

## Multi-Index Ecological Risk Evaluation of Heavy Metal Contamination in Agricultural Soils Influenced by Auto-Mechanic Activities in Anyigba, Nigeria

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### Abstract

This study evaluated the influence of auto-mechanic workshops on the physicochemical properties, heavy metal levels, and pollution status of adjacent farmland soils in Anyigba, Kogi State. Soil pH ranged from 5.2 to 6.5, reflecting slight acidification relative to the control (6.8). Electrical conductivity increased to 0.45–1.12 dS/m compared to 0.37 dS/m in the control. Soil organic carbon declined to 0.67–1.83 % compared with the control's 3.24 %, while cation exchange capacity decreased to 4.56–10.38 cmol/kg compared with 16.83 cmol/kg in the control, indicating reduced nutrient retention capacity. Heavy metal concentrations were markedly elevated, reaching 18.97 mg/kg (Pb), 11.09 mg/kg (Cu), 11.22 mg/kg (Ni), 12.16 mg/kg (Cr), and 2.87 mg/kg (Cd), exceeding control values of 0.83, 1.66, 3.58, 4.76, and 0.27 mg/kg, respectively. Contamination factors (CF) indicated high contamination for Pb (3.95–22.86), Cd (4.37–10.63), and Cu (3.05–6.68), and moderate contamination for Ni (1.93–3.13) and Cr (1.39–2.55). Enrichment factors (EF) showed minimal enrichment for Ni (0.88–1.93) and moderate to significant enrichment for Cd (2.16–5.13), Cu (1.26–3.22), and Pb (2.52–11.00). The Nemerow Pollution Index (3.67–17.77) classified the soils as heavily polluted. The Potential Ecological Risk Index (179.23–480.39) indicated moderate to considerable ecological risk, largely driven by Cd and Pb. Overall, the findings confirm substantial anthropogenic metal inputs from auto-mechanic activities and underscore the need for improved waste management, routine monitoring, phytoremediation strategies, and strengthened regulatory enforcement to prevent food chain contamination.

**Keywords:** Agricultural soils, Anthropogenic pollution, Heavy metals, Environmental risk indices, Soil quality degradation

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### Introduction

Soil contamination by heavy metals is a persistent global environmental concern, particularly in rapidly urbanizing regions experiencing unregulated industrial expansion [1]. Anthropogenic sources, including industrial emissions, indiscriminate disposal of metal-containing wastes, agrochemical application, sewage sludge, wastewater irrigation, fossil fuel combustion, and atmospheric deposition, are the main contributors [2]. Heavy metal elements with densities above 5.0 g cm<sup>-3</sup> include essential micronutrients (Cu, Zn, Mn) and toxic elements (Pb, Cd, As, Hg). While naturally present at trace levels, levels beyond geochemical backgrounds disrupts soil function, degrades ecosystems, and poses human health risks [3]. In Nigeria, the influx of second-hand vehicles has driven the expansion of informal automobile mechanic workshops, now among the most widespread and poorly regulated land uses in urban and developing areas [4]. These workshops operate without waste containment, often within or adjacent to residential and agricultural zones. Activities such as engine servicing, brake and transmission repair, spray painting, battery charging, welding, and electrical maintenance produce

substantial hazardous wastes. These wastes include spent oils, lubricants, fuels, solvents, battery electrolytes, metal scraps, asbestos-containing materials, and paint residues [5–7].

Uncontrolled disposal of these wastes leads to persistent soil contamination [8], and these wastes are significant sources of heavy metals which persist in soils due to their non-biodegradable nature, undergoing accumulation, redistribution, and transformation that enhance long-term availability [9]. These metals may be absorbed by plants and soil organisms, resulting in bioaccumulation and biomagnification, increasing ecological and human exposure [10].

While some metals are essential at trace levels, others are toxic and potentially carcinogenic even at low exposure [11, 12]. Chronic exposure is linked to neurological, renal, hepatic, skeletal, dermatological, and dental impairments [13–15]. Despite recognition of these risks, spatially resolved data on heavy metals in soils of farmlands near Nigerian mechanic workshops remain limited. Existing studies often lack local baselines and fail to assess metal effects; hence this study therefore evaluates concentrations, spatial distribution, and environmental implications of selected



heavy metals in farmland soils near auto-mechanic workshops in Anyigba, Kogi state, Nigeria, providing baseline data for environmental risk assessment, regulation, and sustainable land management.

## Materials and Methods

### Study area and soil sampling

The study was conducted in Anyigba, a major administrative and commercial town in Kogi State, North-Central Nigeria, located within the Guinea savanna ecological zone. The area experiences a tropical climate with distinct wet and dry seasons, fertile alluvial soils, and predominantly agricultural land use. Rapid urban expansion and the widespread presence of informal automobile mechanic workshops within residential and farming areas characterize the region [16]. Geographically, Anyigba lies between latitudes 07°00'–07°20'N and longitudes 06°60'–06°80'E, making it suitable for evaluating anthropogenic impacts on agricultural soils.

Soil sampling was carried out at four cultivated farmlands situated near automobile mechanic workshops in Anokwu, Agwudoko, Ajetachi, and Agala-Ate. These sites were selected based on their proximity (approximately 10–15 m) to mechanic workshops and their potential exposure to heavy metals associated with automobile repair activities. A control sample was collected from Iji, a farmland located at least 50 m from any observable anthropogenic activity to represent the control sample.

### Sample collection and pretreatment

Surface soil samples were collected from a depth of 0–10 cm using a pre-cleaned stainless steel scoop. At each site, samples were obtained from four quadrants arranged radially around the workshop and composited to minimize spatial heterogeneity. The samples were placed in labeled polyethylene bags and transported to the laboratory following standard handling procedures. In the laboratory, samples were air-dried at room temperature, mechanically ground, and sieved through a 2.0 mm stainless steel mesh to remove coarse materials. The sieved soils were further pulverized using an agate mortar and pestle to ensure homogeneity. Prepared samples were stored in airtight containers prior to analysis, and triplicate samples were collected at each location to enhance analytical precision and statistical reliability.

### Soil Physicochemical Analysis

#### Soil pH

Soil pH was measured following the 1:2.5 soil-to-water suspension method using a calibrated digital glass-electrode pH meter [17]. Approximately 10 g of air-dried, sieved soil (<2 mm) was mixed with 25 mL of deionised water, stirred thoroughly, and allowed to equilibrate for 30 minutes before pH was measured.

#### Electrical conductivity (EC)

Electrical conductivity, an indicator of soluble salt concentration and ionic strength, was determined using

a 1:5 soil-to-water extract [18]. Ten grams of soil were suspended in 50 mL of distilled water, shaken for 30 minutes, filtered, and the EC of the clear extract was measured with a digital conductivity meter.

#### Organic carbon content

Soil organic carbon was quantified using the Walkley-Black wet oxidation method [19]. One gram of air-dried soil was digested with potassium dichromate ( $K_2Cr_2O_7$ ) and concentrated sulfuric acid ( $H_2SO_4$ ), and the unreacted dichromate was titrated with standardized ferrous ammonium sulfate. Organic carbon was converted to organic matter using a factor of 1.724.

#### Cation exchange capacity (CEC)

The cation exchange capacity of the soils was assessed using the ammonium acetate (1N  $NH_4OAc$ ) method at pH 7.0 [20]. Soils were saturated with ammonium ions, and then displaced with sodium chloride (NaCl), and the released  $NH_4^+$  was quantified to determine CEC.

#### Soil texture (particle size distribution)

Soil texture was determined using the Bouyoucos hydrometer method [21]. Fifty grams of pre-treated soil (organic matter removed using hydrogen peroxide) were dispersed in sodium hexametaphosphate, allowed to settle in a sedimentation cylinder, and hydrometer readings were recorded at specified intervals. The proportions of sand, silt, and clay were classified using the USDA textural triangle.

#### Soil moisture content

Soil moisture was measured gravimetrically [22]. Approximately 20 g of fresh soil were weighed in aluminium crucibles, oven-dried at 105 °C for 24 h, cooled in a desiccator, and reweighed.

#### Heavy metal determination

Heavy metal concentrations were measured using a standard wet acid digestion protocol. For each sample, 1.00 g of homogenized and sieved soil (<2.0 mm) was placed in a 250 mL borosilicate flask and digested with 15 mL of aqua regia (3:1  $HCl:HNO_3$ ) on a thermostatically controlled hot plate under a fume hood until near dryness to ensure complete matrix dissolution. Following digestion, 15 mL of deionized water was added, and the mixture was filtered through Whatman No. 42 paper into acid-washed polyethylene bottles. Filtrates were diluted to a final volume of 25 mL with deionized water.

Metal concentrations were quantified using Flame Atomic Absorption Spectrophotometry (FAAS). Calibration curves were prepared from certified stock solutions, and blanks and quality control samples were included to ensure analytical accuracy and instrument precision. All analyses were performed in triplicate, and metal concentrations were calculated from standard calibration curves.

### Risk assessment

Risk assessment indices were applied to evaluate the extent, sources, and ecological implications of heavy metal contamination in soils. These include the Contamination Factor (CF), Pollution Load Index (PLI), Geoaccumulation Index ( $I_{geo}$ ), Nemerow Pollution Index (NPI), Enrichment Factor (EF), and the Ecological Risk Index (ERI/RI), providing an integrated measure of pollution status and ecological threat.

### Contamination factor (CF)

The level of contamination of the soil is expressed in terms of a contamination factor (CF) calculated as:

$$CF = \frac{\text{Metal concentration of the soil sample}}{\text{Background value of the metal or control sample}} \quad (1)$$

Where the contamination factor  $CF < 1$  refers to low contamination;  $1 \leq CF < 3$  means moderate contamination,  $3 \leq CF \leq 6$  indicates considerable contamination;  $CF > 6$  indicates very high contamination.

### Pollution load index

The pollution load index (PLI) is as follows

$$PLI = \sqrt[n]{CF_1 \times CF_2 \times CF_3 \times CF_4 \dots \dots CF_n} \quad (2)$$

Where, CF = contamination factor, n = number of metals, the PLI value of  $>1$  is polluted, whereas  $<1$  indicates no pollution

### Geoaccumulation index ( $I_{geo}$ )

Geoaccumulation Index ( $I_{geo}$ ) was calculated for soils from various dumpsites in Egume District. The background concentrations used are those of the control site for each metal, and the  $I_{geo}$  was calculated using the formula:

$$I_{geo} = \log_2 \left( \frac{C_n}{1.5 \times B_n} \right) \quad (3)$$

Where:  $C_n$  is the measured concentration of the metal in the sample,  $B_n$  is the background concentration (control sample), and 1.5 is a constant to account for natural fluctuations.  $I_{geo} \leq 0$ : Uncontaminated,  $0 < I_{geo} \leq 1$ : Uncontaminated to moderately contaminated,  $1 < I_{geo} \leq 2$ : Moderately contaminated,  $2 < I_{geo} \leq 3$ : Moderately to heavily contaminated,  $3 < I_{geo} \leq 4$ : Heavily contaminated,  $4 < I_{geo} \leq 5$ : Heavily to extremely contaminated,  $I_{geo} > 5$ : Extremely contaminated.

### Nemerow pollution index (NPI)

The Nemerow index is calculated using the equation:

$$NPI = \sqrt{\frac{CF_{mean}^2 \times CF_{max}^2}{2}} \quad (4)$$

Where:  $CF_{mean}$  = average contamination factor of all metals at a site,  $CF_{max}$  = the highest individual contamination factor at that site, the pollution status is interpreted as:  $NPI \leq 0.7 \rightarrow$  Clean  $0.7 < NPI \leq 1.0 \rightarrow$  Warning level of pollution  $1.0 < NPI \leq 2.0 \rightarrow$  Slight pollution  $2.0 < NPI \leq 3.0 \rightarrow$  Moderate pollution  $NPI > 3.0 \rightarrow$  Heavy pollution.

### Enrichment factor (EF)

Enrichment Factor was calculated using:

$$EF = \left( \frac{\left( \frac{C_{metal}}{C_{reference}} \right)_{sample}}{\left( \frac{C_{metal}}{C_{reference}} \right)_{background}} \right) \quad (5)$$

**EF < 2:** Deficiency to minimal enrichment, **2 ≤ EF < 5:** Moderate enrichment, **5 ≤ EF < 20:** Significant enrichment, **EF ≥ 20:** Very high enrichment.

Chromium (Cr) was selected as the reference element due to its relative geochemical stability and crustal abundance. EF values for Cadmium (Cd), Copper (Cu), Nickel (Ni), and Lead (Pb) were computed using the control sites as the background reference.

### Ecological risk index and potential ecological risk index

The Ecological Risk Index (ERI) assesses the potential hazards of toxic metals in soils by combining their contamination factors ( $C_f$ ) with toxic response factors ( $T_r$ ), with values assigned as Cd = 30, Cu = 5, Ni = 5, Cr = 2, and Pb = 5 (Håkanson, 1980). The formula for calculating the ecological risk for each metal ( $E_r$ ) is:

$$E_r = T_r \times CF \quad (6)$$

and the potential ecological risk index (RI) for each site is:

$$R_I = \sum E_r \quad (7)$$

According to Håkanson's risk classification:  **$E_r < 40$ :** Low risk,  **$40 \leq E_r < 80$ :** Moderate risk,  **$80 \leq E_r < 160$ :** Considerable risk,  **$160 \leq E_r < 320$ :** High risk,  **$E_r \geq 320$ :** Very high risk.

Similarly, for PERI (sum of all  $E_r$ ): **RI < 150:** Low ecological risk.  **$150 \leq RI < 300$ :** Moderate ecological risk,  **$300 \leq RI < 600$ :** Considerable ecological risk, **RI ≥ 600:** Very high ecological risk.

## Results and Discussions

### Soil Physicochemical Properties

#### Soil pH

Soils adjacent to auto-mechanic workshops exhibited slightly acidic conditions, with pH values ranging from 5.2 to 6.5, compared to 6.8 at the control site (Table 1). Acidification is likely driven by oxidative degradation of petroleum hydrocarbons and leaching of acidic ions, such as sulfates and nitrates, from spilt engine oils and battery fluids [23]. Such conditions enhance the solubility and bioavailability of heavy metals, promoting their mobility and plant uptake.

#### Soil moisture content

Moisture content in impacted soils ranged from 8.33 to 16.24 %, lower than the control site's 18.00 % (Table 1). Reduced water retention is attributable to the hydrophobic effects of hydrocarbon contamination, compaction from vehicular activity, and poor soil structure, which collectively impede infiltration and limit microbial activity, thereby slowing natural contaminant attenuation [24].

#### Soil texture

The contaminated soils were predominantly sandy loam to loamy sand, in contrast to loam-clay loam textures at control sites. Low clay content and poor aggregation



facilitate metal leaching, reduce nutrient retention, and enhance contaminant migration toward groundwater [25].

#### Electrical conductivity (EC)

EC values were elevated in impacted soils (0.45–1.12 dS/m) relative to the control (0.37 dS/m), indicating increased soluble salts, likely from leaching of lubricants, brake fluids, and metals [26]. High salinity can disrupt soil structure and induce ionic stress in plants, negatively affecting germination and growth.

#### Soil organic carbon (SOC)

SOC content in contaminated soils (0.67–1.83 %) was markedly lower than in control soils (3.24 %),

reflecting vegetation loss and oxidative degradation of hydrocarbons [27]. Reduced SOC diminishes the soil's capacity to adsorb heavy metals, increasing their mobility and environmental risk.

#### Cation exchange capacity (CEC)

CEC values of affected soils ranged from 4.56 to 10.38 cmol/kg, compared to 16.83 cmol/kg at the control site. The decline is linked to losses of organic matter and clay minerals, which are critical for nutrient retention [28]. Lower CEC reduces soil buffering capacity, heightening susceptibility to heavy metal leaching and nutrient deficiencies.

**Table 1: Soil physicochemical parameters**

Physicochemical parameters	Anokwu	Agwudoko	Ajetchi	Agala-Ate	Control
Soil pH	5.6	5.9	5.2	6.5	6.8
Soil moisture content (%)	12.35	15.16	8.33	16.24	18.00
Soil texture	Sandy loam	Loamy sand	Sandy loam	Loamy sand	Loamy clay
Electrical conductivity(dS/m)	0.57	0.86	1.12	0.45	0.37
Soil organic carbon (%)	0.93	1.44	0.67	1.83	3.24
Cation exchange capacity (cmol(+)/kg)	6.72	8.54	4.56	10.38	16.83

#### Heavy Metal Content

##### Cadmium (Cd)

As shown in Fig. 1, cadmium (Cd) concentrations in soils adjacent to auto-mechanic workshops ranged from 1.18 mg/kg (Anokwu) to 2.87 mg/kg (Agala-Ate), markedly higher than the control site (0.27 mg/kg) and exceeding the WHO [29] permissible limit of 0.3 mg/kg for agricultural soils. The highest levels observed at Agwudoko (2.86 mg/kg) and Agala-Ate (2.87 mg/kg) likely reflect inputs from spillage of lubricants, paints, battery components, and metal plating activities typical of workshop operations. Given its non-essential and highly toxic nature, elevated Cd poses severe ecological and health risks, including bioaccumulation in crops and chronic effects on kidneys, bones, and the liver [30].

##### Copper (Cu)

Copper concentrations (Fig. 2) varied from 5.07 mg/kg (Anokwu) to 11.09 mg/kg (Agala-Ate), with the control soil at 1.66 mg/kg, remaining below the WHO [29] limit of 36 mg/kg. Higher levels at Agwudoko (8.78 mg/kg) and Agala-Ate (11.09 mg/kg) suggest anthropogenic enrichment from brake linings, electrical wiring, radiator leaks, and other metallic workshop components. While Cu is an essential micronutrient, excessive accumulation may inhibit microbial activity, impair root development, and induce phytotoxicity [31].

##### Nickel (Ni)

Nickel concentrations (Fig. 3) ranged between 6.91 mg/kg (Agala-Ate) and 11.22 mg/kg (Agwudoko), compared to 3.58 mg/kg at the control site. The WHO [29] limit of 10 mg/kg was exceeded at Agwudoko, while Ajetachi (8.05 mg/kg) and Anokwu (7.41 mg/kg)

approached the threshold. Ni contamination likely derives from corrosion of metal parts, lubricant degradation, and fuel residues. Elevated Ni levels are of ecological and human health concern due to potential carcinogenic and allergenic effects and may disrupt enzymatic activity in crops, reducing productivity [32].

##### Chromium (Cr)

Chromium concentrations (Fig. 4) ranged from 6.63 mg/kg (Anokwu) to 12.16 mg/kg (Ajetachi), exceeding control levels (4.76 mg/kg) and approaching or surpassing the WHO [29] guideline of 8.0 mg/kg. The highest value at Ajetachi likely reflects the use of Cr-based paints, polishes, and metal finishing agents. Hexavalent chromium (Cr<sup>6+</sup>) is highly toxic, with mutagenic and carcinogenic potential. Its mobility in soils may also pose a risk of groundwater contamination, creating additional human exposure pathways [33].

##### Lead (Pb)

Lead concentrations (Fig. 5) were notably elevated, ranging from 3.28 mg/kg (Anokwu) to 18.97 mg/kg (Agala-Ate), compared with 0.83 mg/kg at the control site. Sites at Ajetachi (17.56 mg/kg) and Agala-Ate (18.97 mg/kg) exceed the WHO [29] permissible limit of 10 mg/kg. High Pb levels are attributed to improper disposal of lead-acid batteries, paints, soldering materials, and petroleum residues. Being highly toxic and persistent, Pb poses severe risks to neurological health and food safety due to potential uptake by crops and entry into the human food chain. The pronounced difference from control soils highlights the significant anthropogenic impact of mechanic workshops on soil lead contamination [34].

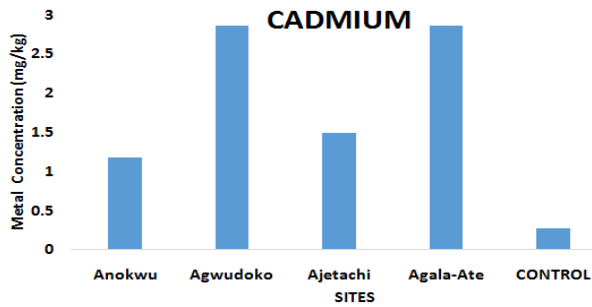


Figure 1: Concentration of cadmium in the sampling and control sites

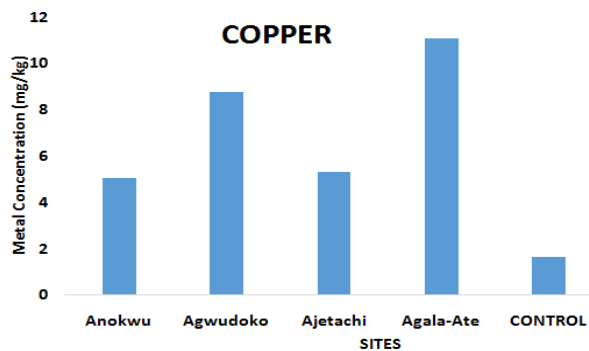


Figure 2: Concentration of copper in the sampling and control sites

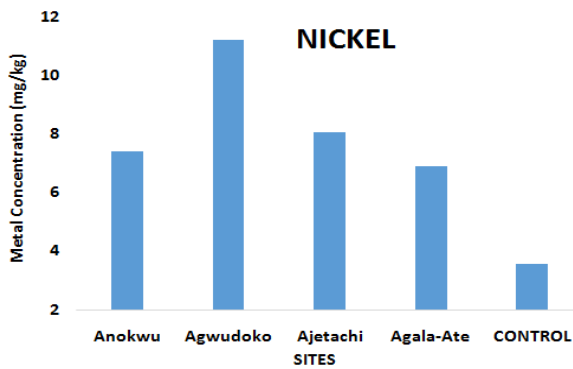


Figure 3: Concentration of nickel in the sampling and control sites

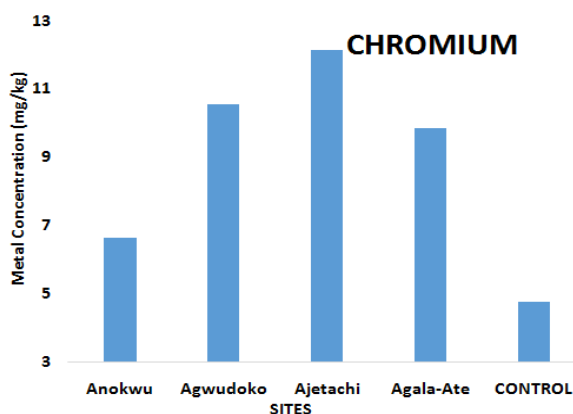


Figure 4: Concentration of chromium in the sampling and control sites

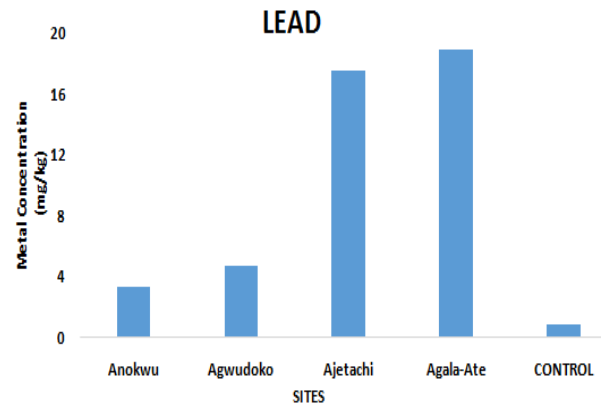


Figure 5: Concentration of lead in the sampling and control sites

### Assessment of Metal Contamination

#### Contamination factor (CF)

Contamination factor (CF) analysis revealed substantial anthropogenic enrichment of heavy metals in soils surrounding auto-mechanic workshops. Cadmium exhibited consistently high contamination across all sites, with CF values of 4.37 (Anokwu), 10.59 (Agwudoko), 5.52 (Ajetachi), and 10.63 (Agala-Ate), indicating moderate to very high pollution (Table 2). These elevated values likely reflect persistent inputs from battery disposal, lubricants, paints, and metal plating activities. Cadmium's high toxicity, long environmental persistence, and bioaccumulation potential pose serious ecological and human health risks, particularly through food crop uptake [35].

Copper showed considerable to high contamination, ranging from 3.05 (Anokwu) to 6.68 (Agala-Ate), with elevated levels at Agala-Ate suggesting intense mechanical activity. The enrichment likely originates from leaching of metallic components, brake dust, grease residues, and radiator leaks [36]. While Cu is an essential micronutrient, excessive accumulation can reduce microbial activity, inhibit root development, and compromise soil fertility.

Nickel displayed moderate contamination, with CF values between 1.93 (Agala-Ate) and 3.13 (Agwudoko). Sources likely include corrosion of engine parts, metal alloys, and residues from fuel and lubricants. Although less severe than Cd and Pb, Ni contamination is concerning due to its phytotoxicity and potential entry into the food chain, which may affect crop yield and quality. Chromium CFs ranged from 1.39 (Anokwu) to 2.55 (Ajetachi), indicating moderate enrichment likely associated with rust-proof coatings, paints, and polishing agents used in workshops. While Cr<sup>3+</sup> is relatively benign, environmental oxidation to hexavalent Cr<sup>6+</sup> could enhance toxicity, increasing risks to soil organisms and groundwater quality [37].

Lead was the most critically enriched metal, with CF values of 3.95 (Anokwu), 5.60 (Agwudoko), 21.16 (Ajetachi), and 22.86 (Agala-Ate), highlighting severe contamination in Ajetachi and Agala-Ate. This



enrichment likely stems from indiscriminate disposal of lead-acid batteries, paint chips, solder, and petroleum residues. Given Pb's persistence, high bioavailability, and non-biodegradability, these soils present significant food safety and human health risks, particularly for children.

**Table 2: Contamination factors of heavy metals in the soil samples**

SITES	Cd	Cu	Ni	Cr	Pb
Anokwu	4.37	3.05	2.07	1.39	3.95
Agwudoko	10.59	5.29	3.13	2.22	5.60
Ajetachi	5.52	3.22	2.25	2.55	21.16
Agala-Ate	10.63	6.68	1.93	2.07	22.86

**Table 3: Pollution load index of heavy metals in the soil samples**

SITES	Anokwu	Agwudoko	Ajetachi	Agala-Ate
PLI	2.72	4.65	4.64	5.79

#### Pollution load index (PLI)

The Pollution Load Index (PLI) values for farmland soils surrounding auto-mechanic workshops in Anyigba revealed substantial and widespread contamination across all sampled sites. Agala-Ate exhibited the highest PLI of 5.79, reflecting severe accumulation of toxic metals (Table 3). This aligns with CF results at the site, which recorded elevated values for Cd (10.63), Cu (6.68), Cr (2.07), and Pb (22.86). The data suggest prolonged exposure to workshop-derived wastes, including lubricants, battery acid, metal filings, and hydrocarbons. Such enrichment, particularly of Cd and Pb, poses serious risks to crop production, soil health, and groundwater quality.

Agwudoko and Ajetachi recorded PLI values of 4.65 and 4.64, respectively, indicating similarly high pollution burdens. At Agwudoko, CF values for Cd (10.59), Pb (5.60), Cu (5.29), and Ni (3.13) highlight intensive and long-standing mechanized activity, while at Ajetachi, an exceptionally high Pb CF (21.16) and moderate Cd and Cu enrichment (5.52 and 3.22, respectively) contributed substantially to the overall pollution load. Chromium and Ni exhibited moderate contamination at both sites, suggesting complex sources from ferrous and non-ferrous vehicle components [38]. Anokwu recorded the lowest PLI (2.72) among the sampled sites but still indicates significant pollution. CF values for Cd (4.37), Pb (3.95), and Cu (3.05) suggesting that contamination, though less intense, remains well above background levels, likely reflecting lower mechanical activity, shorter exposure duration, or partial natural attenuation.

#### Geoaccumulation index ( $I_{geo}$ )

The Geoaccumulation Index ( $I_{geo}$ ) was employed to evaluate the degree of anthropogenic heavy metal contamination in soils adjacent to auto-mechanic workshops.  $I_{geo}$  quantitatively compares current metal concentrations to natural background levels,

incorporating a correction factor of 1.5 to account for lithological variability.

Cadmium exhibited the highest  $I_{geo}$  values, ranging from 1.54 (Anokwu) to 2.83 (Agwudoko and Agala-Ate), indicating moderate pollution (Table 4). Elevated Cd levels likely result from repeated deposition of batteries, lubricants, and metal scraps from workshop activities. The high mobility and toxicity of cadmium pose significant risks to soil quality, crop safety, and human health [39].

Copper showed moderate contamination across all sites, with  $I_{geo}$  values between 1.03 and 2.16. Agala-Ate recorded the highest index (2.16), classifying the soil as moderately polluted. Copper enrichment is likely associated with brake linings, electrical components, and antifreeze residues, reflecting routine auto-mechanic operations. Nickel exhibited lower  $I_{geo}$  values (0.36–1.06), placing soils in the unpolluted to moderately polluted range. Slightly higher values at Agwudoko and Ajetachi suggest minor anthropogenic contributions from mechanical wear, including engine components and lubricants.

Chromium indices varied from -0.11 (Anokwu) to 0.77 (Agwudoko, Ajetachi, Agala-Ate), indicating predominantly unpolluted to moderately polluted conditions (Table 4). The negative  $I_{geo}$  at Anokwu suggests minimal anthropogenic input, possibly due to lower workshop intensity or topographic influences on metal dispersion. Lead presented the most severe contamination, with  $I_{geo}$  values of 3.93 (Agala-Ate) and 3.82 (Ajetachi), classifying these sites as heavily polluted. Agwudoko (1.90) and Anokwu (1.40) were moderately polluted. Elevated Pb levels are attributable to prolonged use and disposal of leaded gasoline, batteries, and soldering materials. The persistence and bioavailability of lead in soils around these farmlands pose substantial ecological and food safety concerns.

**Table 4: Geoaccumulation index of heavy metals in the soil samples**

SITES	Cd	Cu	Ni	Cr	Pb
Anokwu	1.543	1.026	0.465	-0.107	1.398
Agwudoko	2.820	1.818	1.063	0.566	1.901
Ajetachi	1.879	1.101	0.584	0.768	3.818
Agala-Ate	2.825	2.155	0.364	0.467	3.930

**Table 5: Nemerow pollution index of heavy metals in the soil samples**

SITES	CF mean	CFmax	NPI	Pollution Status
Anokwu	2.97	4.37	3.67	Heavy Pollution
Agwudoko	5.37	10.59	8.42	Heavy Pollution
Ajetachi	6.14	21.16	15.61	Heavy Pollution (Very severe)
Agala-Ate	8.03	22.86	17.77	Heavy Pollution (Very severe)

### Nemerow pollution Index (NPI)

The Nemerow Pollution Index (NPI) was applied to provide an integrated assessment of overall soil contamination, accounting for both average and maximum heavy metal concentrations. Across all four farmland sites adjacent to auto-mechanic workshops, NPI values exceeded the threshold of 3.0, categorizing the soils as heavily polluted and reflecting severe degradation of soil quality.

Anokwu, although exhibiting the lowest NPI among the sites, remained within the heavy pollution category, with cadmium (CF = 4.37) and lead (CF = 3.95) as the dominant contributors (Table 5). These findings suggest chronic deposition of Cd and Pb-rich wastes, likely originating from battery residues, lubricants, or metallic scraps via surface runoff and atmospheric deposition [40]. Despite being the least impacted site, soils here are unsuitable for safe agricultural production without intervention. A marked increase in NPI was observed at Agwudoko, primarily driven by high cadmium (CF = 10.59) and lead (CF = 5.60) levels. The elevated index reflects persistent contamination from poorly managed mechanical activities, including motor oil spills, battery disposal, and metallic debris, creating a toxic environment that may suppress microbial activity, hinder organic matter decomposition, and reduce soil fertility.

At Ajetachi, NPI values indicated very severe pollution, with lead (CF = 21.16) as the principal contributor. The extreme contamination is likely linked to accumulated vehicular emissions, discarded lead-containing parts, and residuals from leaded gasoline, highlighting a localized hotspot of heavy metal input. Immediate intervention is warranted to mitigate ecological risks and prevent entry of toxic metals into the food chain.

Agala-Ate recorded the highest NPI, reflecting the most critical soil condition among all sites. Exceptionally high CF values for lead (22.86) and cadmium (10.63) underscore the cumulative impact of long-term, unregulated auto-mechanic activities, including oil spills, battery waste, and corrosion of metallic components. Soils at this site present extreme ecological and human health risks, with long-term cultivation likely to result in unsafe crop production.

### Enrichment factor (EF)

The Enrichment Factor (EF) was also used to assess the degree of anthropogenic contribution to heavy metal accumulation in soils surrounding automotive mechanics workshops. Cadmium exhibited EF values ranging from 2.16 (Ajetachi) to 5.13 (Agala-Ate), representing moderate to significant enrichment. Agwudoko and Agala-Ate recorded the highest Cd enrichment (4.77 and 5.13, respectively), reflecting substantial anthropogenic inputs, particularly from battery disposal, lubricants, and other vehicle maintenance residues (Table 6). The high mobility and toxicity of cadmium reveal its environmental and health implications, with potential bioaccumulation in crops posing serious risks to humans [41].

Copper showed EF values ranging from 1.26 (Ajetachi) to 3.22 (Agala-Ate), indicating minimal to moderate enrichment. Sites such as Anokwu, Agwudoko, and Agala-Ate exceeded the threshold of 2, indicating anthropogenic contributions from the replacement and disposal of copper-rich automotive components, including wires, bearings, and brake pads. The relatively low EF at Ajetachi (1.26) suggests either lower intensity of mechanical activity or dilution via natural soil processes.

Nickel EF values ranged from 0.88 (Ajetachi) to 1.49 (Anokwu), consistently below 2, indicating minimal enrichment and primarily geogenic origin. These values suggest limited anthropogenic input, likely due to less frequent handling or improper disposal of nickel-containing components in local workshops.

Lead exhibited the most pronounced enrichment, with EF values spanning 2.52 (Agwudoko) to 11.00 (Agala-Ate), signifying moderate to significant anthropogenic influence. Agala-Ate recorded the highest Pb enrichment (11.00), while Ajetachi also displayed substantial enrichment (8.27), reflecting prolonged deposition from leaded paints, batteries, lubricants, and fuel residues. The persistence and high toxicity of lead make its accumulation particularly concerning for environmental and human health [42].

**Table 6: Enrichment factors of heavy metals in the soil samples**

SITES	Cd	Cu	Ni	Pb
Anokwu	3.14	2.19	1.49	2.83
Agwudoko	4.77	2.38	1.41	2.52
Ajetachi	2.16	1.26	0.88	8.27
Agala-Ate	5.13	3.22	0.93	11.00

**Table 7: Ecological risk index and potential ecological risk index of heavy metals in the soil samples**

SITES	Cd (x 30)	Cu (x 5)	Ni (x 5)	Cr (x 2)	Pb (x 5)	PERI
Anokwu	131.10	15.25	10.35	2.78	19.75	179.23
Agwudoko	317.70	26.45	15.65	4.44	28.00	392.24
Ajetachi	165.60	16.10	11.25	5.10	105.80	303.85
Agala-Ate	318.90	33.40	9.65	4.14	114.30	480.39

### Ecological risk index and potential ecological risk index

The ecological risk assessment using Håkanson's Potential Ecological Risk Index (RI) revealed substantial risks from heavy metal accumulation in soils adjacent to automotive mechanics workshops. Cadmium (Cd) was the principal contributor to ecological risk across all sites, with  $E_r$  values ranging from 131.10 (Anokwu) to 318.90 (Agala-Ate). Agwudoko and Agala-Ate experienced very high Cd-associated risk, reflecting intensive contamination from automotive battery disposal, lubricant spillage, and paint residues. Anokwu and Ajetachi exhibited moderate-to-high Cd risk (Table 7).



Lead (Pb) also posed considerable to very high ecological risk, particularly at Ajetachi (105.80) and Agala-Ate (114.30); likely sourced from discarded lead-acid batteries, brake linings, and vehicular emissions. Pb's persistence and toxicity amplify its ecological and human health implications. Copper (Cu), nickel (Ni), and chromium (Cr) were associated with lower risk levels. Cu reached moderate risk at Agwudoko (26.45) and Agala-Ate (33.40). At the same time, Ni and Cr consistently remained in the low-risk category ( $E_r < 16$ ), suggesting mixed origins from natural weathering and limited anthropogenic input. Cumulative RI values indicated substantial ecological threats, with Anokwu at 179.23 (moderate risk), Agwudoko at 392.24, Ajetachi at 303.85, and Agala-Ate at 480.39 (considerable to high risk). At Anokwu, elevated Cd and Pb levels dominated the risk profile, whereas Agwudoko's considerable risk reflected intensified anthropogenic input from frequent automotive operations. Ajetachi exhibited localized Pb hotspots, increasing its overall ecological concern, while Agala-Ate presented the highest RI due to prolonged Cd and Pb contamination, highlighting severe ecological stress.

### Conclusion

Soils adjacent to auto-mechanic workshops exhibited significant physicochemical degradation, including slightly acidic pH, reduced moisture, coarse textures, elevated electrical conductivity, low organic carbon and diminished cation exchange capacity, indicating impaired nutrient retention and increased contaminant mobility. Heavy metals, particularly cadmium and lead, frequently exceeded World Health Organisation (WHO) limits, while copper, nickel, and chromium were moderately elevated. Contamination factor, Pollution Load Index, Geoaccumulation Index, and Enrichment Factor analyses identified Cd and Pb as the primary anthropogenic pollutants, linked to battery disposal, oil spills, paint residues, and metal corrosion. Ecological risk indices revealed very high risk from Cd and considerable to very high risk from Pb, with PERI values classifying Agwudoko, Ajetachi, and Agala-Ate under considerable risk. These results highlight persistent environmental and public health threats, including soil acidification, nutrient depletion, and potential metal bioaccumulation in crops. Mitigation requires strict waste management, soil monitoring, targeted remediation, buffer zones, awareness programs, adoption of cleaner technologies, and integration of pollution control into land-use planning to protect soil health, agricultural productivity, and food safety.

**Conflicts of interest:** No conflict of interest.

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