which could suggest the reason for the increased levels of Pb in the soils of the study area. However, a similar high concentration was revealed in soils in the Příbram region of the Czech Republic contaminated by a lead smelter which had concentrations as high as 2500 mg/kg [59]. By producing too many reactive oxygen species (R.O.S.), lead toxicity inhibits ATP production, lipid pe-

roxidation, and D.N.A. damage. Furthermore, [60] stated that lead inhibits seed germination, root elongation, seedling development, plant growth, transpiration, chlorophyll production, and water and protein content.

The concentration of Cr in the soil samples analyzed is shown in **Figure 3**.

Although other anthropogenic sources have been implicated to be sources of Cr and Ni in the environment, Ni in the environment has been reported to be primarily of geogenic origin [61] with a higher concentration to be in subsurface soils. **Figure 4** revealed that most sampling points have concentrations of Cr above D.P.R. limits except PT5, PT7, PT11, PT15, PT18, PT19 and PT23. High concentrations of Cr have been implicated in having toxic effects on plants, as reported by [62]. Some of such effects are seed germination inhibition, reduction of root growth, leaf chlorosis and depressed biomass [63]. The presence of Cr in the crude oil spills as trace metals could have contributed to the elevated concentration in the soil samples. Chromium concentration in this study was higher when compared to chromium in soils impacted with crude oil in the Imomo camp in the Niger Delta [64].

The concentration of Zn is crude oil polluted soil from Okpare-Olomu is shown in **Figure 4**.

Zinc (Zn) and Cu are quite important materials for enzyme production needed for the growth of plants [65]. Ambient background concentration ± 0.0005% to 0.02% of Zn is contained on the earth's crust [66]. However, excess levels of Cu and Zn in soil have been shown to be toxic to plants and can lead to symptoms such as chlorosis, necrosis, retarded growth of the plant, discolouration of the leaf of the plant, and root growth inhibition [67] [68] [69].

The concentrations of Cu from crude oil polluted soil samples from Okpare-Olomu is shown in **Figure 5**.

The Zn and Cu concentrations in the soils of the various study areas were higher than the permissible limits of WHO except for PT4 for Zn, PT4, and PT7 for Cu. Cu concentration in this study was higher when compared to crude oil-impacted soils in the Agaye community in the Ojo local government of Lagos state [70]. Similar high concentrations of Cu and Zn were also recorded in contaminated sites in North Florida at 900 - 2200 mg/kg [71].

The concentration of Niin soil samples is shown in **Figure 6**.

Ten points sampled were detected to be more than the permissible limits for Ni in soil. The most common effects of Ni in soil on plants include wilting, necrosis, plant growth inhibition, and induction of chlorosis [72]. While Ni occurs naturally in soils, [73] reported increased Nickel concentration in soils due to the introduction of crude oil to the soil. Ni in this study was higher when compared to soil samples obtained from an industrial area in Nairobi, Kenya [74].

3.2. Principal Component Analysis (P.C.A.)

Principal component analysis (P.C.A.) of the dataset could streamline the complex data from the sampling points at the Okpare-Olomu community for a bet-

ter understanding of their variability and correlations. The variables were the heavy metals, and the principal components influencing the concentrations and distribution are represented as Factors (F1, F2, F3, F4, F5 and F6), as shown in Table 4.

F1 and F2 significantly influenced the variables and contributed approximately 88.1% (F1: 70.89%; F2: 17.21%). Based on the weight of the contribution of each variable in the P.C.A., as shown in Table 3, F1 influences the contribution of crude oil to the concentration of heavy metals. At the same time, F2 represent the influence of the crude oil spill (88.1%) and natural and anthropogenic (17.21%) sources' contributions to the heavy metal's concentration in the collected soil samples. F1 strongly influenced the concentrations of Pb, Cd, Zn, Cu, Zn, and Ni, while F2 influenced the concentration of Cr.

The Biplot in Figure 7 revealed that F1 strongly influenced the presence of heavy metals in PT9, PT10, PT11, PT12, PT14, PT14, PT17, PT20, PT22 and PT24, while F2 influenced the concentrations of the metals at other sampling locations.

It indicated that almost half of the sampling points had high concentrations due to the pollution of the soil with crude oil spills.

The loadings of Cr, Ni, and Zn (0.318, 0.754, and 0.962) in PC1 (principal component 1) were higher than that of others in PC2 (−0.108, −0.258, and −0.245 for Cd, Pb, and Cu respectively) which may suggest a good correlation, and a singular identifiable source for elements in PC1, amidst influence of other sources. Zn was found to be strongly associated with Ni in PC1, contributing 70.89% to the total variance with high loadings.

High loadings (88.1%), and a good relationship (Figure 8) between Cr, Ni, and Zn, indicate contributions from crude oil pollution, as well as contributions from geological origins [75]. The reduced number of loadings (17.21%) and close relationship between Cd, Pb, and Cu could suggest their common anthropogenic origin (vehicular emissions, indiscriminate waste disposal, and pesticides

Table 4. Correlation between variable and Factor loading with eigenvalues and cumulative variability of heavy metals across all the sampling points at the Okpare-Olomu community.

	F1	F2	F3	F4	F5	F6
Pb (mg/kg)	0.925	−0.258	−0.267	0.042	−0.047	−0.050
Cd(mg/kg)	0.954	−0.108	−0.168	0.215	0.058	0.032
Cr(mg/kg)	0.318	0.892	−0.318	−0.028	−0.026	0.001
Zn (mg/kg)	0.962	0.059	0.137	−0.146	0.176	−0.007
Cu (mg/kg)	0.945	−0.245	−0.055	−0.168	−0.124	0.030
Ni (mg/kg)	0.754	0.309	0.569	0.086	−0.074	−0.009
Eigenvalue	4.253	1.033	0.546	0.106	0.058	0.004
Variability (%)	70.891	17.211	9.093	1.764	0.966	0.075
Cumulative %	70.891	88.102	97.195	98.959	99.925	100.000

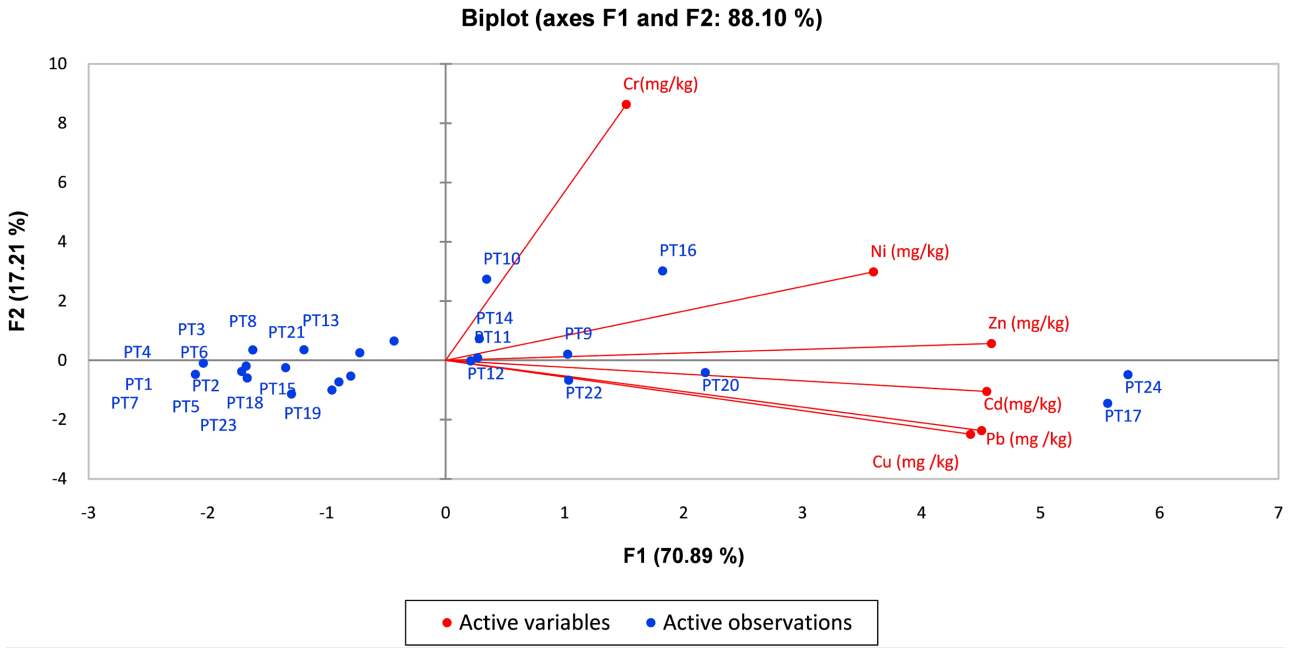

Figure 7. Principal component analysis diagram/plots.

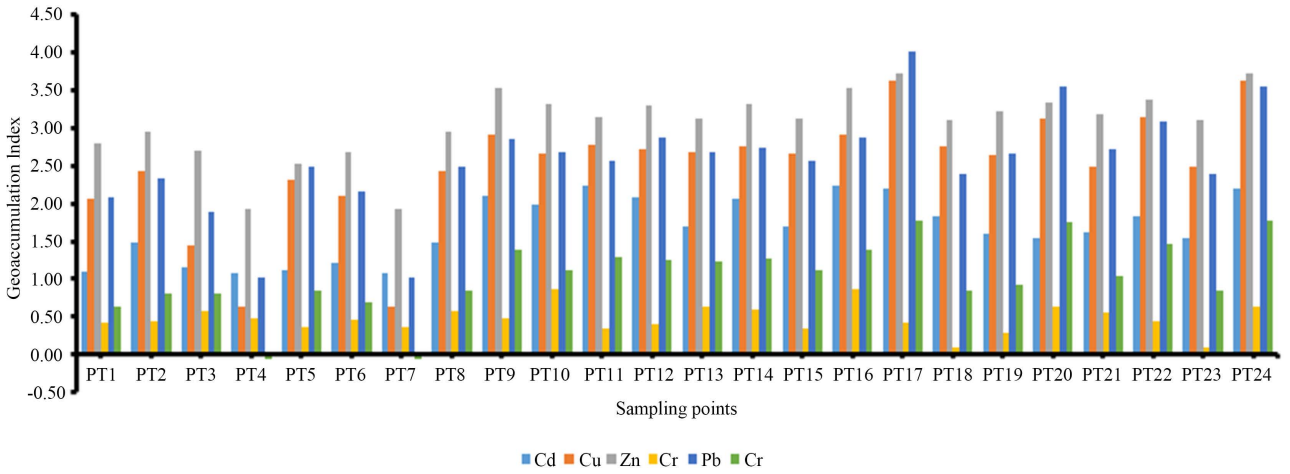

Figure 8. Geoaccumulation index (Igeo) of heavy metals in Crude oil-polluted Okpare-Olomu community.

use in agricultural lands) [76].

These findings indicate that the heavy metals in the soils from Okpare-Olomu are related to crude oil contamination and possibly other identified anthropogenic activities.

3.3. Ecological Risk Assessment of Heavy Metals in Soils of Crude Oil-Impacted Okpare-Olomu Community

3.3.1 Contamination factor (Cf) and Degree of Contamination (DoC)

These concentrations were used to calculate the ecological risk of plants in the study area. The contamination factor (Cf), degree of contamination (DoC) and pollution load index (P.L.I.) of heavy metals in crude oil polluted lands in Okpare-Olomu is presented in **Table 5**.

Table 5. Contamination factor for studied parameters in soil samples.

SP	Ni	Cu	Cd	Cr	Zn	Pb	DoC	PLI
PT1	18.7	173	6.4	3.9	941	180	18.7	172
PT2	45.0	402	9.6	4.1	1312	314	45.0	402
PT3	21.1	41.2	9.5	5.6	733	117	21.1	41.2
PT4	18.0	6.5	1.3	4.5	125	15.7	18.0	6.5
PT5	19.1	308	10.4	3.5	502	464	19.1	307
PT6	24.4	186	7.4	4.3	723	218	24.4	186
PT7	18.0	6.5	1.3	3.5	125	15.7	18.0	6.5
PT8	45.0	402	10.4	5.6	1312	463	45.0	402
PT9	185	1216	36.8	4.5	4971	1073	184	1215
PT10	146	673	19.7	10.8	3148	730	145	672
PT11	262	878	28.9	3.3	2092	543	262	878
PT12	182	782	27.0	3.8	2933	1127	182	781
PT13	74.2	705	25.5	6.4	2028	701	74.2	705
PT14	170	851	27.6	5.8	3034	835	169	850
PT15	74.2	673	19.7	3.3	2028	543	74.2	672
PT16	262	1216	36.8	10.8	4971	1127	262	1215
PT17	238	6305	89.3	4.0	7733	4.0	237	6305
PT18	103	864	10.6	1.8	1898	365	103	864
PT19	59.7	641	12.3	2.9	2500	679	59.7	640
PT20	51.4	2019	84.5	6.4	3239	5405	51.4	2019
PT21	62.3	465	16.4	5.3	2273	770	62.3	465
PT22	103	2059	42.6	4.1	3529	1804	102	2059
PT23	51.4	465	10.6	1.8	1898	365	51.4	464
PT24	238	6306	89.3	6.4	7733	5405	237	6305

DoC—Degree of contamination, P.L.I.—pollution load index.

For contamination factor (Cf), Cd and Cr ranged from moderate to very high contamination across all points sampled. Other metals such as Cu, Pb, Zn, and Ni revealed very high contamination, as shown in **Table 4**. Based on the result of this study Cf values were higher than earlier reported for oil-contaminated soils of Rumuolukwu [77] and higher than values reported for sediments of some Nun-river tributaries [78] and sediment samples from Taylor Creek [79].

Degree of Contamination (DoC) of toxic metals depicted in **Table 4** for each sampling point PT1to PT24 showed very high risks compared with considerable risk reported by [80] on crude oil contaminated soil of Biseni community, Bayelsa state Nigeria.

3.3.2. Pollution Load Index (P.L.I.)

The P.L.I. values were extremely high across all the sampling points within the study area. It was observed that the P.L.I. values were comparably higher than those of heavy metals in soil samples collected from welding workshops at an old market in Kaduna, Nigeria [81].

3.3.3. Geoaccumulation Index (Igeo)

The Igeo were calculated, and the data analyzed are shown in **Figure 8**. Seven (7) classes clearly distinguished in **Table 1** are used for describing soil contamination based on Igeo index values.

Heavy metals such as Cr and Cd were categorized in the study as unpolluted to moderately polluted. In contrast, Cu, Ni and Zn were categorized as moderately polluted to strongly polluted. In comparison, Pb was classified as moderately to strongly polluted. Generally, a high accumulation of heavy metals from crude oil pollution was observed in agricultural soils in the Okpare-Olomu community. Strong Cu, Ni, Zn, and Pb pollution can be a distress call. Increased levels of Igeo values indicate that human activity severely affects the overall quality of the soil in an area [82].

These metals are carcinogenic, and prolonged exposure can lead to cancer and other health-related issues. Other adverse effects include kidney damage and severe influence on sex hormone imbalances [83] [84].

3.3.4. Potential Ecological Risk Index (PERI) and Risk Index (R.I.)

In terms of the potential ecological risk (PERI) of oil-impacted soils in Okpare-Olomu, as depicted in **Table 6**, Ni exhibited considerable risk in PT1, PT3, PT4, PT5, PT6, and PT7. While PT2, PT8, PT19, PT20 and PT23 had high potential ecological risks. Ni in PT9, PT10, PT11, PT12, PT13, PT14, PT15, PT16, PT17, PT18, PT21, PT22, and PT24 exhibited very high potential ecological risks. Cu showed low contamination risk in PT4 and PT7 and considerate risk in PT3 only. All other sampling points recorded very high risks for Cu. Cd recorded low contamination in PT 7 and moderate contamination in PT 4 and PT 7. PT 1, PT 2, PT 3, PT 5, PT 6, PT 8, PT 18 and PT 23 recorded high potential ecological risks of Cd. Other sampling sites recorded very high risks. All sampled points were at low contamination for Cr. Zn in PT4 and PT7 recorded considerable risks, while other sampling points were at very high risks. PT17 was the only point in the sampled area that recorded low contamination of Pb. Every other sampled area was at very high risk.

The risk index (R.I.) was very high across all sampling points in this study, indicating severe pollution of the soil contaminated in Okpare-Olomu. PERI values for toxic heavy metals were high in this study compared to those earlier reported by [85], and values recorded from crude oil polluted soils in the Biseni community in Bayelsa state [80]. A lower risk index scale summation was reported in welding workshops at old Panteka market Kaduna [81]. compared to this study. R.I. of heavy metals was also higher in soils from an open dumpsite along Tombia/Amassoma road in Yenagoa metropolis [79].

Table 6. Potential ecological risk index.

SP	Ni	Cu	Cd	Cr	Zn	Pb	RI
PT1	112	345	191	7.7	940	902	2499
PT2	269	804	288	8.1	1312	1572	4257
PT3	126	82.5	285	11.3	733	586	1826
PT4	108	13.1	40.0	8.9	125	78.4	373
PT5	115	615.	311	7.0	502	2319	3871
PT6	146	372	223	8.6	723	1091	2565
PT7	108	13.1	40.0	7.0	125	78.4	371.5
PT8	269	804	311	11.3	1312	2319	5030
PT9	1108	2431	1104	8.9	4971	5369	14,994
PT10	875	1345	592	21.5	3148	3650	9633
PT11	1573	1756	866	6.6	2092	2716	9011
PT12	1092	1563	808	7.7	2933	5634	12,039
PT13	445	1410	765	12.8	2028	3506	8167
PT14	1018	1701	827	11.5	3034	4175	10,769
PT15	444	1345	592	6.6	2028	2716	7133
PT16	1573	2431	1104	21.5	4971	5634	15,737
PT17	1425	12,611	2678	7.9	7733	20.0	24,476
PT18	618	1728	317	3.6	1898	1827	6393
PT19	358	1281	368	5.7	2500	3395	7910
PT20	309	4039	2534	12.7	3240	27,026	37,161
PT21	374	929	491	10.7	2272	3847	7925
PT22	617	4118	1278	8.1	3529	9024	18,574
PT23	308	929	317	3.6	1898	1827	5284
PT24	1425	12611	2678	12.7	7733	27,026	51,487

RI—ecological risk index, S.P.—sampling points.

4. Conclusions

Results from this study revealed that the level of heavy metals such as Cu, Cd, Cr, Zn, Pb, and Ni in crude oil-polluted agricultural lands in Okpare-Olomu was well above the recommended regulatory levels specified by the World Health Organization (WHO) except for Cr. This high amount of pollution was also revealed in the ecological risk indices, which revealed a reasonable level of depletion in the overall soil quality of the community. Results trend showed increasing pollution down the sampling area, which must have resulted in downward flow due to rainfall and topography of the area, which tends to concentrate runoff. P.C.A. revealed two sources of pollution, with hydrocarbon pointing to the main culprit of pollution. Based on the heavy metals' pollution index, all sam-

pled sites revealed serious deterioration, depicting very high to moderate contamination factors, very dangerous level degree of contamination, geoaccumulation index of moderate to strong pollution, extreme level of pollution across all sampling points, low to a very high level of potential ecological risk index and very high-risk index.

While this study focused on assessment, there are various methods to address heavy metal contamination. These include excavation and removal of contaminated soil, stabilization of metals within the soil to reduce mobility, and phytoremediation, which utilizes plants to absorb and accumulate heavy metals. The most suitable method depends on the specific characteristics of the contamination site.

Several platforms exist for monitoring crude oil contamination. Government agencies often maintain databases on oil spills and environmental incidents. Additionally, remote sensing technologies using satellites and aerial imagery can be employed to detect and track oil spills over large areas.

Based on these findings, there is an urgent need to constitute a continuous ecological risk assessment program for heavy metal pollutants in the study area. Such assessment would help regulatory authorities and individuals in the community determine soil residual heavy metals of concern promptly. The regulatory authorities will need to conduct a remediation of the soil to minimize the long-term impact on human health and the environment.

Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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