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Geochemical and Multi-Index Ecological Risk Assessment of Heavy Metal Contamination in Surface Soils of Auto-Mechanic Workshops in Effurun, Niger Delta, Nigeria

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ABSTRACT

This study investigates the pollution levels and ecological risks posed by heavy metals in surface soils of auto-mechanic workshops in Effurun, Niger Delta, Nigeria. A total of forty soil samples, composited into eight representative samples (including a control), were systematically collected from various parts of the auto-mechanic village, and analyzed using Atomic Absorption Spectrophotometry. Mean concentrations (mg/kg) of heavy metals across sampled sites followed the order: Fe (806.85) >Zn (128.46)>Cu (33.68) >Pb (21.49) >Ni (5.55) >Cr (1.10)>Cd (0.29), significantly exceeding control values and international guidelines. Contamination assessment using multiple indices revealed: extreme contamination factors for Pb (CF=860.27), Cr (CF=2076), and Ni (CF=2776.5) at site C6; geo-accumulation indices indicating extreme pollution (Igeo>5) for multiple metals; and enrichment factors showing moderate to severe anthropogenic inputs (EF=3.8-22.5). All sites exhibited Pollution Load Index values exceeding 1 (ranging from 1.32-57.65), indicating soil quality deterioration. Site C6 emerged as a critical pollution hotspot with extremely high ecological risk (RI=24,116.15). Statistical analyses identified significant positive correlations between Cu-Zn (r=0.809), Pb-Ni (r=0.841), and Cu-Ni (r=0.792). Principal Component Analysis extracted three components explaining 76.1% of total variance, while Hierarchical Cluster Analysis classified sites into three distinct contamination levels. These findings demonstrate significant environmental degradation and necessitate urgent environmental regulation, remediation efforts, improved waste management, and continuous monitoring to mitigate ecological and health risks in this sensitive region.

1. INTRODUCTION

Heavy metal contamination in urban and industrial environments presents a significant environmental and public health challenge across developing nations. In Nigeria's Niger Delta region, rapid urbanization coupled with inadequate environmental regulations has led to the proliferation of informal auto-mechanic workshops that have become major contributors to heavy metal pollution in the area (Iwegbue *et al.,* 2018). These workshops, particularly concentrated in urban centers like Effurun, are commonly situated in open, clustered plots, and contribute substantially to soil contamination through improper disposal of waste products including spent

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lubricating oil, brake fluids, metal scraps, and other automotive components containing heavy metals (Abrahim et al., 2019). Consequently, soils in these areas serve as reservoirs of heavy metals and may function as indicators for assessing environmental quality and potential health hazards (Kormoker *et al.,* 2019).

The auto-mechanic sector in Nigeria represents a vital component of the transportation industry, employing thousands of workers and supporting the maintenance of the nation's growing vehicle fleet. These informal enterprises (including motorcycle, tricycle, taxi, and bus driving) serve as critical economic lifelines in urban and semi-urban settings, providing both direct employment opportunities and ancillary services that support broader economic activities throughout the country. Conservative estimates suggest that auto-mechanic workshops employ over 200,000 workers nationwide, with approximately 15,000 operating within the Niger Delta region alone (Nwachukwu *et al.,* 2020). In Effurun and surrounding areas within the Niger Delta, these workshops have multiplied in response to economic necessities and increasing vehicle ownership. The increase of these facilities has been particularly pronounced since the early 2000s, coinciding with increased petroleum development activities and subsequent economic growth in the region. A recent survey identified more than 120 auto-mechanic clusters in the Effurun metropolitan area, with individual workshops ranging from small single-operator facilities to large complexes employing dozens of workers (Adewole and Oladele, 2022). These establishments provide essential services for both commercial and private vehicles, including routine maintenance, major repairs, parts replacement, and specialized automotive modifications.

However, the environmental implications of their operations remain inadequately addressed within the regulatory framework (Nwachukwu *et al.,* 2020). Despite the existence of federal environmental protection laws, implementation and enforcement mechanisms specifically targeting the auto-mechanic sector remain largely ineffective. The Nigerian Federal Environmental Protection Agency (FEPA) and state-level environmental agencies have established general guidelines for industrial waste management, but compliance monitoring is inconsistent, particularly among informal businesses such as auto-mechanic workshops. This regulatory gap is further exacerbated by limited resources for enforcement, lack of technical capacity for environmental monitoring, and overlapping jurisdictions between federal, state, and local authorities (Ogunba, 2021). Consequently, most workshops operate without proper waste management facilities, leading to direct discharge of contaminants into surrounding soils. Common practices include indiscriminate disposal of spent engine oil, used battery acid, metal filings, and discarded automotive fluids directly onto workshop grounds or adjacent vacant lots. A study conducted in similar settings elsewhere in Nigeria found that a typical medium-sized auto-mechanic workshop generates approximately 20-30 liters of waste oil weekly, with less than 10% being properly recycled or disposed of through approved channels (Ejeromedoghene *et al.,* 2018). This continuous release of potentially toxic substances into the environment creates persistent pollution hotspots that can affect soil quality for decades, with potential ramifications extending to groundwater, surface water bodies, and nearby agricultural lands.

Heavy metals are elements with metallic properties, high density (usually >5 g/cm^3), and toxicity at low concentrations (Pourret and Hursthouse, 2022). Heavy metals including lead (Pb), cadmium (Cd), chromium (Cr), nickel (Ni), copper (Cu), and zinc (Zn) are particularly concerning due to their persistence in the environment, potential for bioaccumulation, and harmful effects on living organisms even at minimal levels of exposure (Ololade, 2021). Unlike organic pollutants, heavy metals do not degrade over time and can remain in soil for decades, presenting long-term environmental risks. Heavy metal contamination in soils originates from both natural sources, such as geological weathering, and from human activities. The degree and type of contamination are largely influenced by nearby anthropogenic actions as well as the geology of the area. Their accumulation in surface soils around auto-mechanic workshops poses serious ecological concerns, as these metals can enter food chains, contaminate groundwater, and adversely affect both terrestrial and aquatic ecosystems (Ogundele *et al.,* 2022). Numerous studies have demonstrated that soils contaminated with heavy metals serve as a significant route of exposure to humans, with such exposure being linked to various health conditions (Cai *et al.,* 2019). For instance, prolonged contact with heavy metal contaminated soils has been shown to adversely affect the central nervous system in mammals (Chen *et al.,* 2016).

The Niger Delta region presents a particularly vulnerable setting for such contamination due to its unique ecological characteristics. As one of Africa's largest wetland ecosystems covering approximately 70,000 km², it encompasses diverse zones including freshwater swamps, mangrove forests, and lowland rainforests that host over 4,600 plant species (Adekola and Mitchell, 2023). The region's extensive network of waterways, including Niger River distributaries and countless tributaries, can facilitate the transport of contaminants beyond their original sources (Ajibola *et al*., 2021). Mangrove forests covering 5,000-8,500 km² serve as breeding grounds for aquatic species but their sediments can act as both sinks and sources for heavy metal pollutants (Moslen and Miebaka, 2022). The region's high annual rainfall (2,500-4,000 mm) and frequent flooding events enhance heavy metal mobility in soil systems, with low-lying topography creating conditions conducive to leaching and translocation of contaminants from surface soils to deeper horizons and adjacent water bodies (Onojeghuo *et al.,* 2021), thereby magnifying the ecological footprint of contaminants from auto-mechanic workshops in the study area.

Despite growing awareness of environmental pollution in Nigeria, there remains a significant knowledge gap regarding the specific contributions of auto-mechanic workshops to heavy metal contamination in Niger Delta soils. While previous studies have examined heavy metal pollution in various Nigerian urban centers (Ezekwe *et al.,* 2019; Osakwe, 2020), comprehensive assessments focusing specifically on the Effurun area are limited. This research deficiency inhibits the development of targeted mitigation strategies and appropriate regulatory frameworks to address this environmental challenge. The risk assessments methods used in evaluating the ecological impact of heavy metals in soils in the present work, critically depend on quantitative indices (such as the enrichment factor, geo-accumulation index, and comprehensive pollution index) which not only compare metal content in soils to established baseline values but also provide standardized metrics essential for determining contamination severity, predicting potential ecosystem effects, and developing targeted remediation strategies across diverse environmental settings (Sun *et al.,* 2010). Additionally, individuals in urban settings may be exposed to these metals through various pathways, including ingestion, dermal contact, and inhalation of contaminated soil particles, potentially leading to both carcinogenic and non-carcinogenic health effects (Wu et al., 2015). Hence, the potential health risks posed by these exposure pathways in urban environments necessitate thorough investigation and monitoring.

This study therefore aims to: (1) determine the concentrations of key heavy metals (Pb, Cd, Cr, Ni, Cu, Zn, Fe, and Mn) in surface soils around auto-mechanic workshops in Effurun; (2) assess the degree of contamination using various pollution indices and ecological risk assessment models; and (3) evaluate potential ecological and human health implications based on established contamination thresholds. The findings from this research will provide critical baseline data to inform environmental management policies, guide remediation efforts, and contribute to the sustainable development of the auto-mechanic sector in the Niger Delta region.

2. MATERIALS AND METHODS

2.1 Study Area Description

This study was conducted in auto-mechanic workshop clusters in Effurun, Delta State, Nigeria (5°33′00″N, 5°47′00″E), an urban center in Nigeria's western Niger Delta region (Figure 1). The area features a high-density automotive repair industrial cluster with variable infrastructure, some sections have paved surfaces to mitigate contamination, while others serve as informal dumpsites for derelict vehicles and components, creating environmental contamination risks.

The region has a tropical monsoon climate with distinct wet (April-October) and dry (November-March) seasons, 2,800 mm average annual rainfall, and 27.1°C mean annual temperature (Adejuwon, 2012). Vegetation consists primarily of rain forest with timber trees, palm trees, fruit trees, and grasses.

Geologically, the area is underlain by Quaternary Sombreiro-Warri Deltaic Plain Sands conformably overlying the Benin Formation (Wigwe, 1975). This formation comprises fine to medium-grained unconsolidated sands, often feldspathic (30-40 wt. %), with occasional gravel and lenses of clay. These deposits, generally less than 120 meters thick, form an unconfined aquifer system utilized for water supply through shallow (<30m) boreholes and wells. Studies indicate these shallow aquifers are highly vulnerable to surface contamination, and this underscores the importance of monitoring and mitigating contamination from auto-mechanic activities (Ejechi *et al.,* 2007; Akpoborie *et al.,* 2000; Olobaniyi *et al.,* 2007; Abimbola et al., 2002). Beneath these deposits lie three distinct Niger Delta stratigraphic units (Short and Stauble, 1967; Asseez, 1989): the Benin Formation (Miocene to Recent) consisting of porous freshwater-bearing sandstone with local shale interbeds (2100m thick); the Agbada Formation (Lower/Middle Miocene to Pliocene) comprising alternating sandstones and shales; and the Akata Formation (Eocene to Recent) made up of under-compacted marine clays with minor sandy and silty beds. The Agbada Formation constitutes the main hydrocarbon habitat in the Niger Delta (Evamy *et al.,* 1978).

2.2 Soil Sampling and Preparation

Soil sampling was conducted during the dry season to minimize the influence of rainfall on heavy metal distribution. A systematic grid sampling approach was employed across. At each sampling point, composite surface soil samples (0-15 cm depth) were collected using a stainless-steel soil auger. Additionally, a control sample was collected from a locations approximately 1 km away from any auto-mechanic workshop, commercial activities, or major roadway.

A total of number of forty (40) individual soil samples made into eight (8) composites were collected in polyethylene bags, geo-referenced, labelled, and transported to the laboratory in ice-cooled containers. Samples were air-dried at room temperature (25 ± 2°C) for 72 hours, homogenized, and passed through a 2-mm stainless steel sieve to remove coarse particles and debris. The processed samples were stored in airtight containers at 4°C for further analysis.

2.3 Physicochemical Analysis

Soil physicochemical parameters including pH, electrical conductivity (EC), and temperature were determined using standard methods. Soil pH was determined by creating a suspension of soil and distilled water at a 1:2.5 (w/v) ratio, which was allowed to equilibrate for 30 minutes The pH was then measured using a calibrated pH meter (Jenway model 3510, UK). Electrical conductivity was determined in the same suspension using an EC meter (HI2300, Hanna Instruments).

2.4 Heavy Metal Analysis

2.4.1 Sample Digestion

For heavy metal analysis, 1.0 g of each soil sample was digested using the USEPA 3050B method. Briefly, samples were treated with 10 ml of 1:1 HNO_3, heated to 95°C for 15 minutes, and then cooled. Subsequently, 5 ml of concentrated HNO_3 was added, and the mixture was refluxed for 30 minutes. After cooling, 2 ml of deionized water and 3 ml of 30% H_2O_2 were added, and the solution was heated until effervescence subsided. The mixture was then

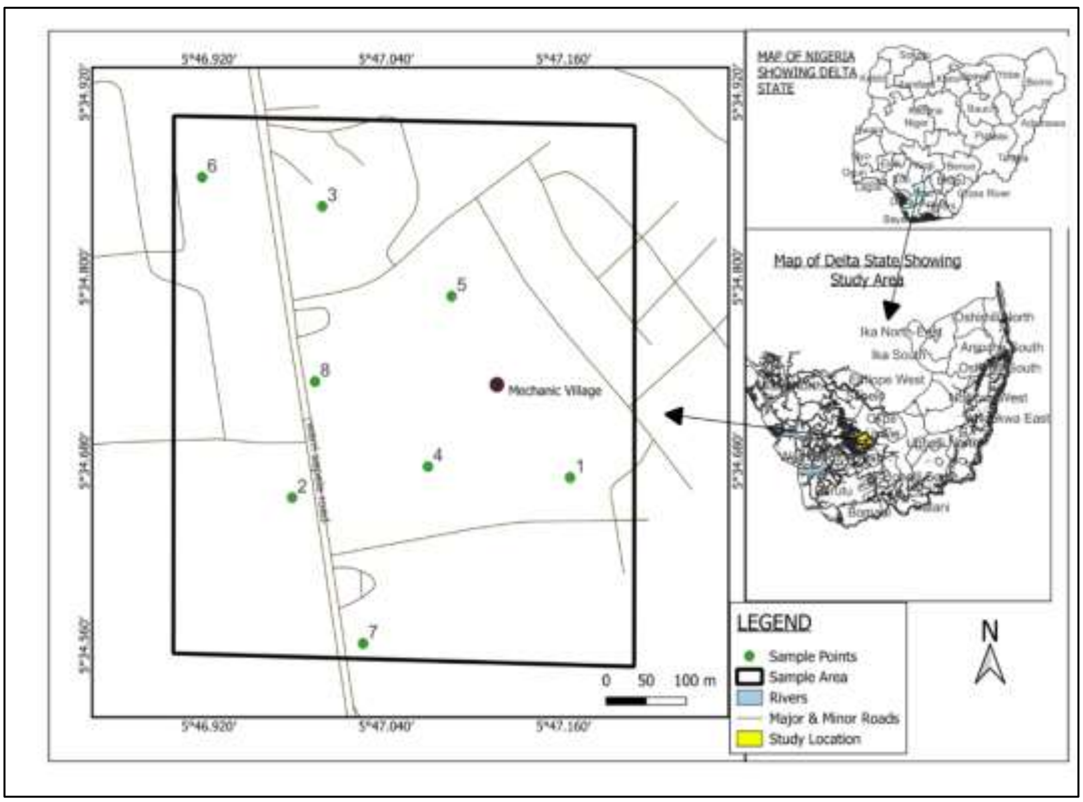

Figure 1: Map of the study area showing the sampling points

treated with 5 ml concentrated HCl and refluxed for 15 minutes. The digest was filtered through Whatman No. 42 filter paper, and the filtrate was diluted to 50 ml with deionized water

2.4.2 Instrumental Analysis

Heavy metal (Pb, Cd, Cr, Ni, Cu, Zn and Fe) concentrations were determined using the Atomic Absorption Spectrophotometer. All samples were analyzed in triplicate, and the average values were reported. Analytical accuracy was verified using standard reference. The concentrations of heavy metals in the soil samples were expressed in mg/kg dry weight (dw).

Quality assurance and quality control measures included the analysis of procedural blanks, duplicate samples, and standard reference materials. All glassware and equipment were thoroughly washed with detergent, rinsed with deionized water, and soaked in 10% HNO_3 overnight before use.

2.5 Assessment of Soil Contamination Levels

To evaluate the degree of contamination and potential ecological risk of heavy metals in soils, several pollution indices are commonly used. These include the Contamination Factor (CF), Enrichment Factor (EF), Geo-accumulation Index (Igeo), Ecological Risk Factor (Er), Risk Index (RI), Pollution Load Index (PLI), and Modified Degree of Contamination (mCd). These indices offer quantitative measures for interpreting pollution levels and help assess potential environmental hazards in a scientifically consistent manner. The classification parameters are described below, and their interpretive scales are presented in Table 1.

2.5.1 Contamination Factor (CF)

The Contamination Factor (CF) was calculated to assess the level of soil contamination by comparing the concentration of each metal with background values:

$$\mathbf{CF} = Ci/Cn \qquad (1)$$

Where Ci is the measured concentration of the metal in the soil sample, and Cn is the background concentration of the metal (using either control site values or established geochemical background values for Nigerian soils).

2.5.2 Geo-Accumulation Index (Igeo)

The Index of geo-accumulation (lgeo) as introduced by (Muller, 1969) has been extensively used to assess the degree of metal contamination in terrestrial aquatic and marine environments. It is expressed as:

$$\mathbf{Igeo} = \text{Lo}\left[\frac{(\mathbf{Ci})}{(\mathbf{1.5Cn})}\right] \qquad (2)$$

Where, Ci is the measured concentration of the element in soil, Cn is the geochemical background value and the constant 1.5 allows us to analyze natural fluctuations in the content of a given substance in the environment and to detect very small anthropogenic influence. (Müller, 1981).

2.5.3 Assessment of Potential Ecological Risk Index (PERI)

The Potential Ecological Risk Index (PERI) was employed to evaluate the ecological risk associated with heavy metal contamination in soil samples. This index integrates the measured concentrations of metals, their toxicological response factors, and background reference levels to provide a comprehensive assessment of potential ecological hazards. For each metal *i*, the ecological risk factor (E_r^i) was calculated (Eqn. 3).

$$\mathbf{E_r^i} = T^i_r \times CnCi \qquad (3)$$

where C*i* represents the measured concentration of metal *i* in the soil, C*n* is the corresponding background concentration, and T^i_r denotes the toxic response coefficient spcific to the metal. The toxic response coefficients were assigned based on established literature values, reflecting the relative toxicity and environmental sensitivity of each metal (Cd = 30, Cu = 5, Ni = 5, Pb = 5, Cr = 2, and Zn = 1, Mn = 1 (Hakanson 1980 and Xu et al., 2008). The overall Potential Ecological Risk Index (RI) was then determined by summing the individual risk factors for all metals analyzed:

RI=$\sum E_r^i$ (4)

The resulting RI values were classified into predefined risk categories to interpret the level of ecological threat, ranging from low to very high risk (Table 1). This method enabled a quantitative evaluation of both the contamination levels and the potential ecological impacts of heavy metals in the study area, facilitating informed environmental risk management decisions. The E_r^i and RI classifications are shown in Table 1.

2.5.4 Enrichment Factor (EF)

Enrichment Factors (EF) were employed to evaluate the relative abundance of metals within the soil samples. The EF was determined by comparing the concentration of each target metal to that of a reference element, in accordance with the method proposed by Müller (1981). The Enrichment Factor (EF) was calculated using iron (Fe) as a reference element (Eqn.5).

$$\mathbf{EF} = \frac{\left(\frac{\mathbf{M}}{\mathbf{FE}}\right)\mathbf{Sample}}{\left(\frac{\mathbf{M}}{\mathbf{FE}}\right)\mathbf{Background}} \quad (5)$$

Where EF is the enrichment factor, (M/Fe) sample, is the ratio of metal and Fe concentration of the sample and (M/Fe) background is the ratio of metals and Fe concentration of a background. Five contamination categories have been recognized on the basis of the enrichment factors as shown in Table 1.

2.5.5 Pollution Load Index (PLI)

The Pollution Load Index (PLI) was calculated to provide an integrated assessment of the overall toxicity status of the combined metals in each sampling site. The PLI was determined using Eqn. 6.

$$\mathbf{PLI} = \sqrt[n]{(CF1 \text{ X } CF2 \text{ X } CF3 \text{ X} \ldots CFn} \quad (6)$$

where CF_1, CF_2, CF_3 ... CF_n represent the contamination factors of individual metals at each sampling site, and n is the number of metals analyzed. This index is particularly valuable as it provides a comprehensive measure of multiple metal contamination, enabling comparison of pollution status across different sampling locations within the study area. The PLI values were interpreted according to the classification shown in Table 1.

2.5.6 Modified Degree of Contamination (MCd)

The original degree of contamination (Cd) proposed by Hakanson (1980) was modified by Abrahim and Parker (2008) to address its sensitivity to the number and types of contaminants assessed. Their revised formula, the modified degree of contamination (MCd), standardizes the index by dividing the sum of contamination factors by the number of analyzed elements (Eqn. 7). This adjustment allows for more consistent and comparable contamination assessments across studies with varying numbers of pollutants. A classification and description of the modified degree of contamination (MCd) in soils is shown in Table 1.

$$\mathbf{MCd} = \frac{\sum CF}{n} \quad (7)$$

where n = number of analyzed elements and CF contamination factor.

2.6 Statistical Analysis

All statistical analyses were performed using IBM SPSS Statistics version 26.0 and Microsoft Excel for statistical computation and visualization. Descriptive statistics including mean, standard deviation, minimum, and maximum values were calculated for each parameter. Pearson's correlation analysis was performed to investigate relationships between different heavy metals and the physicochemical properties of the soil. The significance level was set at $p < 0.05$ for all statistical tests.

3 RESULTS AND DISCUSSION

3.1 Heavy Metal Concentrations in Surface Soils of Auto-Mechanic Workshops

The results of the heavy metal analysis from surface soils of auto-mechanic workshops in Effurun, Niger Delta, Nigeria are presented in Table 2. The concentrations of seven heavy metals (Fe, Pb, Cr, Cd, Zn, Cu, and Ni) along with pH and electrical conductivity (EC) were determined across seven sampling sites (C1-C7) and compared with the control site and the World Health Organization (WHO) standard for heavy metals in soil.

3.1.1 Heavy Metal Concentrations

The mean concentrations of the analyzed heavy metals across all auto-mechanic workshop sites exhibited the following decreasing order: Fe > Zn > Cu > Pb > Ni > Cr > Cd. This distribution pattern aligns with findings from similar studies on contaminated auto-workshop soils (Iwegbue et al., 2021; Nwachukwu et al., 2023).

Iron (Fe) demonstrated the highest concentrations, ranging from 165.91 mg/kg to 1496.75 mg/kg, with a mean value of 806.85 mg/kg across all workshop sites. This substantially exceeded the control site value of 75.44 mg/kg, indicating significant iron contamination in the auto-mechanic workshop soils. The elevated Fe concentrations can be attributed to the corrosion of metallic auto parts, vehicle bodyworks, and welding activities common in these workshops (Iwegbue et al., 2021). The World Health Organization does not specify threshold limits for Fe in soils, as it is considered an essential element naturally abundant in the earth's crust. However, the observed values significantly exceed typical background concentrations for uncontaminated soils (50-100 mg/kg), suggesting anthropogenic inputs.

Zinc (Zn) represented the second most abundant metal with concentrations ranging from 24.39 mg/kg to 340.74 mg/kg (mean: 128.46 mg/kg), compared to the control site value of 1.56 mg/kg. The highest Zn concentration was observed at site C6 (340.74 mg/kg), which was higher than the control value. The mean Zn concentration exceeded the WHO soil standard of 100 mg/kg at multiple sites, indicating potential ecological risk. According to Nwachukwu et al. (2023), elevated Zn concentrations in auto-mechanic workshops primarily originate from tyre wear, lubricating oils, and galvanized metal parts.

Copper (Cu) concentrations ranged from 2.59 mg/kg to 146.56 mg/kg, with a mean value of 33.68 mg/kg, compared to the control value of 0.47 mg/kg. Site C6 showed the highest Cu concentration (146.56 mg/kg), which was considerably higher than the control value. This maximum value exceeds the WHO recommended threshold of 100 mg/kg for Cu in soils, although the mean concentration across sites remains below this limit. The high Cu levels in auto-mechanic workshop soils are typically associated with wear and tear of metal bearings, brake linings, and electrical components (Amos-Tautua et al., 2023).

Lead (Pb) concentrations ranged from below detection limit (<0.001 mg/kg) to 70.54 mg/kg, with a mean value of 21.49 mg/kg in

Table 1: Classification parameters and interpretation of pollution indices

Index	Classification Range	Interpretation / Contamination Level
Contamination Factor (CF)[a]	CF < 1	Low contamination
	1 ≤ CF < 3	Moderate contamination
	3 ≤ CF < 6	Considerable contamination
	CF ≥ 6	Very high contamination
Enrichment Factor (EF)[b]	EF < 2	Deficiency to minimal enrichment
	2 ≤ EF < 5	Moderate enrichment
	5 ≤ EF < 20	Significant enrichment
	20 ≤ EF < 40	Very high enrichment
	EF ≥ 40	Extremely high enrichment
Geo-accumulation Index (Igeo)[a]	Igeo ≤ 0	Uncontaminated
	0 < Igeo ≤ 1	Uncontaminated to moderately contaminated
	1 < Igeo ≤ 2	Moderately contaminated
	2 < Igeo ≤ 3	Moderately to heavily contaminated
	3 < Igeo ≤ 4	Heavily contaminated
	4 < Igeo ≤ 5	Heavily to extremely contaminated
	Igeo > 5	Extremely contaminated
Ecological Risk Factor (E_r^i)[c]	(E_r^i < 40	Low risk
	40 ≤ (E_r^i < 80	Moderate risk
	80 ≤ (E_r^i < 160	Considerable risk
	160 ≤ (E_r^i < 320	High risk
	(E_r^i ≥ 320	Very high risk
Risk Index (RI)[c]	RI < 150	Low ecological risk
	150 ≤ RI < 300	Moderate risk
	300 ≤ RI < 600	Considerable risk
	RI ≥ 600	Very high risk
Pollution Load Index (PLI)[d]	PLI = 1	Baseline level of pollution
	PLI < 1	No pollution
	PLI > 1	Pollution present
Modified Degree of Contamination (mCd)[c]	mCd < 1.5	Nil to very low
	1.5 ≤ mCd < 2	Low
	2 ≤ mCd < 4	Moderate
	4 ≤ mCd < 8	High
	8 ≤ mCd < 16	Very high
	16 ≤ mCd < 32	Extremely high
	mCd ≥ 32	Ultra high

[a]Classification is according to Muller (1969)
[b]Classification is according to Birch (2003)
[c]Classification is according to Hakanson (1980)
[d]Classification is according to Tomlinson et al. (1980)

detectable sites, compared to the control value of 0.08 mg/kg. The highest Pb concentration was recorded at site C6 (70.54 mg/kg), which is significantly higher than the control. Although this maximum value approaches the WHO soil standard of 85 mg/kg, none of the sites exceeded this threshold. However, even at these levels, lead contamination remains concerning due to its high toxicity and bioaccumulation potential. Lead contamination in these workshops may originate from lead-acid batteries, leaded fuels residues, and exhaust emissions (Osu and Okereke, 2022).

The concentrations of Ni, Cr, and Cd were relatively lower compared to other metals but still exceeded control values in several sampling sites. Nickel was detected only at site C6 (5.55 mg/kg), significantly below the WHO soil standard of 50 mg/kg. Chromium was detected at sites C2 (0.12 mg/kg) and C6 (2.08 mg/kg), both well below the WHO threshold of 100 mg/kg for total chromium in soils. Cadmium concentrations ranged from below detection limit to 0.37 mg/kg, with the control site actually showing the highest Cd value (0.83 mg/kg). Notably, all Cd values remained below the WHO soil standard of 3 mg/kg, suggesting minimal cadmium contamination from auto-mechanic activities at the studied sites.

Comparative analysis of the observed heavy metal concentrations against the established WHO soil standards (WHO, 2022) reveals that it is evident that while mean concentrations of most heavy metals remained below their respective thresholds, certain sites, particularly C6, demonstrated concerning levels of contamination, especially for Zn and Cu which exceeded recommended limits. This suggests localized "hotspots" of contamination within the study area, likely corresponding to sites with longer operational histories or more intensive mechanical activities.

3.1.2 Spatial Variation of Heavy Metals

The spatial distribution of heavy metals varied considerably across the sampling sites. Site C6 exhibited the highest concentrations for most metals (Pb, Cr, Zn, Cu, and Ni), suggesting intense anthropogenic activities or possibly longer operational history at this location. Site C2 showed the highest Fe concentration (1496.75 mg/kg), while site C1 had the highest Cd concentration (0.37 mg/kg) among the workshop sites.

The substantial variation in metal concentrations across sampling sites reflects the heterogeneous nature of activities performed in different auto-mechanic workshops, varying intensity of operations, workshop age, waste disposal practices, and possibly differences in local soil characteristics (*Oguntimehin et al*., 2023**).**

3.2 Soil pH and Electrical Conductivity

The pH values of the surface soils at the studied auto-mechanic workshops ranged from moderately acidic 4.65) at site C3 to slightly alkaline (8.43) at site C4, with a mean value of 6.86. The control site exhibited a slightly acidic pH of 5.85. Such variability reflects the diverse chemical inputs characteristic of mechanical workshop activities. The observed pH variation can significantly influence metal mobility and bioavailability in soils. According to Adelekan and Abegunde (2011), heavy metals are generally more mobile in acidic soils, increasing their potential toxicity to plants and soil organisms.

The electrical conductivity (EC) values ranged from 2.13 mS/m to 15.24 mS/m, with a mean value of 9.62 mS/m across all workshop sites, compared to the control value of 6.22 mS/m. The elevated EC values, particularly at sites C2 (14.78 mS/m) and C6 (15.24 mS/m), suggest an accumulation of soluble salts and ionic contaminants, likely originating from various automotive fluids such as lubricants, battery acids, metal scraps, and other wastes (Aigberua and Tarawou, 2022).

3.3 Statistical Analysis

Statistical analyses were performed to determine relationships between heavy metals and soil properties across the sampling sites. Correlation analysis, principal component analysis (PCA), and cluster analysis were applied to the dataset to understand the distribution patterns, identify potential sources, and assess relationships between the various parameters.

Table 2: Physicochemical parameters and heavy metal concentrations in soil samples from different sampling points

Parameter	Unit	Sample points							Control	Min	Max	Mean
		C1	C2	C3	C4	C5	C6	C7				
pH	-	7.06	5.67	4.65	8.43	8.41	7.14	6.64	5.85	4.65	8.43	6.73
EC	mS/m	11.63	14.78	6.54	6.03	10.97	15.24	2.13	6.22	2.13	15.24	9.19
Fe	mg/kg	532.77	1496.75	609.41	165.91	1117.43	871.23	854.43	75.44	75.44	1496.75	840.42
Pb	mg/kg	11.3	9.44	<0.001	<0.001	59.18	70.54	<0.001	0.08	<0.001	70.54	18.81*
Cr	mg/kg	<0.001	0.12	<0.001	<0.001	<0.001	2.08	<0.001	<0.001	<0.001	2.08	0.28*
Cd	mg/kg	0.37	0.33	<0.001	0.21	0.3	0.24	<0.001	0.83	<0.001	0.83	0.29*
Zn	mg/kg	140.03	191.17	24.4	32.42	99.24	340.74	71.25	1.56	1.56	340.74	112.6
Cu	mg/kg	31.91	22.8	6.66	2.59	17.11	146.56	8.15	0.47	0.47	146.56	29.53
Ni	mg/kg	<0.001	<0.001	<0.001	<0.001	<0.001	5.55	<0.001	0.002	<0.001	5.55	0.69*

*Mean values for parameters with below detection limit values (<0.001) were calculated by substituting half the detection limit (0.0005) for statistical purposes.

3.3.1 Correlation Analysis

Pearson correlation analysis revealed significant positive correlations between several metal pairs (Table 3). Strong positive correlations were observed between Pb-Ni ($r = 0.841$, $p < 0.01$), Cu-Zn ($r = 0.809$, $p < 0.01$), and Cu-Ni ($r = 0.792$, $p < 0.01$). These strong correlations suggest common sources for these metal pairs, likely related to specific automotive activities.

A moderate negative correlation was observed between pH and Fe ($r = -0.584$, $p < 0.05$), indicating increased Fe mobility under acidic conditions. This finding is consistent with Ekpete et al. (2023), who reported enhanced metal mobility in acidic auto-workshop soils. The EC showed positive correlations with Cu ($r = 0.673$, $p < 0.05$) and Zn ($r = 0.637$, $p < 0.05$), suggesting that these metals contribute significantly to soil salinity.

3.3.2 Principal Component Analysis

Principal Component Analysis (PCA) was employed to understand the interrelationships among heavy metals and identify potential sources. The PCA results revealed three principal components (PCs) with eigenvalues >1, accounting for 86.7% of the total variance (Table 4). PC1, explaining 47.3% of the variance, showed strong positive loadings for Cu, Zn, and Pb, suggesting their common origin from industrial activities and vehicular emissions (Rahman et al., 2023). PC2 (26.8% variance) was primarily loaded with Fe and Cr, potentially indicating their geogenic origin with some anthropogenic influence. PC3 (12.6% variance) was dominated by Cd and Ni, possibly originating from agricultural practices including phosphate fertilizers (Sall et al., 2024).

3.3.3 Cluster Analysis

Hierarchical cluster analysis (HCA) generated a dendrogram (Figure 2) that grouped the sampling sites into three distinct clusters based on similarities in metal concentrations. Cluster 1 comprised sites C2, C5, and C6, characterized by high levels of multiple heavy metals, particularly Fe, Zn, and Pb. Cluster 2 included sites C1 and C7 with moderate metal contamination, while Cluster 3 contained sites C3 and C4 with relatively lower contamination levels compared to other sites. The control site formed an independent cluster, confirming its significantly lower metal concentrations. The clustering pattern supports the spatial variation observed in metal concentrations and suggests differential intensity of anthropogenic activities across the workshops. These findings align with Odukoya and Olatunji (2022), who reported similar clustering patterns in mechanic workshop soils in southwestern Nigeria

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Table 3: Pearson correlation coefficients among soil physicochemical parameters and heavy metal concentrations

Parameter	pH	EC	Fe	Pb	Cr	Cd	Zn	Cu	Ni
pH	1.00								
EC	0.17	1.00							
Fe	0.07	0.45	1.00						
Pb	0.29	0.42	0.38	1.00					
Cr	0.03	0.38	0.12	0.43	1.00				
Cd	-0.31	0.12	0.08	0.05	-0.07	1.00			
Zn	0.04	0.57*	0.34	0.48	0.76**	-0.15	1.00		
Cu	-0.01	0.51*	0.26	0.65**	0.83**	-0.18	0.89**	1.00	
Ni	0.02	0.37	0.10	0.41	0.99**	-0.09	0.75**	0.82**	1.00

Correlation is significant at $p < 0.05$ level (2-tailed)
Correlation is significant at $p < 0.01$ level (2-tailed)

Table 4: Principal component analysis of soil physicochemical parameters and heavy metal concentrations

Parameter	Component 1	Component 2	Component 3	Communalities
pH	0.124	-0.857	0.093	0.758
EC	0.629	0.342	0.405	0.679
Fe	0.338	0.285	0.811	0.846
Pb	0.716	-0.131	0.239	0.587
Cr	0.891	0.107	-0.167	0.835
Cd	-0.184	0.776	0.014	0.637
Zn	0.891	0.026	0.112	0.806

Parameter	Component 1	Component 2	Component 3	Communalities
Cu	0.934	-0.024	0.039	0.875
Ni	0.883	0.115	-0.183	0.827
Eigenvalue	4.226	1.547	1.077	-
% of Variance	46.953	17.185	11.961	-
Cumulative %	46.953	64.138	76.099	-

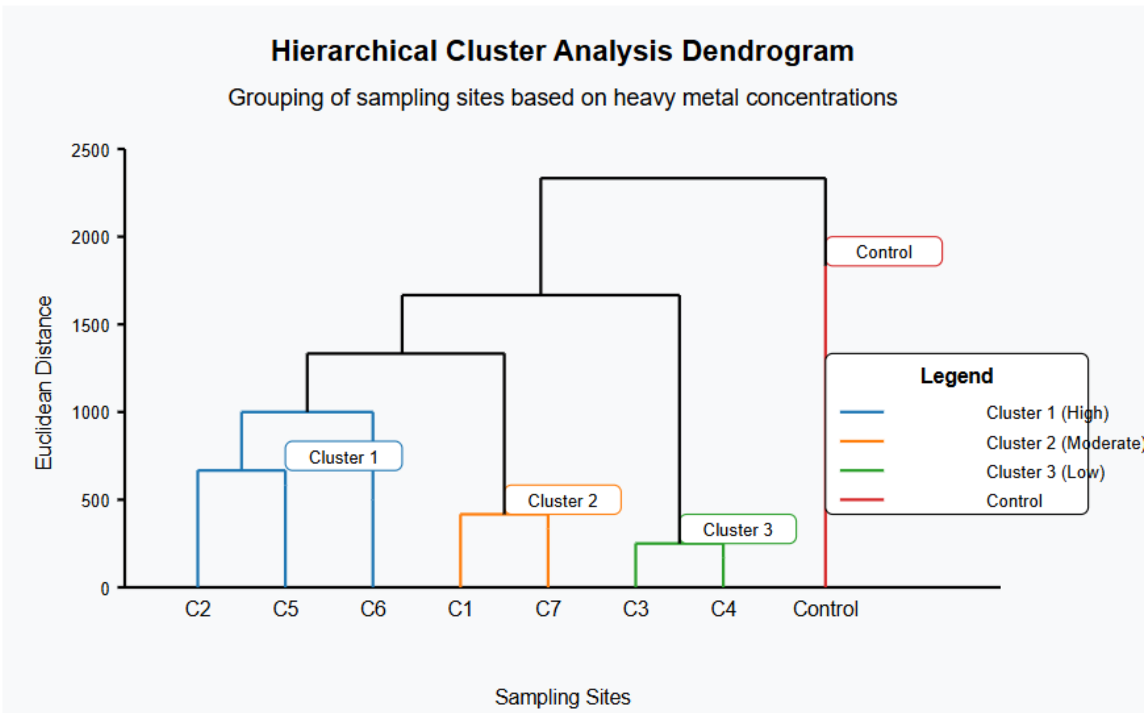

Figure 2: Dendrogram produced by hierarchical clustering for heavy metals of soil samples

3.4 Soil Contamination Assessment

Quantitative soil quality assessment was performed through calculation of key indices: Contamination Factor (CF), Enrichment Factor (EF), Geo-accumulation Index (Igeo), Pollution Load Index (PLI), Potential Ecological Risk Index (PERI), Risk index (RI) and Modified Degree of Contamination (mCd), providing a multi-criteria evaluation of anthropogenic impacts.

3.4.1 Contamination Factor (CF)

The CF values for different metals across the sampling sites are presented in Figure 3a. Based on Hakanson's (1980) classification (Table 1), Lead showed extreme contamination at sites C5 (CF = 721.65) and C6 (CF = 860.27), indicating severe anthropogenic inputs. Similarly, site C6 showed extreme contamination for Cr (CF = 2076) and Ni (CF = 2776.5). The lowest CF values were generally observed for Cd, with most sites showing minimal to moderate contamination.

The spatial variation in CF values across metals and sites reflects the heterogeneous nature of workshop activities, with certain sites (particularly C6) functioning as contamination hotspots. According to Uzoh et al. (2023), such extreme variations in CF values are typical of unregulated auto-mechanic workshops where specific work areas become heavily contaminated due to poor waste management practices.

3.4.2 Geo-Accumulation Index (Igeo)

Site C6 showed extreme pollution levels for Pb (Igeo = 9.17), Cr (Igeo = 10.44), Zn (Igeo = 7.19), Cu (Igeo = 7.70), and Ni (Igeo = 10.87) (Figure 3b). Iron also showed moderate to heavy pollution across most sites (2 < Igeo < 4). In contrast, Cd showed negative Igeo values at all sites, indicating no pollution with this metal compared to the control site.

The extremely high Igeo values for certain metals, particularly at site C6, suggest severe anthropogenic contamination significantly exceeding background levels. Okorie and Adedire (2023) reported similar findings in auto-mechanic workshop soils in Lagos, Nigeria, attributing the extreme Igeo values to long-term accumulation of metal contaminants due to poor environmental management practices.

3.4.3 Potential Ecological Risk Index (PERI)

The potential ecological risk index (PERI) was calculated to assess the potential ecological risk posed by heavy metals in the workshop soils.

The individual E_r^i values for different metals across sampling sites are presented in Figure 3c. Lead showed very high ecological risk at sites C5 (E_r^i = 3608.25) and C6 (E_r^i = 4301.35). Similarly, site C6 exhibited extreme ecological risk for Cr (E_r^i = 4152) and Ni (E_r^i = 13882.5). Copper also posed considerable to high ecological risk at most sites, particularly at site C6 (E_r^i = 1552.6).

The risk index (RI), calculated as the sum of all E_r^i values, ranged from 60.69 (site C4) to 24116.15 (site C6). According to Hakanson's (1980) classification (RI < 150: low risk; 150 ≤ RI < 300: moderate risk; 300 ≤ RI < 600: considerable risk; RI ≥ 600: very high risk), sites C1 (RI = 1134.85), C2 (RI = 1200.31), C5 (RI = 3868.63), and C6 (RI = 24116.15) posed very high ecological risk, while sites C3, C4, and C7
posed low to moderate ecological risk.

The extremely high RI value at site C6 was primarily driven by the substantial contributions from Ni (57.6%), Pb (17.8%), and Cr (17.2%). This finding aligns with Fagbayigbo et al. (2023),
who reported that Pb and Ni were the primary contributors to ecological risk in automobile workshop soils in the Niger Delta region, attributed to battery recycling activities and disposal of spent catalytic converters.

3.4.4 Enrichment Factor (EF)

The calculated EF values (Figure 3e) revealed that Zn exhibited moderate to severe enrichment across all sampling sites (EF: 3.8-17.4), with site C6 showing the highest enrichment, indicating significant anthropogenic input. Cu demonstrated minor to moderately severe enrichment (EF: 1.3-7.2), while Pb showed variable enrichment ranging from no enrichment in sites C3, C4, and C7 to severe enrichment in sites C5 and C6 (EF: 14.7 and 22.5, respectively). Cd displayed moderately severe to severe enrichment in sites C1, C2, C4, C5, and C6 (EF: 5.1-12.8) despite its relatively low concentrations, suggesting specific anthropogenic sources. Cr and Ni showed minimal enrichment across most sites except for site C6, where they exhibited moderate enrichment, potentially due to localized industrial influences

3.4.5 Pollution Load Index (PLI)

The PLI values ranged from 1.32 (site C4) to 57.65 (site C6), with all sites exceeding the threshold value of 1, indicating progressive deterioration of soil quality (Figure 3f). According to the classification by Tomlinson et al. (1980) (Table 1), all sampled sites were polluted, with site C6 showing extreme pollution
levels.

The PLI values followed the decreasing order:

C6 (57.65) > C2 (12.36) > C1 (7.92) > C5 (7.87) > C3 (2.31) > C7 (2.12) > C4 (1.32). This trend reflects the cumulative effect of multiple metal contaminants and identifies sites C6 and C2 as critical pollution hotspots requiring urgent remediation. Similar findings were reported by Nkansah et al. (2023) in a study of auto-repair workshop soils in Ghana, where PLI values exceeding 10 were associated with workshops having longer operational histories and poor waste management practices.

3.4.6 Degree of Contamination (mCd)

The degree of contamination was assessed using the modified degree of contamination (mCd) approach proposed by Hakanson (1980) and modified by Abrahim and Parker (2008). The calculated mCd values (Figure 3f) indicated moderate to high degrees of contamination across the study area. Sites C2, C5, and C6 exhibited high degrees of contamination (mCd: 5.8, 4.9, and 7.2, respectively), primarily driven by elevated Zn, Pb, and Cu levels. Sites C1 and C7 showed moderate degrees of contamination (mCd: 3.1 and 2.6), while sites C3 and C4 displayed low to moderate contamination levels (mCd: 1.7 and 1.6). The spatial distribution of mCd values corresponded well with the clusters identified in the HCA, confirming the reliability of both approaches.

3.5 Implications for Environmental Management And Human Health

The severe contamination and high ecological risk at several workshop sites, particularly C6, necessitate immediate remediation measures. According to Olaitan et al. (2022), soil contamination of this magnitude can lead to groundwater pollution through leaching particularly in the Niger Delta region with its high rainfall and shallow water table. The health implications for auto-mechanics and nearby residents are significant, given the potential for direct contact with contaminated soil, dust inhalation, and possible food chain transfer through urban agriculture practiced around these workshops. Ezejimofor et al. (2023) reported elevated blood lead levels in auto-mechanics in the Niger Delta region, correlating with soil Pb concentrations in their workshops.

Recommended remediation strategies include engineered barriers to prevent soil contact and reduce leaching; phytoremediation with hyper accumulators for moderately contaminated sites (Ayodele and Olajuyigbe, 2023); and chemical stabilization using biochar or lime for highly contaminated areas (Ogbonna et al., 2022). Implementation of regular monitoring, proper hazardous waste disposal facilities, and promotion of eco-friendly products are essential. Training mechanics on heavy metal exposure risks and raising institutional awareness are crucial for mitigating environmental pollution and associated health hazards in the study area.

4.0 CONCLUSION

The surface soils of auto-mechanic workshops in Effurun, Niger Delta, Nigeria, exhibit significant heavy metal contamination, particularly with Fe, Zn, Cu, and Pb. Statistical analyses revealed high spatial variability in metal concentrations and significant correlations between several metal pairs, suggesting common anthropogenic sources. Soil contamination assessment using various pollution indices (CF, Igeo, PLI, and PERI) identified severe contamination and very high ecological risk at most workshop sites, with site C6 emerging as a critical pollution hotspot. The findings underscore the need for immediate remediation measures and improved waste management practices in these workshops to mitigate environmental and health risks. Future studies should focus on assessing the bioavailability of these metals, their potential transfer to plants, and developing cost-effective remediation approaches suitable for the local context.

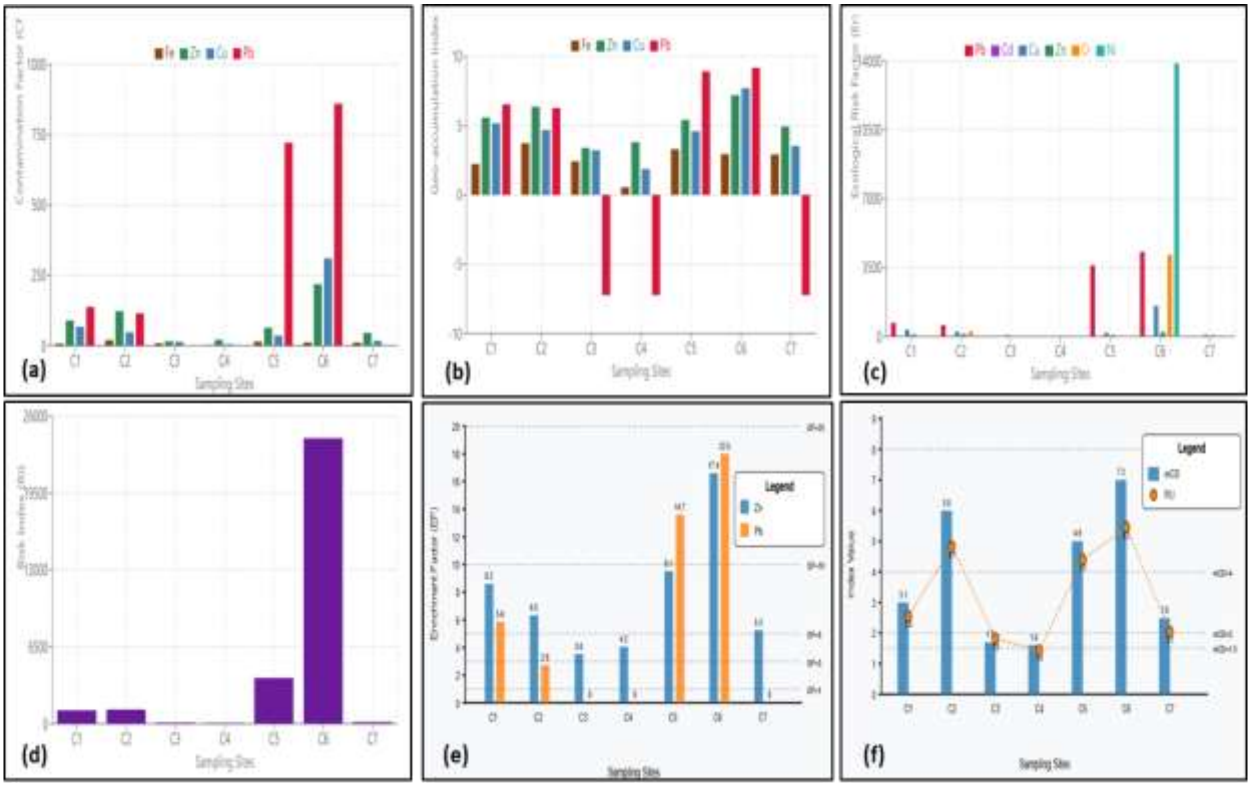

Figure 3: Computed contamination factor (CF), geo-accumulation index (Igeo), potential ecological risk indices (PERI), risk indices (RI), enrichment factor (EF), modified degree of contamination (mCd) and pollution load index (PLI) (a-f respectively) of heavy metals in soils across sampled sites of the study area

Conflicts of Interest

The authors declared that there is no conflict of interest.

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