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ENVIRONMENTAL ASSESSMENT OF HEAVY METAL CONTAMINATION AND ECOLOGICAL RISK IN SOILS AROUND PETROL STATIONS IN ONITSHA, SOUTHEASTERN NIGERIA

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Abstract

Core soil samples were collected from ten selected petrol stations in Onitsha, southeastern Nigeria, with an undeveloped control site at Awka used for background comparison. Particle-size distribution, pH, organic matter, cation exchange capacity (CEC), and concentrations of Pb, Cu, Zn, Cr, Ni, Co, Mo, Cd, Mn and Si were determined using standard laboratory procedures and atomic absorption spectrophotometry. The soils were predominantly sandy and acidic (pH 5.23–5.82), with CEC of 0.171–0.341 Cmol kg−1 and organic matter of 6.592–13.67%. Mean±sd concentrations of Pb, Cu, Zn, Cr, Cd, Ni, Co, Mo, Mn and Si were 1.497±0.232, 0.742±0.228, 3.415±2.706, 2.498±0.273, 0.075±0.053, 1.458±0.324, 0.247±0.097, 0.255±0.071, 6.148±1.068, and 9.291±0.77 mg kg−1, respectively. Although most mean concentrations were below generic soil guideline values, all investigated metals except Mo and Si showed enrichment relative to the local control soil, indicating a measurable anthropogenic contribution. Contamination factors calculated from the control-site background were generally low to moderate, with elevated factors particularly for Ni, Cr, Co and Pb. Pollution Load Index values calculated from Pb, Cu, Zn, Cr, Cd, Ni and Co ranged from 2.42 to 6.07, confirming pollution at all petrol-station sites. The potential ecological risk assessment identified Cd and Ni as the principal contributors to ecological risk, with overall risk ranging from moderate to considerable among the sites. Geoaccumulation indices further indicated strong enrichment of Ni relative to the local background concentration. The results indicate that recurrent fuel handling, spills, traffic-related inputs and facility-associated activities contribute to soil metal enrichment in Onitsha. Regular monitoring, spill prevention, proper storage and handling of petroleum products, and remediation of affected soils are recommended.

Keywords: petrol stations; heavy metals; soil contamination; contamination factor; pollution load index; ecological risk; Onitsha.

INTRODUCTION

Globally, researchers are concerned with problems of soil, air, and water contamination. Soil pollution resulting from industrialization and urbanization, particularly through the use of fossil-fuel-powered machinery, has increased in recent years. Soil ecosystems worldwide have been effusively tainted with heavy metals due to innumerable human activities, perhaps including mobilization of these metals up in the food chain, thus threatening human health (Du et al., 2014). Whether in urban or agricultural zones, soil represent a main sink for metals released into the environment from a multiplicity of anthropogenic sources (Alamgir,2016). When released in soil, the heavy metals have a tendency to be persistent because of their fairly immobile nature (Singh et al., 2017).

They can also be circulated into the atmosphere, by natural geochemical cycling and by other anthropogenic routes (such as smelting and burning leaded gasoline and coal) as well as microbial activities. The uptake of heavy metals from contaminated soils by food and forage plants create a key pathway for such toxic elements to enter the food chain (Abdullahi et al., 2021). Ingestion and buildup of toxic heavy metals constitute a risk to human health (Singh et al., 2017).

Petroleum is used as a common connotation for crude oil and natural gas, which is the hydrocarbons from which many oil and gas products are made (Igwe and Ukaogo, 2015). Crude oil when refined into several petroleum products contains different constituents such as heavy metals, antioxidants, Sulphur, corrosive inhibitors, dye and additives (Adewuyi et al., 2012).

Fuel stations pose risks on soil heavy metal concentration owing to its direct contribution to soil contamination around the stations. There is also the possibility of petroleum products spilling on soil around the facilities thereby increasing the toxic levels of contaminants within the area. Moreover, processes associated with product offloading, washing of storage tanks as well as leakages from underground pipe lines and tanks constitute another key channel of oil pollution in our environment.

In this study, determination of some heavy metal levels that are considered toxic on humans and soil organisms in soil around some selected fuel stations in the city of Onitsha was undertaken to fully understand and document the impact of these facilities.

While heavy-metal contamination around petroleum-retail facilities has been widely investigated in Nigeria and internationally, the available literature shows substantial variation in the metals considered, background controls and assessment indices. The present study addresses a specific regional gap by examining ten elements (Pb, Cu, Zn, Cr, Ni, Co, Mo, Cd, Mn and Si) across ten petrol stations in Onitsha, an intensively urbanized and commercially active city in southeastern Nigeria, using an undeveloped Awka soil as a local background reference. The study integrates concentration data with enrichment factor, contamination factor, pollution load index, geoaccumulation index, potential ecological risk and correlation analyses. This combined approach is intended to

distinguish simple concentration elevation from meaningful enrichment and ecological risk, thereby providing a stronger basis for environmental monitoring and management of petrol-station areas in Onitsha.

DESCRIPTION OF THE STUDY AREA

Location and Geology

The study area lies between Latitudes 6^0 05' 56" and 6^0 12' 02"N, and Longitudes 6^0 46' 0" and 6^0 52' 30" E (fig. 1). The main geologic units within the study area include Ameki Formation (Nanka Sand), Asaba-Ogwashi Formation and Benin Formation (Coastal Plain Sand) (figure 2).

Ameki Formation, classified by Simpson (1955) into two lithological groups, consists of the lower part which is made up of fine to coarse grain sandstones and intercalations of calcareous shales and thin shelly limestone. The upper part comprises of coarse, cross-bedded sandstone with bands of fine, grey-green sandstone and fine – grained fossiliferous sandstone with thin limestone bands. The age, according to Reyment (1965) is early Eocene or early middle Eocene according to Adegoke (1969. The Ameki Formation lies beneath the Imo shale (Paleocene in age) which conformably lie on top the Nsukka Formation according to Reyment (1965).

The Ogwashi–Asaba Formation is also exemplified within the Palaeocene Anambra Basin (Oboh – Ikuenobe et al., 2005). It is also called the Lignite-Series. It is characterized by broadly different lithologies containing repetition of clays, sands, grits and lignites (Dessauvagie and Fayose, 1970; Whiteman, 1982). Reyment (1965) recommended Oligocene–Miocene age for this formation.

The Benin Formation also referred to as the Coastal Plain Sand consists of alternating sequence of gravel, sand, clay and alluvium derived from the neighboring Precambrian basement and cretaceous rocks (Short and Stauble, 1967). The age is upper Miocene–Recent (Kogbe, 1976).

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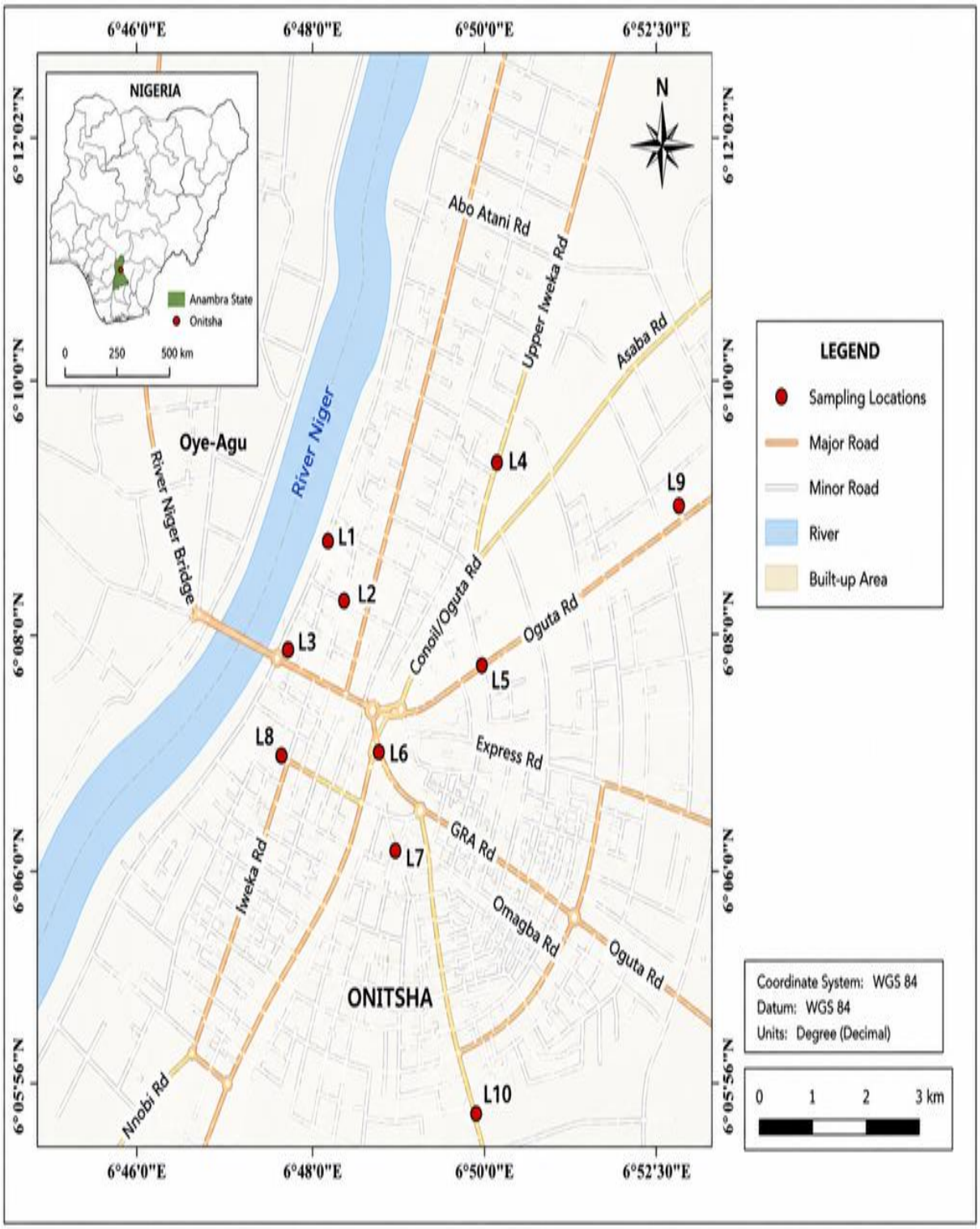

Fig. 1: *Location map of the study area showing sampling points (Inset is the Nigeria map)*.

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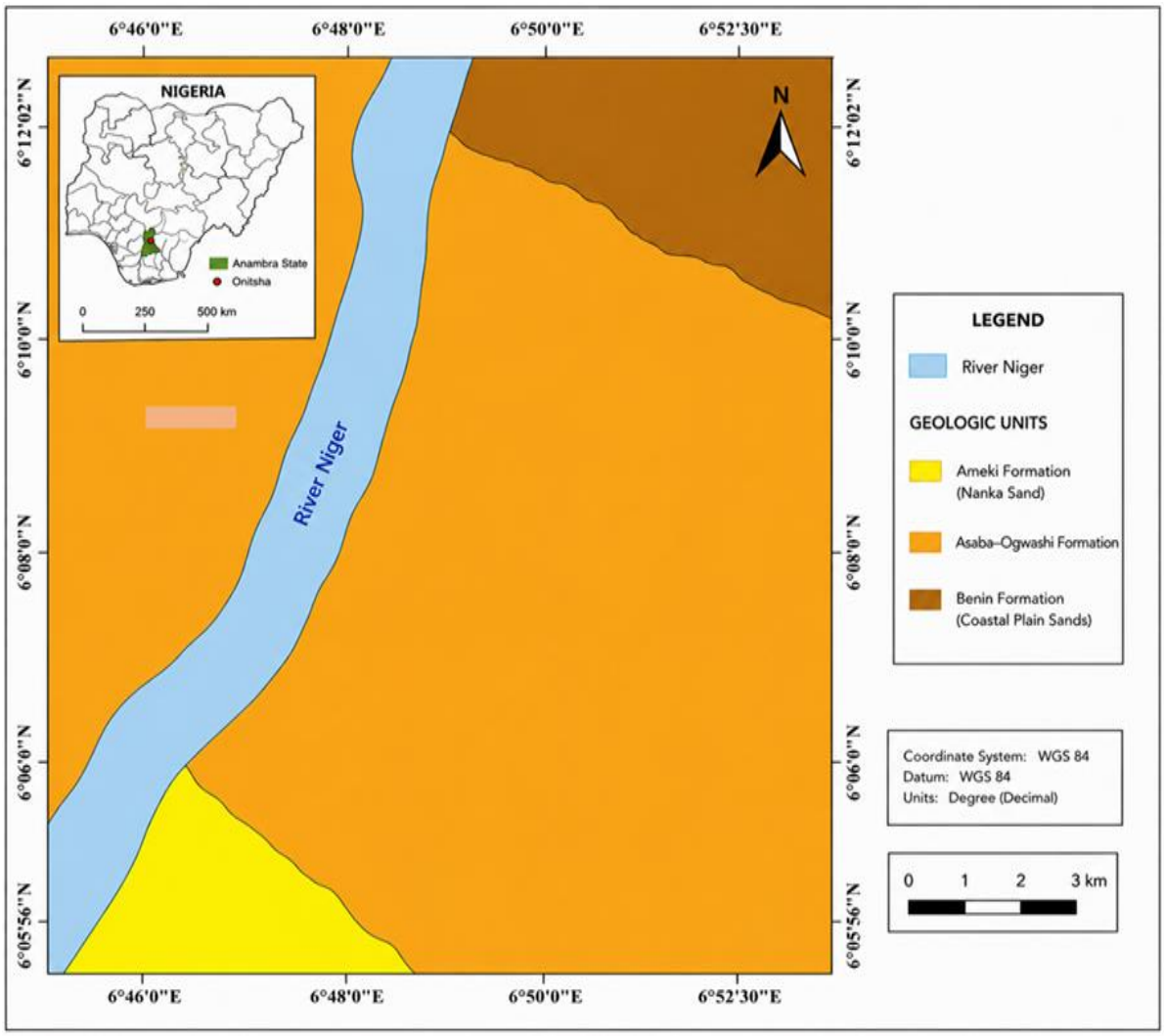

Fig 2: *The geologic map of the study area showing the major geologic units and the Niger River*.

REVIEW OF LITERATURE

Problems of environmental pollution by heavy metals in or near petrol stations have been previously covered in many scientific publications. Among many of them include the work done by Ahmed et al., (2020) which focused on the environmental impact of fuel stations on some heavy metal concentrations in nearby surface crust soils in urban areas in Al Hilla city, Iraq. The research made use of soil samples collected near three fuel stations in Al Hilla city, as a case study. The study discovered that the concentrations of the considered heavy metals were all below the value that should be available in average shale, except that for Pb. The results also counselled that the fuel stations may compromise the nearby soils by increasing concentrations of Pb in them.

Soils samples from oil filling and service stations in Tamale metropolis Ghana were assessed by Emmanuel *et al.,* (2014). Samples were collected from various oil filling and service stations for elemental analysis using AAS at atomic energy laboratory, Accra. The study showed that the soil within the study area were contaminated by heavy metals which originated from a common anthropogenic source such as oil filling activities, tyres wear, brake wear and corroded vehicles engine materials.

Dauda and Odoh (2012) assessed the heavy metals in soil within the vicinity of fuel filling station in some selected local government areas of Benue State, Nigeria. The study was to define the levels of Cd, Co, Cu, Mn, Ni, Pb and Zn in soils within filling stations in some selected local government areas of Benue State, Nigeria. The study made use of Flame Atomic Absorption spectrophotometric technique and discovered that generally, the ranges and mean concentrations (µg/g) of metals in the soil samples were 4.00-4.80 (4.37±0.27), 1.07-1.85 (1.51±0.26), 41.40-68.13 (58.00±7.13),200.67-295.33 (260.00±32.30), 14.00-19.83 (17.13±1.94), 216.00-276.67 (242.67±18.29) and 100.33-162.33(134.75±21.93) for Cd, Co, Cu, Mn, Ni, Pb and Zn respectively. The level of Pb was the highest. Enrichment factors were used to assess the degree of contamination by each metal. The enrichment factors obtained for Cd, Co, Cu, Mn, Ni, Pb and Zn in in this study were 15.46, 1.87, 3.20, 1.80, 1.96, 73.74 and 13.43, respectively. The inter-element correlation was established among the heavy metals. There were positive correlations among the metals determined. Metals such as Pb, Cd, and Zn shows high degree of contamination. However, Co, Cu, Mn and Ni have low degree of contamination in the studied sites.

Domuschy et al., (2022) worked on the assessment of soil contamination by heavy metals in the area affected by petrol stations using the city of Odessa in Ukraine as sample point. The results of experimental research show that heavy metals in the soils of the city of Odessa (Ukraine) within the influence of petrol stations have a much higher level of accumulated heavy metals compared to the background content. According to the indicator of total pollution, 55% of the studied area belongs to the dangerous category of soil pollution. The study also found that priority pollutants that have the highest levels of pollution intensity are zinc and copper. This could significantly affect the increase in the overall morbidity of children and adults in the city. A relationship was proven between the intensity of soil pollution and the total pollution rate ($r = 0.99$), which endorses the negative impact of vehicle emissions/petrol stations on the soil cover of the city.

Kadili et al., (2021) researched on the levels, ecological and human health risk of heavy metals in soils from sites neighboring petrol stations in major cities within Kogi State, Northcentral Nigeria using standard methods. The levels of detected metals (Cd, Cr, Pb, Cu and Fe) in the area of study varied as follows: 0.0391, 0.0241, 0.00552, 16.9 and 388 mg kg−1 respectively. The declining drift of heavy metals in all the sample locations was in the order of: fe > cu > cd > Cr > pb. Ecological risk assessment tools such as contamination factor (cf), degree of contamination (cD), geoaccumulation index (igeo), pollution load index (pli) and enrichment factor (ef) were employed to ascertain

soil health status in the area. Results revealed low level of soil pollution with Cd, Cr, Pb, Fe and moderate pollution with Cu. Metal enrichment factors show extremely high enrichment of Cd and Cu. Correlation study show strong positive relationship among Cd/Cr (r = 0.835), Cd/Cu (r = 0.699) and Cu/Cr (r = 0.859) at 5% level of significance, signifying that soil contamination by the metals originated from a mutual anthropogenic sources such as fuel spills, combustion of fossil fuel, leakage of underground tanks and pipes, wear and tear of vehicle tyres, engine parts and brake shoes.

Iyebor et al., (2020) assessed the heavy metals in soil around leaking underground petroleum facilities in Idu community, Rivers State, Southsouth Nigeria using standard methods. Sampling was done at two depths (0 – 15 cm and 15 – 30 cm) four times a year (January, April, July and October) at ten (10) stations and one control point, established at 1.5 km from the sampling stations. AAS was used to investigate the heavy metals concentrations in soils. The results acquired showed that Pb was relatively high, Cr and Ni were very low, Cd and V were not detected while Fe was generally very high. The concentrations in mg kg−1, recorded were Pb (1.08, 1.10, 0.73, 0.72 and 1.04, 1.14, 0.66, 0.66), Ni (0.02, 0.014, 0.02, 0.01 and 0.01, 0.00, 0.02, 0.01), Cr (0.01, and 0.00), Fe (1568.78, 1697.49, 2101.59, 2087.59, and 1509.03, 1572.69, 1849.77, 1893.81) in surface and subsurface soils in Q1, Q2, Q3 and Q4 respectively. The degree of heavy metals contamination of soil across the studied stations was in this order: SS 7 > SS 10 > SS 6 > SS 8 > SS 9 > SS 2 > SS 1 > SS 5 > SS 3 > SS 4. The study confirmed that Pb was the major contributor to heavy metals contamination of soil in the area.

Adewumi and Ogundele (2024) worked on a project titled: Hidden hazards in urban soils: A meta-analysis review of global heavy metal contamination (2010-2022), sources and its Ecological and health consequences. The Preferred Reporting Items for Systematic Review and Meta-Analysis (PRISMA) approach was employed in the study. The range values (mg/kg) of Arsenic (As), lead (Pb), mercury (Hg), cadmium (Cd), chromium (Cr), cobalt (Co), nickel (Ni), copper (Cu), zinc (Zn) and iron (Fe) as reported in the work were 0.95–152.00, 2.27–5780.00, 0.05–178.19, 0.03–298.90, 1.10–1631.43, 0.41–2560.00, 2.08 12,986.00, 1.14–3420.00 and 28.10 88,531.00. With the exception of Cr and Fe, all metals' average concentrations were higher than their average crustal values. A low to extremely high degree of contamination, presumably impacted by Pb, Hg, and Cd, was shown by the pollution indices. Urbanization, and industrial exhausts, were the main causes of high levels of pollution. Ecological risk showed that metals in urban soils posed a slight to highest environmental risk with mercury and Cd posing the highest ecological risk according to the research. A health risk assessment showed that some of the cities' residents were at risk for non-carcinogenic health risks (HI > 1), which are brought on by oral consumption and skin contact with metals in the soil. Inhabitants of those cities were exposed to carcinogenic health risk (HI > 1×10^{-4}) which were triggered by ingestion and contact with heavy metals in soils.

Despite the plethora of literature on this topic from different parts of the world, there seems to be no research on the effect of fuel stations on soil contamination with heavy

metals at Onitsha, Southeastern Nigeria. This work, therefore, seeks to delve into this obscure field and lay bare the effects of the numerous petrol stations at Onitsha.

MATERIALS AND METHODS

Field procedure

Before the actual sampling activities, a reconnaissance survey was undertaken in order to identify possible sampling points and assess background information, site conditions and historical data. The reconnaissance survey was also used to identify variable possible routes, assess the topography, geology and traffic volume as well as economic land use (commercial and industrial activities) patterns within the study area. The sampling points were selected based on the information gathered during this reconnaissance survey.

During sampling, surface-soil samples were collected from 0–60 cm depth at ten randomly selected petrol stations identified during the reconnaissance survey as shown in Table 1. The stations were distributed within the study area to capture the range of petrol-station settings represented in Onitsha. One control soil sample was collected from an undeveloped plot at Awka characterized by very low traffic and no known industrial activity. The control was collected at the same depth to provide a local background reference.

A T-shaped manual soil auger, hand trowel, polyethylene sampling bags and clean sampling containers were used. The auger and trowel were cleaned with methylated spirit between sampling points to minimize cross-contamination. Samples were placed in pre-labelled containers, preserved during transport and taken to the laboratory for preparation and analysis. In total, eleven soil samples were collected: ten petrol-station samples and one control sample.

Table 1

Table showing the sampling locations and the GPS coordinates

Label	Name	Latitudes	Longitudes	Address
L1	Oweri Rd.	6.12219	6.79353	Near Upper Iweka
L2	Upper Iweka	6.13022	6.7865	Upper Iweka Axis
L3	Upper Iweka	6.13106	6.78864	Upper Iweka
L4	Conoil	6.15364	6.79919	Oguta Rd
L5	-	6.14728	6.81772	Express
L6	-	6.152	6.791	GRA
L7	Oando	6.13853	6.78194	Asaba Rd
L8	Rainoil	6.136	6.788	Iweka Rd
L9	Seaman	6.1848	6.814	Omagba
L10	Total	6.1425	6.7901	Oguta

Laboratory Procedure: Sample Preparation, Digestion and Analysis

The collected soil samples were air-dried at room temperature for sixteen days to remove excess moisture. The soil samples were also disaggregated to facilitate quick drying. At the end of the drying period, the soil samples were crushed in a porcelain mortar with a pestle and thoroughly mixed (homogenized). The mortar and pestle were cleansed with methylated spirit using white handkerchief after crushing each sample to prevent cross contamination of samples.

The crushed soil samples were sieved through a 2.0mm sieve made of stainless steel in order to remove stones, pebbles and plant debris. Some portions of the individual sieved soil samples were further pulverized to a fine powder and passed through a 0.5mm sieve for analyzing organic carbon and total metal content. Mechanical analyses were made using serial sieves. The sieved samples were properly stored as sub- sample for the determination of various parameters. The digestion of soil samples was carried out by weighing approximately 2.0g of the soil sample into a crucible and heating it at a temperature of 5500C for 3hours to get rid of the organic portion of the sample before being removed and allowed to cool. After cooling, it was emptied into a 100ml beaker and 20ml of 20% H_2SO_4 was added, heated on a heating mantle and boiled vigorously for five minutes before being brought down and allowed to cool. It was made up to 50ml with distilled water before being filtered into a sample container for elemental analysis using atomic absorption spectrophotometer (Agilent technologies 200 Series AA).

The prepared samples were analyzed for metal concentrations using Varian AA240 Atomic Absorption Spectrophotometer (AAS) at Springboard Research Laboratory, Udoka Housing Estate, Awka in Anambra State. Analysis for ten (10) metals namely: Lead (Pb), Copper (Cu), Zinc (Zn), Chromium (Cr), Nickel (Ni), Cobalt (Co), Molybdenum (Mo), Cadmium (Cd), Manganese (Mn) and Silicon (Si) were carried out in the digested soil samples.

Particle size analysis

Approximately 50g of the sample was weighed into a 250ml beaker and 200ml of distilled water was added and the mixture was vigorously stirred and allowed to stand for 10mins for sedimentation to take place. At the end of the 10mins, the water was siphoned and the process was repeated four times to wash the sample before 25ml of 25% hexametaphosphate was added and the mixture was allowed to stand till the next day. On the next day, the mixture was siphoned through a 75mm sieve and the sieved particles and the sieved liquid was dried using an oven before being allowed to cool and the following calculations made:

$$\%\text{Silt} = \frac{\text{wt of beaker + dried residue}}{\text{Wt. of sample}} \times 100 \quad (1)$$

$$\%\text{Sand} = \frac{(\text{wt of beaker + dried residue}) - \text{wt of empty beaker}}{\text{Wt. of sample}} \times 100 \quad (2)$$

%Clay = 100 – (%Silt + %Sand). (3)

Loss on Ignition (LOI)

The organic matter content (OM) of the soil samples was estimated from LOI. Approximately 2g of the sample was weighed into a crucible and dried in the oven at 105 °C for 1hr before it was brought down and allowed to cool before the weight was recorded using an electric weighing balance. Then it was transferred into a muffle furnace and heated at 360°C for 3hrs. At the end of 3hrs, it was brought down and allowed to cool in a dessicator and the weight was recorded before the following calculations were made:

$$\mathrm{LOI}\,(\%) = \frac{(\text{wt. at } 105^{\circ}\mathrm{C}) - (\text{wt. at } 360^{\circ}\mathrm{C})}{\text{wt. at } 105^{\circ}\mathrm{C}} \times 100 \quad (4)$$

Soil pH determination

Soil pH was determined using a PH meter with glass electrode. Approximately 1g of air-dried and sieved soil sample was measured into a beaker and 10ml of distilled water was added to it. The suspension was stirred continuously for 30mins and allowed to stand for about 1hour. The digital pH meter was plugged, switched on and calibrated with a known buffer solution (buffer 7). After calibration, the pH electrode was dipped into the beaker containing the suspension and the reading was taken once the digital display became stable. The electrode was rinsed with deionised water between samples.

Cation exchange capacity (CEC)

Approximately 1g of the sample was weighed into a 100ml beaker and 10ml of 1mol of potasssium chloride (KCl) was added. The mixture was allowed to stand for 30mins before being filtered. The filtrate was analysed for Mg, K, Ca and Na using AAS.

Then the concentration levels of these cations were converted from parts per million (ppm) to cmol kg−1 using the following formulae:

Mg(ppm) ÷ 120 = Mg (cmol kg−1) (5)

K(ppm) ÷ 390 = K (cmol kg−1) (6)

Ca(ppm) ÷ 200 = Ca (cmol kg−1) (7)

Finally, the cmol kg−1 results of Mg + K + Ca = CEC (8)

Quality control/assurance

As part of quality control/assurance, measures were taken to check for background contamination and to ensure reliability of data. Series of standard metal solutions in the optimum concentration range were prepared. The reference solutions were prepared daily

by diluting the single stock element solutions with water containing 1.5ml concentrated nitric acid/litre. A calibration blank was prepared using all the reagents except for the metal stock solutions. Calibration curve for each metal was prepared by plotting the absorbance of standards versus their concentrations. Moreover, blank samples were analyzed after five samples. Duplicate analyses were performed on all samples using certified methods and the analytical results reported on a dry weight basis. Precision and accuracy of analyzed metals were checked against standard reference material for every heavy metal.

Statistical analysis of data

Microsoft Excel was used to calculate the range, mean, standard deviation (SD) and coefficient of variation (CV), and to prepare the graphical summaries. SPSS Statistics was used to calculate Pearson correlation coefficients among the measured metals. The concentrations were compared with available national and international soil-quality guidelines. Enrichment Factor (EF), Contamination Factor (CF), Pollution Load Index (PLI), Potential Ecological Risk Index (PERI) and Geoaccumulation Index (Igeo) were used as complementary indicators of contamination and ecological risk.

Pollution Indices

The pollution indicators employed to evaluate the level of contamination in the soils within the study area include: Contamination Factor (CF), Enrichment factor (EF), Pollution Load Index (PLI), Geoaccumulation index, and Potential ecological risk index (Er^i).

Contamination Factor (CF)

The Contamination Factor (CF) was calculated as the ratio of the concentration of each metal in a petrol-station soil sample to its concentration in the local control soil: CF = Ci/Bi, where Ci is the measured concentration and Bi is the corresponding control-site background concentration. CF < 1, 1–3, 3–6 and > 6 were interpreted as low, moderate, considerable and very high contamination, respectively. The CF values were also used as the basis for the PLI and PERI calculations.

$$CF = Ci / Bi \quad (9)$$

Enrichment Factor (EF)

The Enrichment Factor (EF) is applied in differentiating between metals that accumulate due to human activities from those that accumulate due to geogenic or natural processes. To evaluate the magnitude of contaminants in the environment, Enrichment Factors (EF) were computed relative to the abundance of species in source material to that found in the Earth's crust. Silicon (Si) is chosen as the element of normalization because natural sources vastly dominate its input. The following equation (5) proposed by Simex and Helz (1981) was used:

$$EF = (CM/CSi)sample / (CM/CSi)background \quad (10)$$

Where, $(C_M/C_{Si})_{sample}$ is the ratio of concentration of measured heavy metal (C_M) to that of Si (C_{Si}) in the soil sample and $(C_M/C_{Si})_{Background}$ is the same reference ratio in the Earth. The five contamination categories recognized and interpreted as suggested by Birch (2003), adopted by Ololade (2014) and equally used in this research are as follows:

EF < 1 indicates no enrichment,

EF 1 < 3 indicates minor enrichment

EF between 3 < 5 show moderate enrichment

EF between 5 < 10 denotes moderately severe enrichment

EF between 10 < 25 denotes severe enrichment

EF between 25 < 50 denotes very severe enrichment

EF ≥ 50 refers to extremely severe enrichment

Pollution Load Index (PLI)

The extent of pollution in the studied soils by heavy metals has been assessed with the aid of the pollution load index (PLI) proposed by Tomlinson *et al*. (1980).

PLI provides a simple, comparative means for assessing pollution status of an area.

The PLI is proposed as a standardized system for detecting pollution which permits a comparison of pollution levels between different sites and at different times.

The PLI for a single site is the *n*th root of *n* number multiplying the contamination factors (CF values) together:

$$PLI = (CF1 \times CF2 \times CF3 \times \ldots \times CFn)1/n \quad (11)$$

Where CF = contamination factor, n = number of metals at a given site

PLI value > 1 indicates pollution of the site while <1 implies that the site is unpolluted

Potential Ecological Risk Index (Er^i)

The ecological risk index evaluates the toxicity of elements in sediments/soils (Hakanson, 1980). It is calculated as shown follows:

$$Eri = Tri \times Cif \quad (12)$$

Where,

Tr = Toxicity coefficient of each metal

C^i_f [Contamination Factor] = Ci/Bi

[Where Ci = measured conc. of pollutants and Bi= level of geological background. The average compositions of the metals in the control sample were used as background values for the metals].

If Er is less than 40, it implies low contamination risk

If Er falls between 40 – 80, it implies moderate contamination risk

If Er falls between 80 –160, it implies considerable contamination risk

If Er falls between 160 – 320, it implies high

Standard values of Tr are Cd=30, Co=5, Cu=5, Ni=5, Pb=5, Cr=2, Zn=5 (Hakanson, 1980).

Geoaccumulation Index (Igeo)

The geoaccumulation index (Igeo), originally proposed by Muller (1969) for assessing metal contamination in sediments and widely adapted for soils, was additionally computed to complement the EF, PLI and Er^i indices, as recommended by the reviewers of this manuscript. It is calculated as:

$$Igeo = \log2 [Cn / (1.5 \times Bn)] \quad (13)$$

Where Cn is the measured concentration of the metal in the soil sample and Bn is the geochemical background concentration of the metal (the control-site value was used as Bn, consistent with the background reference already adopted for the Er^i calculation); the constant 1.5 corrects for possible lithogenic variation in background values. Igeo values are classified into seven classes: Igeo ≤ 0 (Class 0, uncontaminated); 0-1 (Class 1, uncontaminated to moderately contaminated); 1-2 (Class 2, moderately contaminated); 2-3 (Class 3, moderately to strongly contaminated); 3-4 (Class 4, strongly contaminated); 4-5 (Class 5, strongly to extremely contaminated); and >5 (Class 6, extremely contaminated) (Muller, 1969).

RESULTS AND DISCUSSION

Physicochemical Parameters

The physicochemical characteristics of the soils are presented in Table 2 and Figure 3. The samples were predominantly sandy, with sand, silt, and clay contents ranging from 47.661–59.625%, 20.113–24.223%, and 18.446–31.839%, respectively.

The corresponding mean values were 52.997±4.436%, 21.692±1.438%, and 25.511±4.719%. The sandy texture is consistent with the geology of the Onitsha area, where sand-rich formations are widespread. Similar sandy and acidic soils have also been reported in petroleum-impacted environments in Nigeria, although the precise textural distribution varies with local geology, drainage conditions, and sampling depth. For example, soils from petroleum-impacted areas of the Niger Delta have been reported to exhibit sandy textures and acidic conditions, with pH values ranging from 4.89 to 6.24 and low CEC values (Iyi et al., 2022).

Soil texture is important in interpreting the mobility and retention of potentially toxic metals. The relatively high sand content observed in the present study suggests limited sorption capacity and a greater possibility of downward transport of soluble metals, particularly under acidic conditions. By contrast, finer-textured soils with higher clay contents generally retain metals more effectively through adsorption and ion exchange.

Nevertheless, the moderate clay fraction at some stations may provide localized sites for metal accumulation, especially where petroleum residues, organic matter, and oxide minerals are present.

The soils from the petrol stations were moderately to strongly acidic, with pH values ranging from 5.23 to 5.82 and a mean of 5.60±0.14 compared with a pH of 6.72 at the control site. The acidic condition is comparable to observations from other petroleum-impacted soils in Nigeria. In petroleum-contaminated soils from the Niger Delta, reductions in pH and exchangeable bases have been associated with hydrocarbon inputs, while soils from anthropogenic sites in Abeokuta showed a broader pH range of 5.17–8.28 because of differences among land uses and background conditions. The lower pH around the Onitsha petrol stations may be related to the oxidation of petroleum-derived compounds, acid-forming reactions, atmospheric deposition, and the decomposition of organic residues associated with station operations (Olayinka et al., 2017).

The difference between the petrol-station soils and the control soil is environmentally important. Acidic conditions can increase the solubility and mobility of several metals, including Ni, Cd, Co, and, in some circumstances, Cr and Pb. Consequently, even when total concentrations remain below regulatory limits, the metals may become more bioavailable or may leach into shallow groundwater. The acidic pH therefore provides a reasonable mechanism linking petrol-station activities with the elevated contamination factors observed for Ni, Cr, Cu, Co, and Cd.

CEC values ranged from 0.171–0.341 cmol kg^{-1}, with a mean of 0.244±0.054 cmol kg^{-1}, whereas the control soil had a higher value of 0.566 cmol kg^{-1}. These values are lower than those reported for soils around petrol stations in Karu, Nasarawa State, where CEC values of approximately 6.80–11.20 cmol kg^{-1} were reported. The difference may reflect variations in soil mineralogy, clay content, organic-matter status, extraction procedures, and the degree of petroleum impact. It also indicates that the Onitsha soils have relatively limited capacity to retain exchangeable cations and metal ions (Bankole et al., 2024).

The lower CEC at the petrol stations may be associated with the depletion or alteration of organic matter and exchange sites by petroleum products. However, it should not be concluded solely from the present data that heavy metals displaced exchangeable cations, because CEC is also strongly controlled by clay mineralogy, pH, organic matter, and the parent material. The lower pH and lower organic-matter content at the petrol stations probably acted together to reduce the soil's buffering and retention capacity. As reported in previous Nigerian studies, soil pH and CEC are important controls on metal mobility and should therefore be considered when interpreting contamination indices and ecological risk (Ibrahim et al., 2021; Okpanachi et al., 2025).

Organic matter ranged from 6.592 to 13.670%, with a mean of 10.684±1.994%, compared with 17.30% at the control site. The lower organic-matter content at the petrol stations may reflect reduced vegetation cover, repeated disturbance, hydrocarbon-related

inhibition of microbial processes, and the removal or burial of organic surface material during station construction and maintenance. However, petroleum contamination can produce either increases or decreases in measured organic matter depending on the age of the contamination, and whether petroleum residues are included in the loss-on-ignition fraction. Therefore, the present difference is interpreted as an association with petrol-station land use rather than definitive proof that fuel retailing alone caused organic-matter depletion.

The combined influence of acidic pH, low CEC, sandy texture, and reduced organic matter is significant. These conditions may increase the mobility of metals and reduce the soil's capacity to immobilize contaminants. They also help explain why some metals were substantially enriched relative to the control despite having absolute concentrations below commonly cited regulatory thresholds. Similar studies around petrol stations in Nigeria have emphasized that soil contamination may be evident from background enrichment and pollution indices even when individual metal concentrations do not exceed guideline values (Kadili et al., 2021).

Concentrations of Heavy Metals

The concentrations of the investigated metals are presented in Table 3 and Figure 4. Overall, the petrol-station soils exhibited elevated concentrations of several metals relative to the control soil, indicating varying degrees of anthropogenic enrichment within the study area. However, elevated concentrations relative to the local background should be distinguished from direct exceedance of established regulatory guideline values. Although most of the measured metal concentrations remained below the applicable guideline values cited in this study, the observed enrichment at several sampling locations suggests the influence of petrol-station-related activities on the geochemical composition of the soils. Such enrichment may reflect the cumulative effects of fuel handling, vehicular emissions, lubricants, metal-containing particulates, and other operational activities associated with petroleum-retail facilities. The observed pattern is broadly consistent with reports from petroleum-retail environments, where anthropogenic inputs may initially manifest as increased concentrations relative to local background levels before reaching regulatory intervention thresholds.

Lead

Lead concentrations ranged from 1.052–1.821 mg kg^{-1}, with a mean of 1.397±0.232 mg kg^{-1} and a low coefficient of variation (16.6%). The mean concentration was approximately 3.5 times the control value of 0.400 mg kg^{-1}, indicating enrichment relative to local background. Nevertheless, it remained below the guideline values including the DPR value of 85 mg kg^{-1}, the EPA ecological screening value of 30.2 mg kg^{-1}, and the Dutch target value of 85 mg kg^{-1}.

The low variability suggests that Pb was relatively uniformly distributed among the stations, which may indicate a widespread rather than highly localized source. Possible sources include historical fuel-related emissions, vehicle exhaust, road dust, and

lubricants. The attribution of Pb specifically to leaded gasoline should be treated cautiously because the use of leaded petrol has been phased out in many countries, and present-day Pb in urban petrol-station soils may also originate from traffic-related dust, batteries, paints, lubricants, and historical deposition.

The present Pb concentrations are much lower than those reported around petrol stations in Tamale, Ghana, where Pb concentrations ranged from approximately 4.93–74.20 mg kg^{-1} and lower than the mean Pb concentration of 25.47 mg kg^{-1} reported around fuel stations in Al Hilla, Iraq. They are also considerably lower than the values reported in petroleum-impacted agricultural soils in the Niger Delta, where Pb concentrations reached tens to thousands of mg kg^{-1} at severely affected sites. Thus, the Onitsha soils show clear background enrichment but comparatively low absolute Pb contamination when evaluated against these more heavily impacted environments (Emmanuel et al., 2014).

Copper

Copper ranged from 0.359–1.122 mg kg^{-1}, with a mean of 0.689±0.228 mg kg^{-1} and a coefficient of variation of 33.2%. The mean concentration was approximately 4.3 times the control value of 0.160 mg kg^{-1}, indicating substantial relative enrichment. However, it was far below the guideline and shale-composition values of Shales (45 mg kg^{-1}) according to Turekian & Wedepohl (1961); the EPA (1995) Ecological Screening Value of 18.7 mg kg^{-1}; the range of 36 and 190 mg kg^{-1} set as target and intervention values respectively by the Dutch Soil Quality Standard (MHSPE, 1994) as well as the target concentration of 36 mg kg^{-1} set by FAO/WHO (1996) and DPR (2002).

The moderate variability suggests that Cu inputs were not completely uniform across the stations. Potential sources include fuel and lubricant residues, vehicle components, brake wear, tyre wear, and corroded metal infrastructure. The concentration range is substantially lower than the 3.2–22.68 mg kg^{-1} reported around oil filling and service stations in Tamale, Ghana, and lower than the mean Cu concentration of 16.9 mg kg^{-1} reported around petrol stations in Kogi State, Nigeria. It is also much lower than the concentrations observed in crude-oil-impacted soils of the Niger Delta, where Cu reached several thousand mg kg^{-1} at severely contaminated locations (Emmanuel et al., 2014).

The results therefore suggest low absolute Cu contamination but meaningful enrichment relative to the Onitsha control soil. The distinction is important because Cu is an essential micronutrient at low concentrations but can affect soil microorganisms and plants when accumulation continues. Continued monitoring is warranted, particularly at stations where Cu has a high contamination factor.

Zinc

Zinc concentrations varied widely, from 0.441–10.725 mg kg^{-1}, with a mean of 3.290±2.706 mg kg^{-1} and a high coefficient of variation (82.2%). The mean was only about 1.6 times the control value of 2.050 mg kg^{-1}, but the broad range indicates strong

spatial heterogeneity. PS 4 recorded the maximum concentration, whereas PS 5 recorded the minimum.

The high variability suggests localized sources or differences in station characteristics, including traffic volume, tyre and brake wear, fuel-spillage history, drainage, and surface maintenance. Zinc is commonly associated with tyres, lubricants, galvanized materials, vehicle components, and road dust. In this case, the observed levels are not attributed exclusively to petroleum spills. The mean Zn concentration in Onitsha was lower than the 7–51-fold background accumulation reported for soils influenced by petrol stations in Odessa, Ukraine, and lower than the 84.38 mg kg^{-1} mean reported around fuel stations in Al Hilla, Iraq (Domuschy et al., 2022).

The values recorded in this study were also lower than the 122.69–632.94 mg kg^{-1} range reported in Nigerian anthropogenic sites, including petrol stations and other urban land uses in Abeokuta. Although the Zn concentrations do not indicate severe absolute contamination, the elevated value at PS 4 and the high coefficient of variation point to localized anthropogenic inputs that should be investigated through station-specific records and additional spatial sampling (Olayinka et al., 2017).

Chromium

Chromium ranged from 2.095–3.132 mg kg^{-1}, with a mean of 2.293±0.273 mg kg^{-1} and a low coefficient of variation (11.9%). The mean was approximately 9.2 times the control value of 0.250 mg kg^{-1}, and all petrol-station samples exceeded the control concentration. Nevertheless, the absolute concentrations remained well below the guideline values and shale concentrations (90 mg kg^{-1}) according to Turekian & Wedepohl (1961); the range of 100 and 380 mg kg−1 set as target and intervention values respectively by the Dutch Soil Quality Standard (MHSPE, 1994); the DPR (2002) and the WHO (1996) target value of 100 mg kg−1 in soil; the EPA (1995) Ecological Screening Value of 52.3 mg kg−1; the DPR (2002) and the WHO (1996) target value of 100 mg kg−1 as well as the general mean abundance of 40 - 50 mg kg−1 (Rose et al, 1979).

The low variability and consistently elevated CF values indicate that Cr represents a widespread component of the contamination signal. Potential sources include fuel and lubricant residues, vehicle and brake wear, industrial dust, metal corrosion, and geogenic contributions from local parent materials. Because the analysis measured total Cr and did not distinguish Cr(III) from the more toxic Cr(VI), conclusions regarding carcinogenicity or toxicity cannot be made. The present concentrations are lower than those reported around petrol stations in Tamale, Ghana, where Cr reached approximately 15 mg kg^{-1}, and lower than concentrations reported in crude-oil-impacted soils of the Niger Delta (Bankole et al., 2024).

The strong enrichment relative to the control, despite low absolute concentration, suggests that Cr should be treated as a priority indicator of anthropogenic influence in the study area. Additional work involving Cr speciation and source apportionment would

help determine whether the observed enrichment is primarily related to station activities, traffic, or local geology.

Nickel

Nickel concentrations ranged from 0.909–2.231 mg kg^{-1} with a mean of 1.331±0.324 mg kg^{-1} and a coefficient of variation of 24.4%. The mean concentration was approximately 20 times the control value of 0.066 mg kg^{-1}. All stations therefore showed strong relative enrichment, and the CF values placed Ni in the very-high-contamination category.

The strong enrichment is consistent with the known association of Ni with petroleum-related materials, combustion residues, lubricants, vehicle emissions, and industrial activities. However, the absolute Ni concentrations were below the average Ni composition in Shales which is 68 mg kg^{-1} (Turekian & Wedepohl, 1961), the EPA (1995) value of 15.9 mg kg^{-1} and the Dutch Soil Quality Standard values of 35 and 210 mg kg^{-1} for target and intervention values respectively. The Ni levels were also below the 35 mg kg−1 recommended by the DPR (1999; 2002) and the WHO (1996). They also were much lower than the 86.65 mg kg^{-1} mean reported around fuel stations in Al Hilla, Iraq but lower than the 12–174 mg kg^{-1} Ni range reported in crude-oil-impacted soils of the Niger Delta (Ahmed et al., 2020).

Cobalt

Cobalt concentrations ranged from 0.094–0.362 mg kg^{-1}, with a mean of 0.230±0.097 mg kg^{-1} and a coefficient of variation of 42.2%. The mean concentration was higher than the control value of 0.060 mg kg^{-1}, indicating relative enrichment. Despite falling below standard maximum values in soils, Cd levels were also below both the general mean abundance (0.1-0.5 mg kg^{-1}) and the control concentration which implies enrichment from regular spills of petroleum products within the petrol stations. In addition, the values are equally below the control site value of 0.04 mg kg^{-1}, the average composition of Shales value of 0.3 mg kg^{-1} (Turekian & Wedepohl, 1961), the Dutch Soil Quality Standard (MSHPE, 1994) target value of 0.8 mg kg^{-1}; below the EPA (1995) Ecological Screening Value of mg kg^{-1} and the Dutch intervention value of mg kg^{-1}.

The moderate variability suggests that Co inputs were partly localized. Possible sources include fuel residues, vehicle and brake components, industrial dust, and parent material. The Onitsha concentrations are much lower than the Co values reported in several heavily impacted Nigerian settings, including soils associated with industrial activities and petroleum contamination. The relatively low absolute concentration suggests limited immediate risk from Co.

Molybdenum

Molybdenum ranged from 0.182–0.364 mg kg^{-1}, with a mean of 0.255±0.070 mg kg^{-1} and a coefficient of variation of approximately 27.5%. The mean exceeded the

control value of 0.130 mg kg^{-1}, indicating modest enrichment. The values remained below the 4 mg kg^{-1} guideline given by WHO (2003) limit of 4 mg kg^{-1} recommended for soils but this indicates enrichment relative to the control soil. resulting from petrol handling activities at the fueling stations.

Compared with the other elements, Mo showed limited spatial variability and generally low enrichment. Its presence may reflect fuel additives, lubricants, traffic-related deposition, or mineralogical sources.

Cadmium

Cadmium concentrations ranged from 0.022–0.159 mg kg^{-1}, with a mean of 0.067±0.053 mg kg^{-1} and a high coefficient of variation (73.3%). Although the mean concentration was only modestly above the control value of 0.040 mg kg^{-1}, the large variability and elevated concentrations at PS 4, PS 9, and PS 10 indicate localized inputs. In addition, the values were equally below the average composition of Shales value which is 0.3 mg kg^{-1} (Turekian & Wedepohl, 1961), the Dutch Soil Quality Standard (MSHPE, 1994) target value of 0.8 mg kg^{-1}, but below the EPA (1995) Ecological Screening Value of 1.00 mg kg^{-1} and the Dutch intervention value of 12 mg kg^{-1}.

Moreover, the mean Cd concentration was lower than the mean value of 0.0391 mg kg^{-1} reported around petrol stations in Kogi State, Nigeria, although the maximum value in Onitsha was higher than the Kogi mean. It was also substantially lower than Cd concentrations reported around petrol stations in Tamale, Ghana, where values reached approximately 6.63 mg kg^{-1} (Emmanuel et al., 2014). Possible sources include fuel residues and atmospheric deposition.

Manganese

Manganese concentrations ranged from 4.410–7.654 mg kg^{-1}, with a mean of 6.148±1.125 mg kg^{-1} and a low coefficient of variation (18.3%). The mean was approximately 2.4 times the control value of 2.522 mg kg^{-1}, indicating enrichment relative to local background. However, the absolute concentrations were well below the general crustal abundance reported in the literature and far below the Mn concentrations commonly observed in Nigerian urban and industrial soils. In Abeokuta, for example, mean Mn concentrations across anthropogenic sites ranged from approximately 182.69 to 697.06 mg kg^{-1} (Olayinka et al., 2017).

The relatively low and uniform Mn concentrations in Onitsha suggest that Mn is not a major contaminant at the studied petrol stations.

Silicon

Silicon ranged from 7.577–10.383 mg kg^{-1}, with a mean of 9.087±0.940 mg kg^{-1} and a low coefficient of variation (8.2%). The concentration was slightly lower at the control site than at most petrol stations. Because Si is strongly associated with sand and silicate minerals, its distribution is more plausibly related to local geology, particle-size composition, and mineral weathering than to petrol-station activities. The relatively

uniform values support its use as a normalization element, but the suitability of Si should be confirmed by examining its relationship with grain size and other conservative lithogenic elements.

Soil Quality Assessment

Enrichment Factor

The EF results (Table 4) indicate varying degrees of enrichment among the sampling stations. Pb generally showed minor to moderate enrichment, whereas Cu, Cr, Ni, Co, and particularly Al displayed higher enrichment classes at several locations. The widespread enrichment of Cr and Ni is consistent with the CF results and suggests that these metals are important indicators of anthropogenic influence in the study area.

Similar patterns have been reported in Nigeria. Around petrol stations in Kogi State, Cd and Cu showed particularly high enrichment factors, even though the absolute concentrations of several metals remained low. In industrial soils from southwestern Nigeria, the ecological-risk order was reported as Cd > Pb > Cu > Ni > Cr > Mn, demonstrating that metals with relatively modest concentrations can dominate risk when toxicity and background values are considered together. International evidence also supports the use of background-normalized indices: soils influenced by petrol stations in Odessa, Ukraine, showed substantially higher mobile heavy-metal contents than background soils, with Zn, Cu, and Pb among the principal pollutants (Kolawale et al., 2018).

Contamination Factor

The CF results (Table 5) provide clearer spatial differentiation than the concentration data alone. Ni showed the most consistent and severe contamination, with values of 13.77–33.80, while Cr values of 8.38–12.53 placed all stations in the very-high-contamination category. Pb, Cu, Co, Cd, and Zn displayed more variable patterns. The highest multi-element loads occurred at PS 6 and PS 9, where elevated CF values were simultaneously observed for Ni, Cr, Cu, Co, and Cd.

This pattern is broadly comparable with Nigerian studies in which pollution indices identified station-specific differences linked to fuel spills, vehicle activity, leaking tanks, and local drainage. In Kogi State, researchers found low pollution for several metals but extremely high enrichment for Cd and Cu, illustrating that contamination categories may differ depending on whether they are based on concentration, CF, EF, or toxicity-weighted risk. In contrast, studies of crude-oil-impacted soils in the Niger Delta have reported much larger CF values and pervasive extreme pollution, reflecting the greater intensity of direct crude-oil exposure (Kadili et al., 2021).

The consistently high CF values for Ni and Cr across the Onitsha stations suggest a widespread source, potentially involving traffic emissions, fuel handling, or a combination of these factors. The variable distributions of Cd, Cu, and Co point to additional localized

sources such as fuel spills, corrosion, dust generated by tyre and brake wear. Because CF uses the control soil as the denominator, the high values also partly reflect the unusually low concentrations at the control site. Accordingly, the findings demonstrate strong enrichment relative to local background but should not be interpreted automatically as evidence that all sites exceed regulatory limits.

Pollution Load Index

The PLI values ranged from 2.42 to 6.07, with a mean of 4.36 (Table 6). Because all values exceeded 1, every petrol-station site was classified as polluted by the combined metal burden. PS 6 recorded the highest PLI, followed by PS 9 and PS 4, whereas PS 5 had the lowest value.

The spatial pattern agrees with the CF results and indicates that the pollution burden is not evenly distributed among the stations. The PLI values are higher than those reported in some Nigerian studies where overall pollution was low or moderate, but they are lower than values associated with heavily crude-oil-impacted soils in the Niger Delta, where PLI values indicate pervasive extreme pollution. They are also consistent with the observation from Nigerian industrial and mining environments that PLI can identify combined contamination even when individual metals do not exceed regulatory (Yahaya, 2021).

The present values indicate a significant anthropogenic metal burden and justify additional monitoring, but risk-management decisions should also consider metal speciation, bioavailability, land use, exposure pathways, and groundwater vulnerability.

Ecological Risk Assessment

The ecological risk values and the potential ecological risk index (PERI) for the toxic metals across the petrol stations are presented in table 7. The individual ecological risk for each metal shows that Lead recorded Er^i values ranging from 13.1 to 22.8, with a mean of 18.7. All Pb values were below 40, indicating low ecological risk at every petrol station. The highest Pb risk occurred at PS 6, followed by PS 4 and PS 10. Although Pb was enriched relative to the control soil, its toxicity-weighted contribution to the total ecological risk was comparatively limited.

Copper had Er^i values ranging from 11.2 to 35.0, with a mean of 23.15. All values remained below the low-risk threshold of 40. The highest Cu ecological risk was observed at PS 6, while the lowest occurred at PS 4. The relatively higher value at PS 6 is consistent with the elevated Cu contamination factor at that location.

Zinc recorded the lowest ecological-risk values, ranging from 0.2 to 5.2, with a mean of 1.66. All sites therefore fell within the low-risk category. The low Zn risk is attributable to both its low toxicity coefficient and its generally modest contamination relative to the control soil. PS 4 had the highest Zn risk, corresponding to the maximum Zn contamination at that station.

Chromium showed Er^i values ranging from 16.8 to 25.1, with a mean of 19.99. All Cr values were below 40 and therefore represented low ecological risk. The highest Cr risk was recorded at PS 6, followed by PS 9 and PS 4. Although Cr was consistently enriched across the petrol stations, its toxicity-weighted ecological risk remained low based on the coefficient applied in this assessment. Because total Cr was measured, the results do not distinguish between Cr(III) and Cr(VI), which have different environmental toxicities.

Cadmium produced a much wider range of ecological-risk values, from 12.0 to 119.4, with a mean of 56.46. The lowest Cd risk occurred at PS 8, whereas the highest values were recorded at PS 4, PS 9, and PS 10. Based on the classification Er^i < 40 for low risk, (40–80) for moderate risk, and (80–160) for considerable risk:

PS 1, PS 3, PS 6, and PS 7 indicated low ecological risk while PS 2 and PS 5 indicated moderate ecological risk.

Moreover, PS 4, PS 9, and PS 10 indicated considerable ecological risk while PS 8 remained in the low-risk category.

Cadmium was therefore one of the most important risk-driving metals, particularly at PS 4, PS 9, and PS 10. It is important to observe that this result reflects the high toxicity coefficient of Cd (30), rather than its concentration alone.

Nickel was the dominant contributor to the ecological-risk assessment. Its Er^i values ranged from 68.8 to 169.0, with a mean of 110.42. All stations showed at least moderate ecological risk from Ni. The highest value occurred at PS 6, followed by PS 9, PS 4, and PS 10. Based on the risk categories, PS 5 recorded moderate Ni risk while PS 1, PS 2, PS 3, PS 7, PS 8, PS 9, and PS 10 showed considerable Ni risk. Also, PS 4 and PS 6 showed high Ni risk, with values of 119.5 and 169.0, respectively, although PS 4 falls within the considerable class under the stated (80–160) threshold and PS 6 falls within the high class of (160–320).

The consistently elevated Ni risk across the sites suggests that Ni is the most widespread toxicity-weighted contaminant in the study area. Its distribution may reflect common anthropogenic inputs associated with fuel handling, vehicle emissions, lubricants, combustion residues, or other petrol-station activities. However, the use of a single control site means that the magnitude of the Ni risk remains dependent on the selected background concentration.

Cobalt recorded Er^i values ranging from 7.9 to 31.3, with a mean of 20.59. All values were below 40 and therefore classified as low ecological risk. The highest Co risk was recorded at PS 9, followed by PS 2 and PS 6. Although Co contributed to the overall metal burden, its toxicity-weighted contribution was much smaller than those of Ni and Cd.

Potential Ecological Risk Index

The PERI values ranged from 157.5 to 338.7, with the lowest value recorded at PS 5 and the highest at PS 9. Based on the commonly used classifications <150 -Low, 150–300 – Moderate, 300–6000 –Considerable, >600 -Very high, all petrol stations recorded

PERI values above 150. Therefore, none of the sites fell within the low overall ecological-risk category.

PS 5 recorded a PERI of 157.5, indicating moderate ecological risk. PS 1, PS 2, PS 3, PS 7, PS 8, and PS 10 recorded PERI values between 194.6 and 297.4, indicating moderate ecological risk. Moreover, PS 4, PS 6, and PS 9 recorded PERI values of 318.3, 333.7, and 338.7 respectively, indicating considerable ecological risk.

The spatial pattern shows that PS 9, PS 6, and PS 4 were the most environmentally concerning sites. Their elevated PERI values were driven mainly by the combined effects of Ni and Cd. PS 6 had the highest Ni risk (Er^i =169), while PS 4 and PS 9 had high Cd risks of 119.4 and 114.0, respectively. PS 10 also recorded a relatively high Cd risk of 107.1, although its overall PERI remained within the moderate-risk class.

The relative contribution of each metal to the combined risk was estimated from the sum of the mean Er^i values as shown in the table 8:

The mean risk contribution was therefore dominated by Ni, followed by Cd. Together, Ni and Cd accounted for approximately 66% of the average individual-metal ecological risk. This identifies them as the priority metals for environmental monitoring and management in the study area.

Environmental Interpretation

The PERI results indicate that the petrol-station soils have a moderate to considerable potential ecological risk, despite the relatively low absolute concentrations of several metals compared with international soil-quality standards. This apparent contrast occurs because PERI incorporates both contamination relative to background and metal-specific toxicity. Consequently, a metal such as Cd can make a large contribution to ecological risk even when its concentration is lower than that of Pb, Cu, or Ni.

The predominance of Ni and Cd suggests that environmental management should focus on preventing continued inputs from fuel and lubricant spills, vehicle-related emissions, storage and dispensing operations, corroded infrastructure, and improper disposal of petroleum-related wastes. The higher PERI values at PS 4, PS 6, and PS 9 indicate that these locations should receive priority for follow-up sampling and inspection.

The results should nevertheless be interpreted cautiously. PERI is a screening-level index and does not represent a direct measurement of biological damage or human-health risk. Its values depend strongly on the selected background concentrations, toxicity coefficients, and metal suite. In this study, the background was based on one control soil from Awka, which may not fully represent the natural geochemical background of Onitsha. Additional reference sites, repeated sampling, metal speciation, bioavailability measurements, and biological monitoring would improve the reliability of the ecological-risk assessment.

Overall, all petrol-station sites showed at least moderate potential ecological risk, with PS 4, PS 6, and PS 9 classified as considerable-risk locations. Nickel was the principal

contributor to the overall risk, followed by cadmium, while zinc, lead, copper, chromium, and cobalt contributed comparatively lower individual risks.

Geoaccumulation Index

The mean-based Igeo results, as shown in Table 9, classify Ni as strongly contaminated, Al as extremely contaminated, and Cu and Pb as moderately contaminated, while Co, Cd, and Zn fall within the uncontaminated-to-moderately-contaminated class. These results broadly support the identification of Ni, Cu, and Pb as important indicators of enrichment.

The contrast between Igeo and the absolute concentrations illustrates the sensitivity of geoaccumulation indices to the selected background. Similar studies in Nigeria have reported low or moderate pollution from individual metals alongside high enrichment factors for Cd or Cu, while severely oil-impacted soils in the Niger Delta have shown moderate-to-strong geoaccumulation for Pb and Zn. International studies around petrol stations have likewise found elevated metal accumulation relative to background even where the degree of contamination varied (Domuschy et al., 2022).

Correlation Analysis of Soil Heavy Metals

Correlation values (Table 10) of Pb show a strong positive correlation with Mo (+0.897) and Mn (+0.947) indicating that these metals come from common sources. Also, there is some observed weak positive correlations between Pb/Zn (+0.356) and Pb/Cd (+0.164). On the other hand, there is a strong negative correlation between Pb and Al (-0.797); weak negative correlation between Pb/Ni (-0.164). Cu/Al (+0.624) has a moderate positive correlation while Cu/Cr (+0.058), Cu/Co (+0.133), Cu/Si (+0.032) show a weak positive correlation and showing strong negative correlation. Strong negative correlation also exists between Cu/Cd (-0.768), Cu/Mo (--0.794), Cu/Mn (-0.712). Moderate negative correlations (0.5-0.7) exist between Cu and Zn (-0.644). Zn has a strong positive correlation with Cd (+0.873) and Ni (+0.815). It shows weak positive correlation with Co (+0.415), Mo (+0.247) and Mn (+0.408). However, Zn/Al (-0.786) shows a strong negative correlation while Zn/Si has weak negative correlation. Cr has a strong positive correlation with Ni (+0.837) and Co (+0.837) while there is a weak positive correlation between Cr/Cd (+0.361).

Cd has a moderate correlation with Ni (+0.691) and weak positive correlation with Mo (+0.263), Mn (+0.23) and Co (+0.074). Ni/Co (+0.507) has a moderate positive correlation while Ni/Mo (-0.343), Ni/Mn (-0.163), Ni/Si (-0.495) have weak positive correlation. Co/Mn (+0.076) and Co/Si (+0.319) have weak positive correlation while Co/Mo (-0.339) has a weak negative correlation. Mo/Mn (+0.904) shows a strong positive correlation while Mo/Si (-0.002). Mn/Si (+0.082) has a weak positive correlation.

Overall Interpretation

Taken together, the physicochemical data and contamination indices indicate that petrol-station soils in Onitsha have undergone measurable anthropogenic enrichment.

The acidic pH, low CEC, sandy texture, and lower organic matter may increase the mobility and bioavailability of some metals. Ni and Cr are the most consistently enriched elements, while Cd is the most important toxicity-weighted contaminant and contributes disproportionately to ecological risk. Cu, Co, and Pb show station-specific enrichment, and Zn displays the greatest concentration variability.

Compared with studies from Nigeria, Ghana, Iraq, Ukraine, and severely petroleum-impacted areas of the Niger Delta, the absolute metal concentrations in Onitsha are generally low. The principal significance of the present study therefore lies not in widespread exceedance of regulatory limits but in the consistent enrichment relative to the control soil, the pollution-load values above unity, and the moderate-to-considerable ecological risk at selected stations. These findings support regular soil monitoring, improved spill prevention, inspection of underground storage and dispensing systems, and further investigation of groundwater and bioavailable metal fractions.

Comparison with Global Urban Studies

The metal concentrations measured in the Onitsha petrol-station soils were generally lower than those reported in many heavily industrialized and densely urbanized environments worldwide as shown in Table 11. The mean concentrations recorded in Onitsha were 1.397 mg kg^{-1} - Pb, 0.689 mg kg^{-1} - Cu, 3.290 mg kg^{-1} - Zn, 2.293 mg kg^{-1} - Cr, 1.331 mg kg^{-1} - Ni, 0.072 mg kg^{-1} - Cd, and 0.230 mg kg^{-1} - Co. By comparison, a global meta-analysis of urban soils from 174 cities reported average concentrations of approximately 206.97 mg kg^{-1} - Pb, 179.35 mg kg^{-}1 - Cu, 256.26 mg kg^{-1} - Zn, 87.67 mg kg^{-1} - Cr, 65.58 mg kg^{-1} - Ni, 8.68 mg kg^{-1} - Cd, and 18.59 mg kg^{-1} – Co (Adewumi and Ogundele, 2024). Thus, the Onitsha petrol-station soils contain substantially lower absolute concentrations than the global urban-soil averages.

The difference is particularly pronounced for Pb, Cu, Zn, Ni, and Cd. The mean Pb concentration in Onitsha is approximately 148 times lower than the global urban mean, while the mean Cu, Zn, Cr, Ni, Cd, and Co concentrations are approximately 260, 78, 38, 49, 121, and 81 times lower, respectively. This contrast suggests that the Onitsha sites do not represent the same degree of cumulative urban-industrial contamination observed in major global cities affected by long-term traffic emissions, metallurgical activities, coal combustion, waste disposal, industrial deposition, and intensive urban development.

The Onitsha results are also lower than concentrations reported for several international petrol-station studies. In Al-Hilla, Iraq, soils around fuel stations recorded mean concentrations of approximately 25.47 mg kg^{-1} - Pb, 86.65 mg kg^{-1} - Ni, 84.38 mg kg^{-1} -Zn, and 96.71 mg kg^{-1} -Mn. The corresponding Onitsha values are approximately 18 times lower for Pb, 65 times lower for Ni, and 26 times lower for Zn. Similarly, studies of soils affected by petrol stations in Odessa, Ukraine, reported substantially higher accumulation of several heavy metals than in background soils, with Zn, Cu, and Pb identified as important pollutants (Ahmed et al., 2020).

Compared with petrol-station soils in Tamale, Ghana, the Onitsha concentrations are also generally lower. The Tamale study reported ranges of approximately 4.93–74.20 mg kg^{-1} for Pb, 3.20–22.68 mg kg^{-1} for Cu, and 0.12–6.63 mg kg^{-1} for Cd. The Onitsha ranges for Pb, Cu, and Cd were 1.052–1.821, 0.359–1.122, and 0.022–0.159 mg kg^{-1}, respectively. These results indicate that the absolute metal burden in the Onitsha sites is comparatively low when evaluated against other urban petrol-station environments in West Africa.

A similar contrast is observed when the Onitsha data are compared with highly contaminated petroleum-impacted soils. In one petroleum-contaminated environment, peak soil concentrations reached 95.890 mg kg^{-1} - Co, 280.953 mg kg^{-1} - Ni, 714.864 mg kg^{-1} – Pb. The Onitsha values are several orders of magnitude lower than these concentrations. This indicates that the study sites are better characterized as soils with measurable background enrichment and localized anthropogenic influence rather than severely contaminated petroleum-release zones (Wu et al., 2024).

However, the relatively low absolute concentrations should not be interpreted as evidence of an absence of environmental impact. The Onitsha petrol-station soils showed substantial enrichment relative to the local control, particularly for Ni and Cr. The mean Ni concentration was about 20 times higher than the control value, while the mean Cr concentration was approximately nine times higher. In addition, all PLI values exceeded 1, indicating pollution relative to the selected background. This distinction is important because global urban studies show that contamination indices and background-normalized values can reveal anthropogenic influence even when total concentrations remain below regulatory limits (Adewumi et al., 2024).

The pattern observed in Onitsha also differs from the typical metal ranking reported in global urban soils. Worldwide urban soils are often dominated by Pb, Zn, Cu, Cr, Ni, and Cd, with the highest concentrations linked to traffic, industrial emissions, construction materials, waste disposal, and historical fuel combustion. In the present study, Ni and Cr were the most consistently enriched metals based on CF values, whereas Zn and Cu had lower mean concentrations and greater spatial variability. This suggests that the Onitsha contamination signature may reflect a combination of petrol-station operations, vehicular activity, local geology, and the low metal concentrations at the control site rather than a single dominant source.

The ecological-risk results further distinguish the Onitsha sites from global urban centers. Although the absolute Cd concentration was low, Cd contributed substantially to the potential ecological risk because of its high toxicity coefficient. Ni also made an important contribution at selected locations, particularly PS 6. This toxicity-weighted pattern is comparable to studies in Nigeria where Cd dominated ecological-risk calculations despite relatively low concentrations. Therefore, comparison based only on total concentrations may underestimate the environmental importance of particular metals.

Overall, the Onitsha petrol-station soils exhibit a lower absolute heavy-metal burden than many global urban soils and international petrol-station environments. Nevertheless, they show clear anthropogenic enrichment relative to the local control, widespread Ni and Cr contamination, localized Cd, Cu, and Co inputs, and moderate-to-considerable ecological risk at selected stations. The findings suggest that Onitsha may represent an early or moderate stage of urban petrol-station-related contamination rather than the severe contamination characteristic of long-industrialized cities or sites affected by major petroleum releases. Continued monitoring is therefore warranted to prevent progressive accumulation and to identify whether current station activities could eventually produce contamination levels comparable to those documented in other urban environments.

Table 2
Physicochemical parameters of the samples from the petrol stations

Site	%Sand	%Silt	%Clay	pH	CEC (Cmol/kg)	OM (%)
CONTROL	39.957	37.484	22.559	6.720	0.560	17.300
PS 1	47.661	22.484	29.855	5.820	0.198	6.592
PS 2	48.869	21.292	31.839	5.230	0.216	11.760
PS 3	50.269	20.343	29.388	5.630	0.221	13.670
PS 4	56.784	20.387	22.828	5.630	0.199	12.085
PS 5	48.916	21.737	29.347	5.630	0.171	9.518
PS 6	49.223	23.952	26.825	5.630	0.221	11.840
PS 7	52.337	20.225	27.438	5.630	0.317	12.427
PS 8	58.953	22.163	18.884	5.630	0.261	10.537
PS 9	57.331	24.223	18.446	5.630	0.341	9.857
PS 10	59.625	20.113	20.262	5.630	0.297	8.553
Min	47.661	20.113	18.446	5.230	0.171	6.592
Max	59.625	24.223	31.839	5.820	0.341	13.670
Mean	52.997	21.692	25.511	5.609	0.244	10.684
SD	4.436	1.439	4.719	0.138	0.054	1.994
CV	8.371	6.632	18.497	5.630	22.141	18.664

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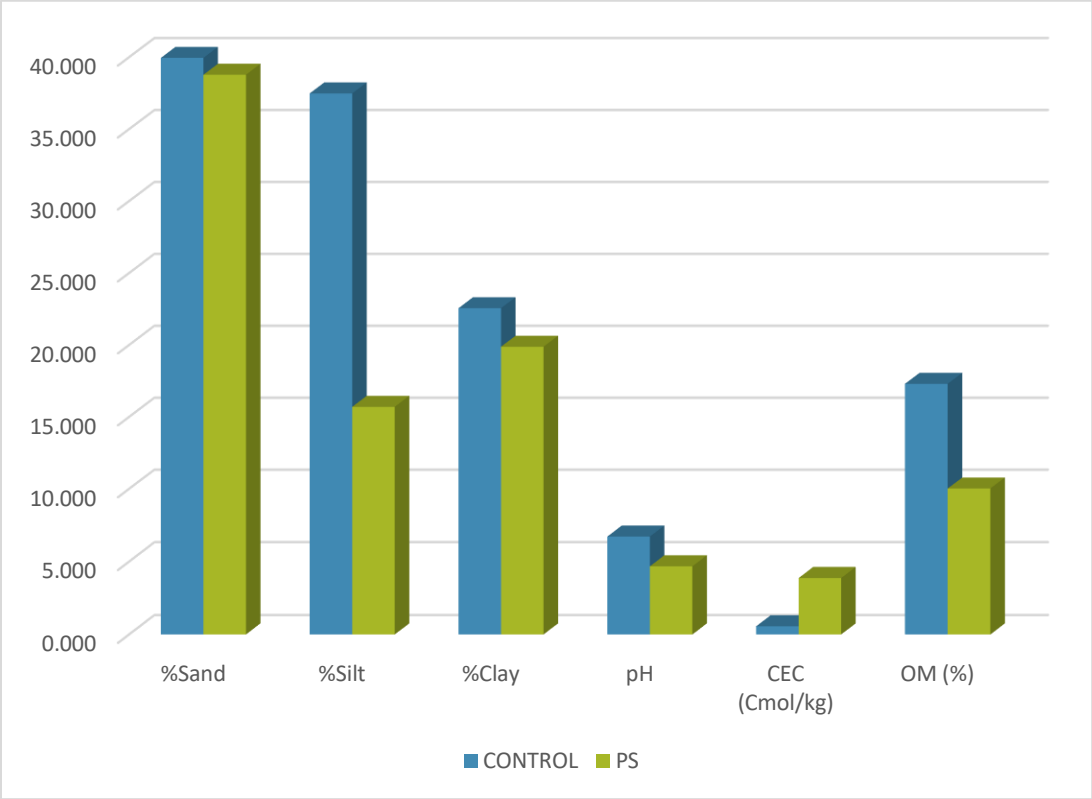

Fig. 3: *Bar chart showing the physicochemical variations in the samples from the control and the petrol stations*

Table 3

Heavy metals concentrations (mg kg−1) in the soil samples from the petrol stations

Locations	Pb	Cu	Zn	Cr	Cd	Ni	Co	Mo	Mn	Si
CONTROL	0.4	0.16	2.05	0.25	0.04	0.066	0.06	6.13	2.522	10.388
PS 1	1.052	0.743	1.036	2.236	0.078	1.259	0.11	0.186	4.41	9.234
PS 2	1.283	0.875	2.053	2.527	0.022	1.268	0.362	0.183	5.731	10.383
PS 3	1.471	0.886	3.396	2.411	0.043	1.399	0.178	0.206	5.462	7.577
PS 4	1.661	0.359	10.725	2.537	0.159	1.577	0.264	0.303	7.097	8.657
PS 5	1.78	0.561	0.441	2.095	0.032	0.909	0.094	0.355	7.325	9.583
PS 6	1.821	1.122	4.643	3.132	0.066	2.231	0.361	0.231	6.463	9.531
PS 7	1.472	0.926	3.433	2.541	0.042	1.352	0.254	0.182	7.084	9.361
PS 8	1.253	0.624	2.331	2.322	0.016	1.381	0.278	0.203	7.654	8.755
PS 9	1.534	0.882	3.534	2.752	0.152	1.622	0.376	0.364	5.371	9.617
PS 10	1.642	0.439	2.553	2.422	0.143	1.577	0.192	0.332	4.883	10.211
Min	1.052	0.359	0.441	2.095	0.016	0.909	0.094	0.182	4.41	7.577
Max	1.821	1.122	10.725	3.132	0.159	2.231	0.376	0.364	7.654	10.383
Mean	1.497	0.742	3.415	2.498	0.075	1.458	0.247	0.255	6.148	9.291
SD	0.232	0.228	2.706	0.273	0.053	0.324	0.097	0.071	1.068	0.77
CV	15.51	30.788	79.257	10.937	70.21	22.238	39.294	28.079	17.366	8.284

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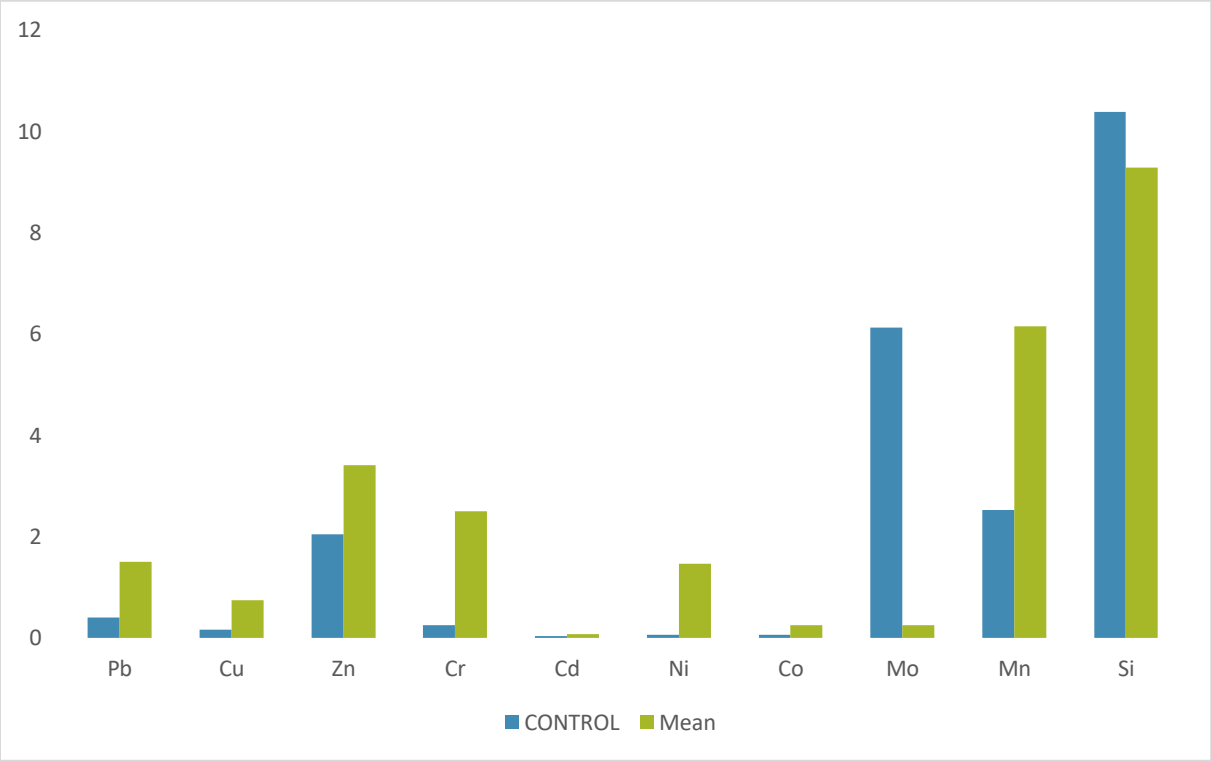

Fig. 4: *Bar chart comparing average heavy metal levels in the petrol stations with the control.*

Table 4

Contamination Factor (CF) of heavy metals at the petrol-station sites, calculated using the Awka control soil as background.

Locations	Pb	Cu	Zn	Cr	Cd	Ni	Co	Mo	Mn	Si
PS 1	2.63	4.64	0.51	8.94	1.95	19.08	1.83	0.03	1.75	0.89
PS 2	3.21	5.47	1.00	10.11	0.55	19.21	6.03	0.03	2.27	1.00
PS 3	3.68	5.54	1.66	9.64	1.08	21.20	2.97	0.03	2.17	0.73
PS 4	4.15	2.24	5.23	10.15	3.98	23.89	4.40	0.05	2.81	0.83
PS 5	4.45	3.51	0.22	8.38	0.80	13.77	1.57	0.06	2.90	0.92
PS 6	4.55	7.01	2.26	12.53	1.65	33.80	6.02	0.04	2.56	0.92
PS 7	3.68	5.79	1.67	10.16	1.05	20.48	4.23	0.03	2.81	0.90
PS 8	3.13	3.90	1.14	9.29	0.40	20.92	4.63	0.03	3.03	0.84
PS 9	3.84	5.51	1.72	11.01	3.80	24.58	6.27	0.06	2.13	0.93
PS 10	4.11	2.74	1.25	9.69	3.58	23.89	3.20	0.05	1.94	0.98

Table 5

Enrichment Factor (EF) of heavy metals across the sampling points

Locations	Pb	Cu	Zn	Cr	Cd	Ni	Co	Mo	Mn	Si
PS 1	2.96	5.47	1.00	10.11	2.19	21.46	2.06	0.03	1.97	1
PS 2	3.21	7.59	2.27	13.22	0.55	19.22	6.04	0.03	2.27	1
PS 3	5.04	2.69	6.28	12.18	1.47	29.06	4.07	0.05	2.97	1
PS 4	4.98	3.80	0.23	9.08	4.77	28.67	5.28	0.06	3.38	1
PS 5	4.82	7.64	2.47	13.65	0.87	14.93	1.70	0.06	3.15	1
PS 6	4.96	6.42	1.86	11.28	1.80	36.84	6.56	0.04	2.79	1
PS 7	4.08	4.63	1.35	11.02	1.17	22.73	4.70	0.03	3.12	1
PS 8	3.72	5.95	1.86	1.05	0.47	24.83	5.50	0.04	3.60	1
PS 9	4.14	2.79	1.27	9.86	4.10	26.55	6.77	0.06	2.30	1
PS 10	4.18	3.08	0.29	11.49	3.64	24.31	3.26	0.06	1.97	1
	Pb	Cu	Zn	Cr	Cd	Ni	Co	Mo	Mn	Si

Table 6

Pollution Load Index (PLI) across the sampled petrol-station sites.

Site	PLI	Pollution class
PS 1	1.68	Polluted (PLI > 1)
PS 2	1.94	Polluted (PLI > 1)
PS 3	2.03	Polluted (PLI > 1)
PS 4	2.74	Polluted (PLI > 1)
PS 5	1.54	Polluted (PLI > 1)
PS 6	2.77	Polluted (PLI > 1)
PS 7	2.19	Polluted (PLI > 1)
PS 8	1.83	Polluted (PLI > 1)
PS 9	2.78	Polluted (PLI > 1)
PS 10	2.28	Polluted (PLI > 1)

Table 7

Ecological risk (ER) and potential ecological risk index (PERI) of toxic metals in soils across the across the petrol stations

	Er Pb	Er Cu	Er Zn	Er Cr	Er Cd	Er Ni	Er Co	PERI
Tri	5	5	1	2	30	5	5	
PS 1	13.1	23.2	0.5	17.9	58.5	95.4	9.2	217.8
PS 2	16.1	27.3	1	20.2	16.5	96.1	30.2	207.3
PS 3	18.4	27.7	1.7	19.3	32.1	106	14.9	220
PS 4	20.8	11.2	5.2	20.3	119.4	119.5	22	318.3
PS 5	22.2	17.5	0.2	16.8	24	68.8	7.9	157.5
PS 6	22.8	35	2.3	25.1	49.5	169	30.1	333.7
PS 7	18.4	28.9	1.7	20.3	31.5	102.4	21.2	224.4
PS 8	15.6	19.5	1.1	18.6	12	104.6	23.1	194.6
PS 9	19.1	27.5	1.7	22	114	122.9	31.3	338.7
PS10	20.5	13.7	1.2	19.4	107.1	119.5	16	297.4
Min	13.1	11.2	0.2	16.8	12	68.8	7.9	
Max	22.8	35	5.2	25.1	119.4	169	31.3	
Mean	18.7	23.15	1.66	19.99	56.46	110.42	20.59	

Table 8

Table showing Er^i contributions of each metal to the combined risk

Mean	Mean Er^i	Approx. contribution (%)
Pb	18.7	7.4
Cu	23.15	9.2
Zn	1.66	0.70
Cr	19.99	7.90
Cd	56.46	22.40
Ni	110.42	43.80
Co	20.59	8.20

Table 9

Geoaccumulation Index (I_{geo}) of heavy metals across the petrol-station sites.

Location	Pb	Cu	Zn	Cr	Cd	Ni	Co	Mo	Mn	Si
PS 1	0.810	1.630	-1.570	2.576	0.379	3.669	0.290	-5.627	0.221	-0.755
PS 2	1.096	1.866	-0.583	2.752	-1.447	3.679	2.008	-5.651	0.599	-0.586
PS 3	1.294	1.884	0.143	2.685	-0.481	3.821	0.984	-5.480	0.530	-1.040
PS 4	1.469	0.581	1.802	2.758	1.406	3.994	1.553	-4.923	0.908	-0.848
PS 5	1.569	1.225	-2.802	2.482	-0.907	3.199	0.063	-4.695	0.953	-0.701
PS 6	1.602	2.225	0.594	3.062	0.138	4.494	2.004	-5.315	0.773	-0.709
PS 7	1.295	1.948	0.159	2.760	-0.515	3.772	1.497	-5.659	0.905	-0.735
PS 8	1.062	1.379	-0.400	2.630	-1.907	3.802	1.627	-5.501	1.017	-0.832
PS 9	1.354	1.878	0.201	2.876	1.341	4.034	2.063	-4.659	0.506	-0.696
PS 10	1.452	0.871	-0.268	2.691	1.253	3.994	1.093	-4.792	0.368	-0.610
Minimum	0.810	0.581	-2.802	2.482	-1.907	3.199	0.063	-5.659	0.221	-1.040
Maximum	1.602	2.225	1.802	3.062	1.406	4.494	2.063	-4.659	1.017	-0.586
Mean	1.300	1.549	-0.272	2.727	-0.074	3.846	1.318	-5.230	0.678	-0.751
Mean class	M	M	U	M–S	U	S	M	U	U–M	U

*__Class abbreviations:__ U = unpolluted; U–M = unpolluted to moderately polluted; M = moderately polluted; M–S = moderately to strongly polluted; S = strongly polluted; E = extremely polluted.

Table 10

Pearson correlation matrix for heavy metals in soils from the selected petrol stations.

Metals	Pb	Cu	Zn	Cr	Cd	Ni	Co	Mo	Mn	Si
Pb	1									
Cu	-0.072	1								
Zn	0.36	-0.282	1							
Cr	0.395	0.605	0.416	1						
Cd	0.305	-0.401	0.586	0.268	1					
Ni	0.386	0.392	0.486	0.914	0.39	1				
Co	0.105	0.461	0.345	0.799	0.133	0.62	1			
Mo	0.634	-0.476	0.182	-0.028	0.64	0.002	-0.064	1		
Mn	0.371	-0.112	0.248	0.018	-0.356	-0.051	0.146	0.004	1	
Si	0.094	0.013	-0.323	0.15	0.113	0.021	0.266	0.252	-0.179	1

Table 11

Comparative Summary of Global Urban mean of heavy metals with the present study (Source: Adapted from Adewumi and Ogundele, 2024).

Metal	Onitsha mean (mg kg^{-1})	Global urban mean (mg kg^{-1})	Interpretation
Pb	1.397	206.97	Much lower than the global urban average
Cu	0.689	179.35	Very low absolute concentration, despite local enrichment
Zn	3.290	256.26	Lower than typical global urban-soil concentrations
Cr	2.293	87.67	Low absolute concentration but consistently enriched relative to control
Ni	1.331	65.58	Low absolute concentration but highest and most widespread CF signal
Cd	0.072	8.68	Low concentration but important because of high toxicity weighting
Co	0.230	18.59	Low absolute concentration with localized enrichment
Metal	Onitsha mean (mg kg^{-1})	Global urban mean (mg kg^{-1})	Interpretation
Pb	1.397	206.97	Much lower than the global urban average
Cu	0.689	179.35	Very low absolute concentration, despite local enrichment

Environmental and Human-Health Implications

The contamination indices demonstrate that petrol-station activities have altered the metal status of soils in Onitsha relative to the control site. The observed enrichment may result from multiple sources associated with petroleum-retailing operations, including accidental fuel and lubricant spills, losses during storage and dispensing, vehicular exhaust, tyre and brake wear, corrosion of metallic infrastructure, and traffic-related atmospheric deposition. These inputs may be particularly significant under the acidic soil conditions observed in the study area. Low pH can enhance the dissolution and mobility of several potentially toxic metals, thereby increasing their availability for plant uptake, downward migration through the soil profile, and eventual transport to shallow groundwater.

The ecological significance of the results is particularly evident for Cd and Ni, which made substantial contributions to the potential ecological-risk assessment. Following their introduction into the soil, these metals may be retained by clay minerals, organic matter, and iron or manganese oxides, or redistributed through soil–water interactions. Nickel is commonly adsorbed onto soil particles; however, its mobility may increase under acidic conditions, thereby enhancing the potential for leaching into deeper soil horizons and groundwater (Oyeleke et al., 2016; Chokor, 2016). Elevated Ni concentrations may also adversely affect soil microorganisms, enzyme activity, plant growth, and nutrient cycling. Cadmium is a non-essential element with a strong tendency to accumulate in soils and biological tissues. Its persistence and mobility increase the likelihood of transfer to plants and other components of the food chain. Chronic human exposure to Cd has been associated with renal toxicity, carcinogenic effects, and other adverse health

outcomes (Hartwig, 1998). Severe Cd exposure has also been linked to skeletal and renal disorders, including Itai-Itai disease (Kazantzis, 2004).

Lead is of particular concern because of its persistence, toxicity, and capacity to remain in surface soils and dust. Exposure to Pb has been associated with impaired neurological and physical development, especially in children, as well as elevated blood pressure and adverse reproductive outcomes in adults (Needleman et al., 1990; Oyeleke et al., 2016). Accordingly, the occurrence of Pb in soils within petrol stations is environmentally important even where measured concentrations remain below regulatory intervention values. Contaminated soil and re-suspended dust may provide continuing exposure sources for petrol-station attendants, motorists, children, and nearby residents. Chromium also deserves attention. Although the present study determined total Cr rather than individual species, some Cr species are associated with dermatitis, mutagenic effects, and carcinogenicity (Scragg, 2006; Chokor, 2016).

The implications of Zn and Cu differ from those of Pb and Cd because both elements are essential micronutrients at low concentrations but may become toxic when their concentrations or bioavailability increase. Excessive Zn exposure may cause gastrointestinal irritation, interfere with physiological processes, and contribute to Cu deficiency (Hurley & Keen, 1979). In soil systems, elevated Zn may inhibit microbial activity, affect earthworms, and disrupt organic-matter decomposition and nutrient cycling. Similarly, excessive Cu may interfere with plant physiological processes, including fatty-acid and protein metabolism, respiration, and nitrogen fixation (Fernandez & Henriques, 1991; Konstantinidis et al., 2003). High dietary Cu exposure may also produce gastrointestinal symptoms and promote accumulation in organs such as the liver and kidneys (Pizarro et al., 1999). In the present study, the environmental significance of Zn and Cu is therefore more closely related to their spatial enrichment and potential long-term accumulation than to immediate toxicity based solely on their measured total concentrations.

Manganese is also an essential micronutrient, but excessive exposure may produce neurological effects, including motor and psychiatric disturbances (Klaassen, 2001; Chokor, 2016). Its ecological significance is similarly related to its potential effects on plants. Excess Mn may interfere with chlorophyll synthesis and produce chlorosis, necrotic lesions, impaired root development, and reduced plant vigor (Clairmont et al., 1986). Cobalt and molybdenum may also become environmentally relevant when present in excessive or bioavailable forms. Elevated Co exposure has been associated with respiratory, cardiovascular, and dermatological effects, whereas inhalation of fine or ultrafine Mo-containing particles has been associated with respiratory symptoms and reduced lung function. Because the concentrations of these elements in the present study were generally low, their principal significance lies in their contribution to the overall contamination pattern and their possible accumulation with continued petrol-station activities.

Potential Exposure Pathways

The location of petrol stations within residential, commercial, and transportation environments in Onitsha creates practical pathways for human exposure to contaminated soil and dust. These pathways include incidental ingestion of soil or settled dust, inhalation of re-suspended particles, and dermal contact with contaminated soil and petroleum-impacted materials. Occupational exposure may be particularly important for petrol-station attendants, mechanics, maintenance personnel, and waste handlers who spend extended periods at the sites.

Indirect exposure may also occur through the transfer of metals from contaminated soils to vegetation, surface runoff, infiltrating water, or shallow groundwater. The likelihood of such transfer may increase under the acidic and relatively sandy soil conditions observed in the study area, which can promote the dissolution and downward movement of some metals. However, since the present study did not measure metal concentrations in groundwater, plants, dust, or edible crops, these pathways should therefore be regarded as likely environmental routes rather than demonstrated exposure pathways.

The presence of contamination does not, by itself, establish adverse health effects in exposed populations. The present investigation did not include site-specific exposure frequencies, exposure durations, body weights, soil-ingestion rates, dermal-contact parameters, inhalation rates, metal speciation, bioavailability, or biomonitoring data. Consequently, a quantitative human-health risk assessment cannot be reliably derived from the measured total soil concentrations alone. The contamination indices and ecological-risk estimates should therefore be understood as indicators of environmental concern and relative site priority, rather than as direct estimates of individual health risk.

Environmental Management Implications

Overall, the findings indicate that petrol-retailing environments in Onitsha function as localized sources of metal enrichment and contribute to the deterioration of soil quality. The combination of elevated contamination relative to the control, acidic soil conditions, and credible human-contact pathways creates a basis for precautionary environmental management. Particular attention should be given to Pb, Cd, Ni, Cr, and other metals identified by the contamination indices as important contributors to environmental risk.

The following measures are recommended:

i. Periodic monitoring of soil, shallow groundwater, surface dust, and, where relevant, vegetation around petrol stations.
ii. Routine inspection and maintenance of underground storage tanks, pipelines, dispensing equipment, and drainage systems.
iii. Immediate containment and remediation of fuel and lubricant spills.

iv. Proper collection, storage, and disposal of contaminated soil, used oil, filters, absorbents, and other petroleum-related wastes.

v. Reduction of dust generation through appropriate surfacing, drainage control, and regular cleaning of high-traffic areas.

vi. Provision and enforcement of suitable personal protective equipment and hygiene practices for petrol-station workers.

vii. Establishment of additional reference sites and repeated sampling to distinguish local geological background from anthropogenic enrichment.

viii. Determination of metal speciation and bioavailable fractions, particularly for Cr, Ni, Cd, and Pb, in future investigations.

These measures would reduce the continued accumulation and redistribution of potentially toxic metals and limit their transfer through soil, dust, vegetation, surface runoff, and groundwater pathways. Because the present study is based on a limited number of samples and a single control site, the results should be considered a baseline assessment that warrants confirmation through larger, spatially replicated, and exposure-oriented investigations.

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Compliance with ethical standards

Disclosure of conflict of interest

No conflict of interest to be disclosed.

Statement of informed consent

The authors have no competing interests to declare that are relevant to the content of this article

Authors declarations

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***Study limitation*:** The investigation was based on one sampling campaign and a single control soil; therefore, temporal variation and regional background variability were not fully characterized. Future work should include replicated controls, multiple depths and seasons, and site-specific human-health exposure modelling.

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