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GEOCHEMICAL BASELINE AND ECOLOGICAL RISK ASSESSMENT OF HEAVY METALS IN TROPICAL BASEMENT COMPLEX SOILS OF NASARAWA STATE, NIGERIA

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Abstract

This study evaluates heavy metal contamination and ecological risk in surface soils across the three senatorial districts of Nasarawa State, Nigeria. A total of 45 surface soil samples (15 per district) were analyzed for Cd, Pb, Zn, Cu, Cr, Ni, and Fe concentrations. Contamination levels were assessed using contamination factor (CF), pollution load index (PLI), geoaccumulation index (Igeo), Nemerow pollution index (NPI), and potential ecological risk index (RI), while principal component analysis (PCA) was used to identify possible sources. Results showed a spatial trend of metal concentrations in the order Nasarawa North > Nasarawa West > Nasarawa South. Cadmium concentrations in Nasarawa North (0.82 ± 0.15 mg/kg) approached background levels, whereas Pb concentrations in Nasarawa West were significantly lower than background values. CF values were generally <1, indicating low contamination. PLI values (0.009–0.576) and Igeo values (−0.71 to −3.47) confirmed unpolluted soil conditions. Ecological risk indices were low (RI <150), although Cd contributed substantially to the total risk due to its high toxicity response factor. PCA extracted two principal components explaining 78.4% of the total variance, indicating predominantly lithogenic sources with minor anthropogenic contributions. Compared with heavily contaminated sites in Nigeria and other regions, metal concentrations in the study area were significantly lower. From all indication, the results indicate that surface soils in Nasarawa State are largely uncontaminated and pose low ecological risk. Although the soils are presently largely uncontaminated and pose low ecological risk, the proximity of the Nemerow pollution index to the warning threshold in Nasarawa North warrants sustained environmental monitoring and periodic reassessment to prevent future contamination.

Keywords: Heavy metals; soil contamination; pollution indices; ecological risk assessment; principal component analysis; Nasarawa State.

INTRODUCTION

Determining heavy metal concentrations in soils is an imperative part of the evaluation of the environmental quality, especially in areas that are experiencing rapid land use changes because of urbanization and agricultural intensification. The heavy metals are also known to be long-term environmental contaminants, since they are non-biodegradable by natural means. As a result, they are prone to accumulation in soils and can further be introduced into ecological and human food chains via bioaccumulation and biomagnification which poses significant risks to ecosystem stability and human health (Ray et al., 2023; Angon et al., 2024; Collin et al., 2022; Joshi et al., 2026). Since soils act as sinks and secondary sources of potentially toxic elements (PTEs), the distribution, behavior, and bioavailability of heavy metals in soils have become primary areas of interest in environmental geochemistry and sustainable land management studies (Sahoo et al., 2025; de Figueiredo et al., 2025; Palansooriya et al., 2020; Tepanosyan et al., 2025).

Heavy metal soil pollution is a significant environmental concern in Sub-Saharan Africa due to increasing anthropogenic pressures from agricultural intensification, small-scale mining, and unplanned urbanization. These operations lead to released or mobilized of cadmium (Cd), lead (Pb) and zinc (Zn) and copper (Cu), chromium (Cr) and nickel (Ni) in the soil regimes (Bouida et al., 2022; Rashid et al., 2023). When these metals are at high concentrations in farmlands, they may damage the soil fertility, crop safety, and food security, and pose environmental and human health hazards. This is why the accurate measurement of soil metal levels is essential for correct environmental risk assessment, as well as sustainable agricultural management.

Nevertheless, there are critical methodological challenges associated with the accurate evaluation of heavy metal contamination in the tropics. Tropical soils are typically characterized by intense chemical weathering, long-term leaching, and high pedogenic activity, all of which greatly modify soil mineralogy and elemental distribution (Nzeukou et al., 2025; Adekiya et al., 2024). In acidic conditions, the most soluble elements, particularly the mobile base cations (Ca, Mg, K, and Na), are dissolved first. These elements are subsequently leached from the topsoil layers through eluviation, leading to nutrient depletion and increased soil acidity. The geochemical baseline of tropical soils is intrinsically defined by their advanced stage of weathering, resulting in a composition dominated by low-activity clays and resistant oxides, unlike the soils for which most commonly used contamination indices were originally developed. These differences can contribute to the misinterpretation of contamination levels when conventional assessment methods are applied without local calibration.

The recent literature has highlighted the significant role of mineralogical composition, texture, and organic matter of soil in the regulation of the mobility and retention of potentially toxic elements in tropical soils. As an illustration, mafic and ultramafic-derived soils in the Brazilian Amazon have high levels of iron and aluminum oxides which enhance adsorption and retention of heavy metals. On the contrary, soils that formed out of felsic parent materials tend to have lower sorption abilities and are more mobile in these soils (Lawrence et al., 2021; Silva et al., 2021). Likewise, studies at tropical river basins reported that high levels of SiO_2 tend to indicate active leaching activities, whereas rising levels of Fe_2O_3 and TiO_2 would be a sign of progressive pedogenic enrichment in the context of long-term weathering (Beckford et al., 2023; Sababa et al., 2021).

These geochemical processes make interpreting patterns of metal enrichment more difficult and make it necessary to have regionally relevant contamination assessment models. Another important factor influencing heavy metal distribution in tropical landscapes is the dynamic nature of soil–water interactions. Floodplain environments, for example, may act as temporary storage zones where metals transported from upland areas accumulate before being redistributed downstream (Geyman et al.,2025). In addition, metal speciation may vary significantly across environmental settings. Lead, for instance, may occur in association with carbonate minerals in upland soils but co-precipitate with iron oxyhydroxides in floodplain sediments. Seasonal variability further influences heavy metal mobility and environmental risk, particularly in wastewater-irrigated agricultural systems where significant temporal fluctuations in soil metal concentrations have been reported (Luo et al., 2024; Wang et al., 2023; Yan et al., 2023).

These processes highlight the importance of considering geochemical speciation, soil fractionation, and landscape dynamics when evaluating heavy metal contamination.
Amidst these complications, several studies continue to rely primarily on traditional indices of pollution like the contamination factor (CF), enrichment factor (EF), geoaccumulation index (Igeo) and pollution load index (PLI). Although these metrics are commonly employed to evaluate the environment, they typically rely on the global background levels of average shale amounts or other universal reference levels (Omran, 2016).

Even in highly weathered tropical soils, natural soil-forming processes can significantly alter the distribution of elements. As a result, using standard background values may lead to inaccurate assessments of contamination levels (Bocardi et al., 2020; Heidari et al., 2022). Moreover, iron is usually used as a reference element in the computations of the enrichment factors. This procedure adds more unwelcome uncertainty in the tropical setting in which iron oxides are naturally enriched as an outcome of severe weathering and pedogenic actions (Button et al., 2022; Street, 2012). As a result, contemporary sources state that it is necessary to consider the locally obtained geochemical background values and combine various methods of analysis, such as a spatial one and a landscape context, to enhance contamination analysis in tropical environments (Hernandez et al., 2024).

The case of Nasarawa State, which is situated in the North-central part of Nigeria, is an appropriate example to investigate these methodological and environmental issues. The state is subdivided into three senatorial areas, namely Nasarawa North, Nasarawa West and Nasarawa South, and is principally covered by the formations of Nigerian Basement Complex that are mainly made of granitic and metamorphic rocks. These geological circumstances, along with the growing agricultural practice and localized artisanal mines, can have a significant impact on the spatial pattern of heavy metals in the local soils. Few systematic geochemical baseline studies have been conducted in this area. The vast majority of past studies on the heavy metal pollution in Nigeria have prioritized industrialized or mining-intensive parts of the country, including the Niger Delta, the Zamfara mining environment, and the large urban hubs (Okon et al., 2021; Omoyajowo et al., 2024). Basement complex terrains, which are primarily used for agriculture, have received little research attention. This represents a significant gap because natural weathering in these areas can greatly influence soil metal levels.

This paper therefore presents a comparative analysis of heavy metal distribution across the three senatorial districts of Nasarawa State. Unlike previous studies that rely on global reference values, this study incorporates locally derived geochemical baseline levels, various contamination indices, and spatial analytical methods to determine soil metal contamination levels. The hypothesis tested in this study is that the distribution of heavy metals in the soils of Nasarawa State is primarily controlled by geological and pedogenic processes rather than anthropogenic contamination. The study also addresses the potential overestimation of contamination in highly weathered tropical soils when global background values and traditional iron-normalized indices are used. To overcome this limitation, the study integrates locally derived geochemical baselines with multiple contamination assessment approaches. The aim is to develop location-specific assessment frameworks that provide a more accurate understanding of soil metal distribution and environmental risk in tropical basement complex terrains.

2. MATERIALS AND METHODS

2.1 Study Area

Nasarawa State is in both north-central Nigeria between 7°45W and 8°45W and 7°00E and 9°30 E. It has a projected land area of 27,117km^2. Table 1 shows that the study area was administratively subdivided into three senatorial areas; Nasarawa North (NN), Nasarawa West (NW) and Nasarawa South (NS). It has a tropical climate with two different seasons: wet (April- October) and dry (November-March). An average annual rainfall is between 1100 -1500 mm with an average temperature between 25° C-32°C. To the west, the Precambrian Basement Complex comprises of granites, gneisses, migmatites, and schists, which constitute the principal rocks found in Nasarawa State and which were deposited between the Precambrian and the early Paleozoic periods. The study was carried out in selected localities across the three senatorial divisions of the state, Nasarawa North (NN), Nasarawa West (NW), and Nasarawa South (NS), to capture trends in the geologic environment, land use, and environmental factors. The predominant land-use activity in the study areas (Figure 1) is agriculture, and farming is the major source of livelihoods to most of the residents.(Rahman et al., 2023).

2.2 Sampling Strategy

A total of 45 locations were sampled in the three senatorial zones (15 different locations in each zone), and the samples were taken in the dry season "January 2024–March 2024. The sampling sites needed to be representative of the background conditions of the region and therefore there were no known sources of contamination like mining sites, major roads and industrial plants. Two kinds of samples were taken at every site:

The collection of surface samples was done at depths of 0 to 15 cm to determine the contamination with the help of a stainless-steel auger. Five subsamples were provided in a grid of 10 m x 10 m at every sampling point to come up with a representative sample. These profound samples were collected in uncontaminated localities namely undisturbed forest or grasslands in each senatorial area. Deep horizon samples indicate material of parent material that has not undergone significant influence of surface processes or anthropogenic inputs providing a suitable baseline for contamination assessment. All the samples were placed in polyethylene bags, taken to the laboratory, air-dried at ambient temperatures, swirled, and sieved using a 2 mm nylon mesh to eliminate coarse particles.

2.3 Analytical Methods

2.3.1 Sample Digestion

Total metal concentrations were determined using aqua regia digestion (HCl:HNO_3, 3:1 v/v) according to ISO 11466, 2025. 1 g of sieved soil was placed into a digestion tube, 10 mL of aqua regia was added and left to stand overnight at room temperature. Afterwards, the tubes were incubated at 130°C for 2 hours on a digestion block. The digest was filtered using Whatman No. 42 filter paper after cooling followed by dilution using deionized water up to 50 mL.

2.3.2 Metal Analysis

Concentrations of Cd, Pb, Zn, Cu, Cr, Ni, and Fe were determined using inductively coupled plasma optical emission spectrometry (ICP-OES, PerkinElmer Optima 5300 DV). Reagent blanks and duplicate samples. All metals had a recovery of 92 to 105. Limitations of detection (mg/kg) Cd (0.01), Pb (0.1), Zn (0.5), Cu (0.2), Cr (0.2), Ni (0.2), Fe (10).

2.4 Pollution Indices Calculation

2.4.1 Contamination Factor (CF)

Contamination Factor (Hakanson, 1980) was calculated:

CF=Csample/Cbackground

C is the sample metal concentration and C background is the local background value which is determined using C-horizon samples. The CF values were defined as: $CF < 1$ (low contamination), $1 \leq CF < 3$ (moderate contamination), $3 \leq CF < 6$ (considerable contamination) and $CF \geq 6$ (very high contamination).

2.4.2 Pollution Load Index (PLI)

The Index of pollution load was computed as:

PLI= (CF1×CF2×CF3×...×CFn) ^(1/n)

M Metals n is the number of metals. PLI greater than 1 is a sign of pollution whereas PLI less than 1 is a sign of absence of pollution.

2.4.3 Geoaccumulation Index (Igeo)

Geoaccumulation Index was determined as:

I geo= log2 (C sample/ (1.5 C background))

where 1.5 is to serve as natural lithological fluctuation. Igeo values were graded as: Igeo 0 (uncontaminated), Igeo 0-1 (uncontaminated to moderately contaminated), 1-2 (moderately contaminated), 2-3 (moderately-heavily contaminated), 3-4 (heavily contaminated), 4-5 (heavily-extremely contaminated), and Igeo 5 (extremely contaminated).

2.4.4 Potential Ecological risk Index (RI)

Potential Ecological Risk Index was obtained as:

RI=∑E_r^i=∑(T_r^i×CF^i)

and T r i is the toxic response coefficient of metal i (Cd = 30, Pb = Cu = Ni = Cr = 2 = Zn = 1). The RI values were categorized as: RI < 150 (low risk), 150 RI < 300 (moderate risk), 300 RI < 600 (considerable risk), and RI 600 and above (very high risk).

2.4.5 Nemerow Pollution Index (NPI)

Nemerow Pollution Index was obtained as:

NPI=√((CF_max^2+CF_mean^2)/2)

for CF max is the maximum CF and CF mean is the average CF of all the metals at a location. The values of NPI were determined as NPI < 0.7 (clean), 0.70 NPI < 2.0 (slight pollution), 2.0 0.0 NPI < 3.0 (moderate pollution) and NPI 0.030 (heavy pollution).

2.5 Statistical Analysis

Descriptive statistics (mean, standard deviation, and range) were computed for all metals. Significant differences between senatorial areas were assessed using one-way analysis of variance (ANOVA). Principal component analysis (PCA) with rotation was performed to examine correlations among elements and identify potential sources. Pearson's correlation coefficient (r) was used to assess relationships between metals. Statistical testing was performed in SPSS 26.0 version (IBM Corp., Armonk, NY, USA).

RESULTS AND DISCUSSION

3. Results

3.1 Metal Concentrations

Table 2 presents the summary statistics of metal concentration in the surface soils in the three senatorial zones. All concentrations were below international screening guidelines. Table 3 shows the highest concentration of Cd was at NN (0.82 ± 0.15mg/kg) followed by NW (Pb: 12.4 ± 3.2 mg/kg) and NS (Pb: 6.8 ± 1.9 mg/kg).

3.2 Contamination Factors

Figure 2 shows the contamination factors of individual metals, wheras Table 4 summarizes the same. All CF values were less than 1 which meant low contamination as far as the classification of Hakanson is used. Cd, Pb and Pb had the highest CFs at NN (0.914), NW (0.585) and NS (0.327) respectively.

3.3 Pollution Load Index

The values of PLI of the three senatorial zones are; NN (0.576), NW (0.018), and NS (0.009). All the values were significantly less than 1.0, which indicated that there is no pollution (Figure 3).

3.4 Geoaccumulation Index

The values of Igeo were negative at all the locations of metals with a minimum at -0.71 (Cd at NN) and a maximum of -2.20 (Pb at NS). The entire values were within the uncontaminated category (Igeo 0).

3.5 Potential Ecological Risk Index

The values of RI (Table 5, Figure 4) were: NN (29.97), NW (4.52), and NS (3.20). All the values were in the low ecological risk category (RI < 150). Cd was of disproportionate contribution to RI in NN because it had a high toxicity response factor (Tr = 30).

3.6 Nemerow Pollution Index

The values of NPI (Figure 5) were NN (0.666), NW (0.424) and NS (0.238). The values were all less than 0.7, that is equivalent to a category of clean conditions according to the Nemerow index. But NN had come close to the warning value, which was 0.7 and was mainly Cd that increased to 0.914 (CFmax).

3.7 Spatial Distribution

Figure 6 presents the spatial distribution of NPI values across the study area. A clear gradient was observed: NN > NW > NS, with NN exhibiting consistently higher values for all indices.

3.7 Principal Component Analysis

PCA results (Table 6, Figure 7) extracted two principal components explaining 78.4% of total variance. Component 1 (56.2% of variance) showed high loadings for Cd, Fe, and Cr, interpreted as a lithogenic component reflecting parent material composition. Component 2 (22.2% of variance) showed high loadings for Pb and Zn, interpreted as a mixed component with potential anthropogenic influences.

4. Discussion

The current study offers an evaluation of the surface soils in relation to the presence of heavy metal in the 3 senatorial areas of Nasarawa State in Nigeria. Combining various pollution indices, including contamination factor (CF), pollution load index (PLI), geoaccumulation index (Igeo), potential ecological risk index (RI), and Nemerow pollution index (NPI) with multivariate statistical analysis (PCA) provides a solid tool to consider the soil quality and distinguish the sources of contaminants. These findings are critically reviewed in this discussion in terms of regional, continental, and global scholarly literature, especially, in terms of methodological comparability, source apportionment, and ecological implications.

The concentrations of metals in context compare concentrations with external or nominal concentrations, relative to exposure duration and pathway exposures of different metals. The metal concentrations in this work were consistently lower than these international screening guidelines that have been set by the Canadian Council of Ministers of the Environment (CCME) and the Dutch Ministry of Housing, Spatial Planning and Environment (VROM)(Hassan et al., 2026). This result places the soils of Nasarawa State within a baseline category, indicating minimal anthropogenic influence compared to industrial and urban hotspots. However, the observed spatial gradient, in which the Nasarawa North (NN) zone consistently exhibited relatively higher metal levels than Nasarawa West (NW) and Nasarawa South (NS), should be interpreted with caution. The levels of cadmium in NN were close to the established background values, while lead concentrations in NW and NS remained well below their respective background levels. This pattern suggests that the variation across the zones is more likely driven by natural geological and pedogenic controls rather than external contamination sources.

When compared with heavily impacted environments in Nigeria, the distinction becomes more evident. Previous studies in industrial and petroleum-impacted regions have reported substantially elevated heavy metal burdens, particularly in areas associated with auto-mechanic activities and crude oil processing. In such environments, intense anthropogenic inputs significantly alter the natural geochemical balance of soils. In contrast, the relatively low levels observed across the Nasarawa senatorial districts reinforce the limited influence of such activities in the study area.

However, the disparity between these findings and those from contaminated regions underscores the dominant role of localized anthropogenic processes in elevating soil metal concentrations. The results therefore support the conclusion that soils in Nasarawa State remain largely unaffected by significant human-induced contamination and retain characteristics typical of relatively undisturbed tropical basement complex environments.

On a continental scale, a meta-analysis of urban soils in Africa (Sarfo et al., 2024) found that the weighted mean content of Pb, Cd, and Cr in most of the African states was higher than what is permitted by FAO and industrial activities (27) and traffic emissions (26) contributed more than half of the sources of contamination. This review also reported Cd levels in urban soils in Africa between 0.03 and 299 mg/kg with an average of 22.6mg/kg which is far much higher than those found in Nasarawa. The point of this comparison is that land use context is of the essential importance that, although the current research covered senatorial zones as mixed land use involving agricultural and residential lands, the wider African literature has overly emphasized urban-industrial hotspots, which may overestimate background conditions on the continent**.**

The values reported in this study fall within the geogenic baseline ranges typically observed in non-industrialized regions worldwide. Zhang et al. (2021) conducted a bibliometric review that consolidated 2,822 articles on pollutants at contaminated sites globally and found that Cd, Pb, and Zn were the most common pollutants, with global mean Igeo values of 5.91 for Cd, 4.12 for Pb, and 3.73 for Zn. In contrast, the substantially lower Igeo values observed in Nasarawa (−0.71 to −3.47; −1.36 to −2.20) indicate that the soils do not fall within the global classification of contaminated sites. Rather, they represent a baseline condition against which potential anthropogenic effects may be assessed.

4.2 Pollution Indices: Low Contamination and Conspicuous Pattern.

The metals factors of contamination (CF) in all the zones were less than 1, the category of low contamination according to the classification of Hakanson(Mohajane & Manjoro, 2022) . This observation is not new based on the absolute concentrations but the relative patterns should be mentioned. The cadmium at NN (CF = 0.914) and Fe at NN (CF = 0.913) were near unity that is a near background state of these elements. High CF of Cd at NN and relative to other metals and regions suggests that there is some examples of either slight enrichment or natural variation in the structure of parent material. The pollution load index (PLI) values for NN (0.576), NW (0.018), and NS (0.009) provide an integrated measure of the overall pollution status of all the assessed metals. None of these values exceeded the threshold of 1.0, indicating the absence of significant pollution.

However, the difference between the PLI values of NN and NS spans nearly three orders of magnitude, suggesting the presence of pronounced spatial heterogeneity that cannot be attributed solely to analytical noise. This gradient may be associated with variations in anthropogenic pressures, differences in soil characteristics affecting metal retention, or spatial differences in the geochemistry of the parent materials across the senatorial zones.

Comparative studies of the polluted sites in Nigeria reveal that the sites have PLI values that are way beyond the 1.0 mark.

According to (Preonty et al., 2025) the values of PLI were 1.32 to 57.65 at the locations of auto-mechanic workshops in Effurun in Niger Delta. The values of PLI exhibited were as high as 5.10 on the territory around waste landfills occupied by the dye industry, and none of the values fell below the contamination level. These frequencies and the present findings were dissimilar and this indicates the sensitivity of PLI as an integrative variable to determine the damaged and unaffected areas all Igeo was negative with values ranging between -0.71 (Cd at NN) and -3.47 (Cd at NS). In case the values of negative Igeo are negative, the values of the measured concentrations have a lower value in comparison to the geochemical background which is in relation to low enrichment(Bolaji et al., 2025) . This observation is in line with the CF results and all these findings are combined to confirm the conclusion of the uncontaminated conditions. However, the values of Igeo in zone - NN (29.97) and NW (4.52) and NS (3.20) were close to the index of the possible ecological risk (RI < 150) introduced by Hakanson (1980). Curiously, the highest contributor of RI at NN (Er = 27.42 which constituted 91.5% of total RI) was cadmium since the toxicity response factor (Tr = 30) of cadmium was high.

The implication of the finding is important: Cd is the dominant one in estimating ecological risks even at the level lower than the international standards due to its toxicity. This movement Cd topping index even with low absolute concentrations has been witnessed throughout the world. Cd was present in the reducible fractions of the soils in the Kipushi mining region of the Congolese Copperbelt, which means that it has a high potential of being remobilized, and the PERI values were extremely high which revealed high ecological risks (Mputu et al., 2025). Similarly, the possible ecological risk value of Cd was highest (60.4) in the direct environments of solid waste management sites in Akure, Nigeria, even though the level was lower than the international limit. Even the values of the Nemerow pollution index (NN) NN (0.666), NW (0.424) and NS (0.238) tend to prove the uncontaminated status as all the values were less than 0.7 that is the indicator of the clean situation (Nemerow, 1985). However, the NN value that is near the warning of 0.7 is worthy of attention particularly considering the fact that Cd (CFmax = 0.914) has been the most contributory element. This tendency means that NN may soon enter a stage when the further introduction of anthropogenic effect may push soils into the state of warning and clean to the state of warning and dirty. The NPI that is a combination of mean contamination and maximum contamination provides a conservative measure on the occurrence compared to PLI by itself and can serve as a priori indicator of degradation at its earliest stage.

4.3 Source Apportionment: Principal Component Analysis

The principal component analysis (PCA) identified two components which conveyed a total of 78.4 percent of the total variance and gave strong discrimination of sources of metals. Component 1 (56.2% of variance) had large loadings of Cd (0.86), Fe (0.82), Cr (0.79), and Ni (0.68), and Component 2 (22.2% of variance) large loadings of Pb (0.81) and Zn (0.74). This division is a clear indication that these metal assemblies have their own source, that is, different. The Fe-Cd, Fe-Cr and Fe-Ni association in Component 1 indicates a lithogenic interpretation. Iron is known to be a conservative element in soil systems universally which is largely procured through parent material weathering as opposed to anthropogenic inputs (Facchinelli, Sacchi, and Mallen, 2001). The concentration of Cd on this component is very high even though Cd is known to be toxic, which may indicate that geology is the dominant factor and not pollution in the distribution of Cd in Nasarawa soils.

This interpretation can be generalized with low absolute Cd concentrations and closeness of NN Cd values to the background. Schneider et al. (2016) also found a lithogenic component in PCA of soils around a secondary lead smelter, where Fe, Cr, and Ni loading go hand in hand as evidences of parent material makeup. Pb and Zn are the components of component 2 that is more complicated to interpret. Although such metals are traditionally related to anthropogenic sources, especially traffic emissions (Pb via gasoline additives in the past), and agricultural inputs (Zn via fertilizers and pesticides), the fact that their concentrations are low would negate major contamination. The association of these metals with another part of Fe indicates that they have a source that is other than bulk parent material of soil, but it might be diffuse atmospheric deposition of regional and not local character, or slight variations in mineralogy between the senatorial areas.

The fact that the space gradient was highest in NW with the data reporting the highest concentrations of Pb could be indicative of the closeness to the transportation path or land use dissimilarities. The intermediary behavior or mixed sources are indicated by moderate loadings of Cu (0.58 on Component 1; 0.42 on Component 2) and Ni (0.68 on Component 1; 0.36 on Component 2). Copper, especially, is usually lithogenic and anthropogenic-related according to land use, and the use of agriculture (fungicides, fertilizers) tends to enrich surface soil (Keiblinger et al., 2018). The PCA findings of this paper are methodologically consistent with the international best practices in source apportionment. One of the most commonly used methods to discriminate the sources of contaminants at polluted sites(Kadadou et al., 2024) was PCA, and successful source apportionment is usually indicated by a requirement to explain more than 70% of the overall variance. In this case, the variance explained is 78.4 percent and it is above this value which proves that the interpretation is strong. Nevertheless, the lack of a distinctly defined anthropogenic component with high loadings of numerous metals and large absolute values also makes the occurrence of the anthropogenic component distinctively unsuitable as compared to studies of actually contaminated sites, wherein the anthropogenic components tend to account for significant varian. The principal component analysis (PCA) identified two components which conveyed a total of 78.4 percent of the total variance and gave strong discrimination of sources of metals. Component 1 (56.2% of variance) had large loadings of Cd (0.86), Fe (0.82), Cr (0.79), and Ni (0.68), and Component 2 (22.2% of variance) large loadings of Pb (0.81) and Zn (0.74).

This division is a clear indication that these metal assemblies have their own source, that is, different. The Fe-Cd, Fe-Cr and Fe-Ni association in Component 1 indicates a lithogenic interpretation. Iron is known to be a conservative element in soil systems universally which is largely procured through parent material weathering as opposed to anthropogenic inputs (Jolaosho et al., 2024). The concentration of Cd on this component is very high even though Cd is known to be toxic, which may indicate that geology is the dominant factor and not pollution in the distribution of Cd in Nasarawa soils. This interpretation can be generalized with low absolute Cd concentrations and closeness of NN Cd values to the background. (Victor et al., 2026) also found a lithogenic component in PCA of soils around a secondary lead smelter, where Fe, Cr, and Ni loading go hand in hand as evidences of parent material makeup. Pb and Zn are the components of component 2 that is more complicated to interpret. Although such metals are traditionally related to anthropogenic sources, especially traffic emissions (Pb via gasoline additives in the past), and agricultural inputs (Zn via fertilizers and pesticides), the fact that their concentrations are low would negate major contamination. The association of these metals with another part of Fe indicates that they have a source that is other than bulk parent material of soil, but it might be diffuse atmospheric deposition of regional and not local character, or slight variations in mineralogy between the senatorial areas. The fact that the space gradient was highest in NW with the data reporting the highest concentrations of Pb could be indicative of the closeness to the transportation path or land use dissimilarities. The intermediary behavior or mixed sources are indicated by moderate loadings of Cu (0.58 on Component 1; 0.42 on Component 2) and Ni (0.68 on Component 1; 0.36 on Component 2). Copper, especially, is usually lithogenic and anthropogenic-related according to land use, and the use of agriculture (fungicides, fertilizers) tends to enrich surface soil(Eduah et al., 2024; Secu & Lesenciuc, 2024). The PCA findings of this paper are methodologically consistent with the international best practices in source apportionment. One of the most commonly used methods to discriminate the sources of contaminants at polluted sites (Kadadou et al., 2024)was PCA, and successful source apportionment is usually indicated by a requirement to explain more than 70% of the overall variance. In this case, the variance explained is 78.4 percent and it is above this value which proves that the interpretation is strong. Nevertheless, the lack of a distinctly defined anthropogenic component with high loadings of numerous metals and large absolute values also makes the occurrence of the anthropogenic component distinctively unsuitable as compared to studies of actually contaminated sites, wherein the anthropogenic components tend to account for significant variance and show strong spatial resolution (armah etal,2010) and show strong spatial resolution (Li, Ma, van der Kuijp, Yuan, and Huang, 2014).

4.4 Spatial Distribution and Implications

Spatial gradient in all indices, NN > NW > NS- is one of the most regular findings in this study. This trend is observed in concentrations of metals, CF values, PLI, Igeo, RI and NPI indicating a systematic spatial distribution instead of randomness. There are a few possible explanations of the consistency of this gradient that should be taken into account. To begin with, geochemistry variations between the parent materials in the senatorial zones could be a cause of the patterns. The three areas might be geologically underlain by the variations in background metal concentrations, where NN is over metal richer substrates. This can be explained by the PCA findings that indicate lithogenic control of the majority of metals. Second, the land use intensity and patterns can be systematically dissimilar among the zones with NN having more agricultural inputs, regional-based atmospheric deposition, or population density. Third, the characteristics of soils that can influence the retention of metals, including organic matter content, clay mineralogy, and pH, might also vary between zones and impact the ability of soils to fix metals deposited to the atmosphere (Li et al., 2022). The fact that NN is approaching the NPI warning threshold (0.7) and yet it is classified within the clean category begs the question as to whether the existing background values are appropriate. The backgrounds that are admired in the current study (Cd: 0.89 mg/kg; Pb: 21.2 mg/kg) are global averages (as opposed to geogenic site baselines). In the event that the actual geological background in NN is less than these values, the indices would be underestimated. As an alternative, anthropogenic effect would be over-estimated in the case where NN is inherently higher in metals because of geological factors. Such ambiguity highlights the paramount significance of determining site-specific background concentrations to make sound pollution assessments, an idea that is also supported across the African body of literature (Awolesi et al., 2025).

The international literature about contaminated sites highlights the significance of the spatial scale in explaining the patterns of pollution. Geological factors are mostly important at the regional scale (tens to hundreds of kilometers), whereas the anthropogenic sources are of paramount importance at local scales (meters to kilometers)(Betts et al., 2024). The Nasarawa study, which is done across three senatorial zones, is at a regional level where lithogenic control is anticipated. This interpretation is scale-appropriate, which supports the conclusion that the observed patterns can be attributed mainly to a natural variation, as opposed to pollution.

4.5 Methodological Contemplations and Uncertainties.

These results are subject to interpretation by a number of methodological factors. To begin with, the use of total metal concentrations as opposed to bioavailable ones could over-estimate ecological risk because metals in residual soil fractions are largely inaccessible to biological uptake. The sequential extraction studies of the contaminated sites in Africa have shown that the speciation of metals is a critical factor in risk assessment. The soils in the Kipushi mining region of the Congolese Copperbelt showed that Cd, Cr and Pb were concentrated in reducible fractions indicating that they would easily be remobilized in response to changing redox conditions (Mputu et al., 2025). It is not known how much the metal concentrations at Nasarawa are truly relevant to the ecological environment without the speciation data. Second, the fact that international screening guidelines (CCME, 2007; VROM, 2000) are used instead of the Nigerian-specific soil quality standards indicates that there is no local regulatory threshold. This is also practiced in African environmental studies (Ota et al., 2024), which creates uncertainty since the guidelines that were constructed in temperate regions may be ineffective in the soil systems of the tropics with unique mineralogy, organic matter interactions, and weathering. Environmental regulatory agencies should focus on developing soil quality standards of Nigerian soil on heavy metals. Third, the sampling design (n=15 per zone) gives strong characterization of central tendency but little resolution concerning the localized hotspots of contamination.

The small standard deviations compared to means indicate rather homogeneous conditions in zones, and the representativeness of the samples. Nevertheless, until an increased density of sampling is achieved or grid structures are taken as systematic, they cannot rule out the occurrence of localized hotspots (Paredes et al., 2026). Fourth, background values selection is the basic determinant of all computed indices. The values involved in this research (Table 1) seem to depict the world averages or regional standards, yet their suitability to the Nasarawa soils is not proven empirically. In future the focus of the studies must be on the deep soil sample (at least 1 m deep) collection of representative profiles to determine site-specific geogenic baselines against which surface enrichment may be measured (Blessing et al., 2025).

4.6 Comparative Synthesis: Nigeria, Africa, and Global Context

When the Nasarawa results are placed in the context of the general literature, one can see both similarities and differences that inform the overall state of the soil heavy metal studies on scales. The research in Nigeria has been overrepresentative of contamination hotspots, i.e. auto-mechanic workshops in the Niger Delta muze,etal,(2020), oil-impacted communities in Delta State (Enuneku et al.,2021), solid waste dumpsites in Akure (Olanipekun et al., 2024) whereby the metal levels are orders of magnitude higher than the international thresholds. The Nasarawa study is important as it records natural conditions in senatorial areas that have mixed land use and no point-source industrial pollution. This type of baseline information is necessary to set reference conditions on which industrialization or agricultural intensification can be measured in the future, as a systematic review by (Xie et al., 2019) has found that Nigeria and Ghana are the most covered regions, without large regions having been studied yet. The same review has also cited industrial activities (27%), and traffic emissions (26%), as the major sources of contamination where weighted mean concentrations of Pb, Cd, and Cr in most countries were found to be beyond the FAO limits. The Nasarawa results are apparently a contrast to this continental image, which supports the idea that the soil metal contamination in Africa is not homogenous and that overarching information about African urban soils distorts a significant regional diversity. The literature on the topic of heavy metal contamination at the contaminated locations has rapidly increased around the world, with China, India, and the USA being the most prolific contributors (Yu et al., 2025). The meta-analysis of the world by (Yu et al.,2025) indicated that Cd, Pb, and Zn were priority pollutants and reported the mean Igeo values (Cd: 5.91; Pb: 4.12; Zn: 3.73) which were overwhelmed by those in Nasarawa. This analogy is important in reminding the disparity between polluted industrial locations and control settings as well as in emphasizing the necessity of standardized procedures that would allow relevant inter-study comparisons (Singh et al., 2023).

4.7 Policy and Managerial Implications.

Although the Nasarawa soils are at the moment not contaminated, various results indicate the need to have proactive management. The attitude of the NN zone to the NPI warning level, along with the disproportional share of Cd in the ecological hazard, makes this region one of the priorities of the next monitoring. The NN > NW > NS spatial gradient indicates that the causes of metal deposition, be it geological or anthropogenic, are strong in NN, therefore, the land-use history and potential sources of contaminants in the NN area should be investigated. Additionally, the absence of Nigeria-specific soil quality standards represents a critical gap that hinders evidence-based environmental management.

The focus of the regulatory agencies should be on creating locally appropriate guidelines to take into consideration the tropical soil conditions, background geochemistry, and Nigerian exposure scenarios. These standards would facilitate better interpretation of the data of monitoring and lead to finding the sites where intervention is needed (Waylen et al., 2019). Another important point of the study is the importance of various pollution indices in assessing the quality of soil comprehensively. The total metal concentrations alone were indicative of low levels of contamination, but the RI indicated that Cd-dominated ecological risk and the NPI indicated that NN was close to the warning mark. Multi-index methods should be used in the future instead of simple comparisons of concentrations (Cruzado-Tafur et al., 2021).

5.0 CONCLUSION AND RECOMMENDATIONS

5.1 Conclusion

This comprehensive assessment of heavy metal contamination in surface soils from the Nasarawa senatorial zones, Nigeria, demonstrates that all measured metals (Cd, Pb, Zn, Cu, Cr, Ni, Fe) occur at concentrations below international screening guidelines. Multiple pollution indices—including contamination factor, pollution load index, geoaccumulation index, potential ecological risk index, and Nemerow pollution index—consistently classify the soils as uncontaminated and of low ecological risk. Principal component analysis indicates that metal distribution is primarily controlled by lithogenic factors (Component 1: Cd, Fe, Cr, Ni; 56.2% of variance), while a secondary component (Pb, Zn; 22.2% of variance) may reflect diffuse anthropogenic inputs or subtle mineralogical differences. A consistent spatial gradient (NN > NW > NS) across all indices suggests systematic variation due to either parent material geochemistry or land use intensity across the senatorial zones. Although cadmium concentrations are low, it dominates ecological risk calculations because of its high toxicity, approaching the Nemerow pollution index warning threshold at NN. Overall, this study establishes essential baseline data for relatively pristine areas, highlights the importance of site-specific background measurements, and provides a framework for continued monitoring and early detection of contamination, contributing meaningfully to both national and African-scale soil contamination literature.

5.2 Recommendations

Although the soils are presently largely uncontaminated and pose low ecological risk, the proximity of the Nemerow pollution index to the warning threshold in Nasarawa North warrants sustained environmental monitoring and periodic reassessment to prevent future contamination.

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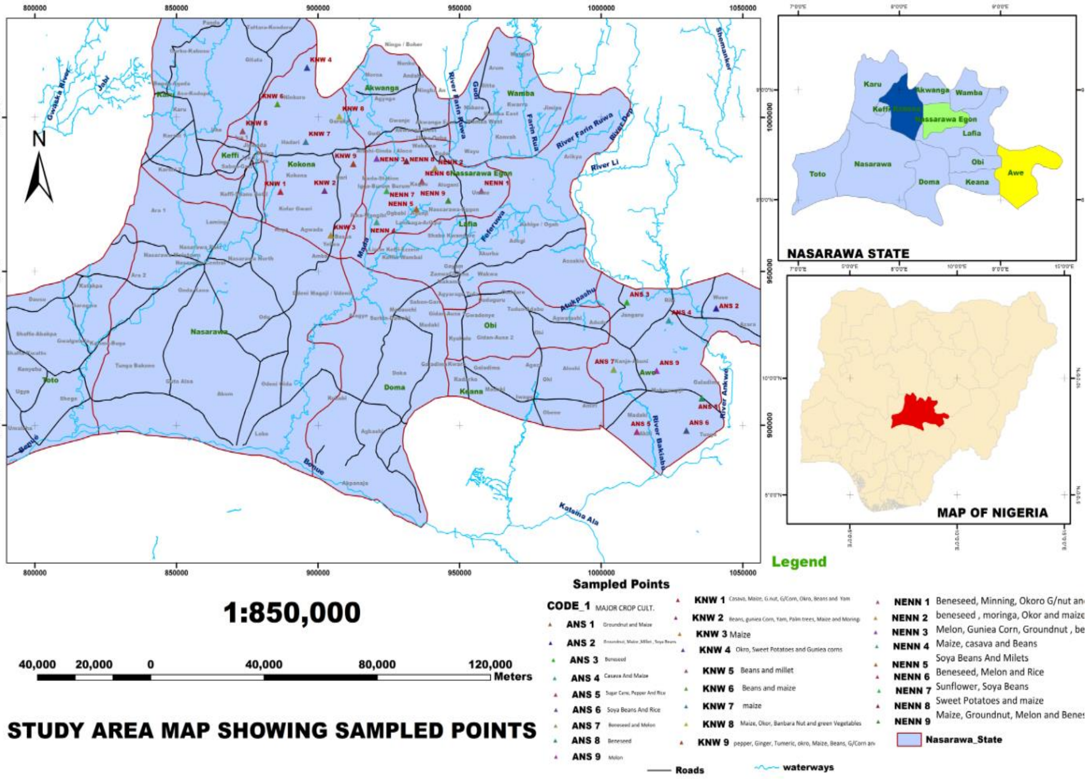

Figure 1: study area map showing sampled point (NAGIS, 2024)

Table 1: Geographic Coordinates, Land Area, and Population Characteristics of Study Area

Senatorial Zone	LGA	Population (2006 POP)	Area (Km^2)	Coordinates
Nasarawa South	Awe	116080	2800.00	Lat 8.1101° N, Long 8.4404° E
Nasarawa North	Nasarawa Eggon	110613	1199.34	Lat 8.7495^0 N Long 8.4404^0 E
Nasarawa West	Kokona	110591	1847.03	Lat; 8.8556^{O}N Long; 8.0611^{0}E

Source: Bureau for Land and Survey (2005); National Population Commission (2006).

Table 2. Summary of metal concentrations (mg/kg) in surface soils from Nasarawa senatorial zones.

Metal	NN (n=15)	NW (n=15)	NS (n=15)	Background
Cd	0.82 ± 0.15	0.21 ± 0.06	0.12 ± 0.04	0.89
Pb	8.60 ± 2.10	12.40 ± 3.20	6.80 ± 1.90	21.20
Zn	25.40± 4.80	18.60 ± 3.50	15.20± 2.80	42.50
Cu	6.80 ± 1.40	4.20 ± 0.90	3.60 ± 0.70	14.80
Cr	18.20 ± 3.60	12.40 ± 2.50	8.90 ± 1.80	32.60
Ni	7.40 ± 1.60	4.80 ± 1.10	3.20 ± 0.80	15.40
Fe	28500 ± 4200	22600 ± 3500	18900 ± 2800	31200

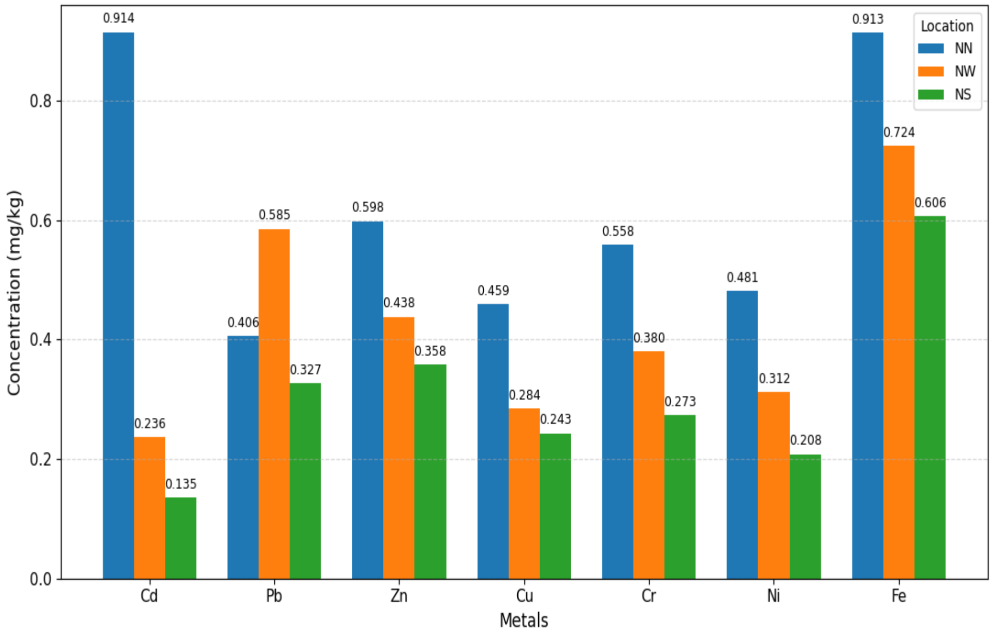

Figure 2. Contamination factors (CF) for individual metals across across the three senatorial zones

Table 3. Contamination factors (CF) for individual metals across across the three senatorial zones.

Metal	NN (mg/kg)	NW (mg/kg)	NS (mg/kg)
Cd	0.914	0.236	0.135
Pb	0.406	0.585	0.327
Zn	0.598	0.438	0.358
Cu	0.459	0.284	0.243
Cr	0.558	0.380	0.273
Ni	0.481	0.312	0.208
Fe	0.913	0.724	0.606

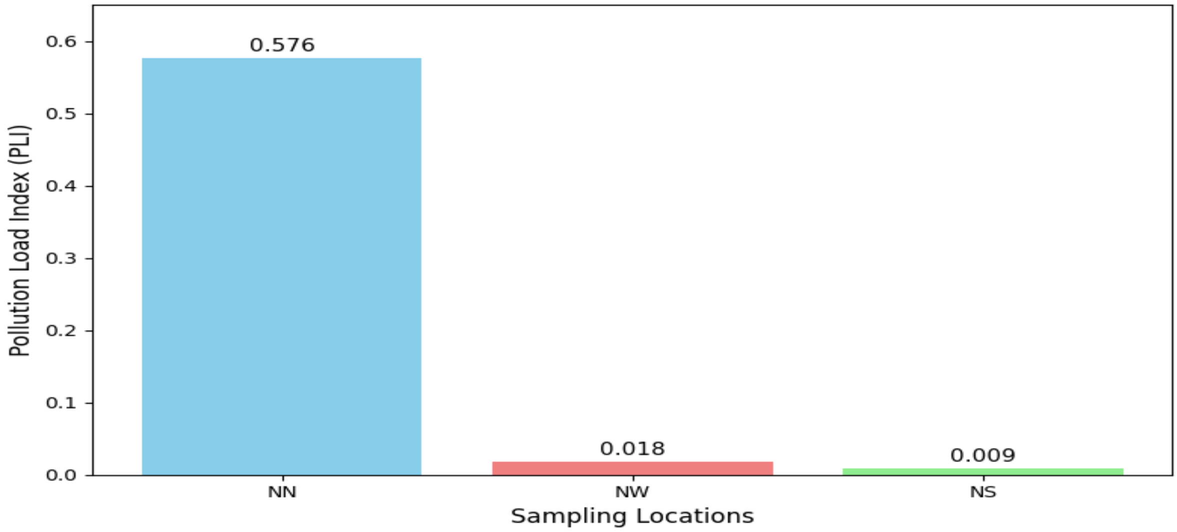

Figure 3 pollution load index (PLI) across soil locations

Table 4. Geoaccumulation index (Igeo) values across senatorial zones.

Metal	NN	NW	NS
Cd	-0.71	-2.67	-3.47
Pb	-1.88	-1.36	-2.20
Zn	-1.33	-1.78	-2.07
Cu	-1.71	-2.40	-2.62
Cr	-1.43	-1.98	-2.46
Ni	-1.64	-2.27	-2.85
Fe	-0.72	-1.05	-1.31

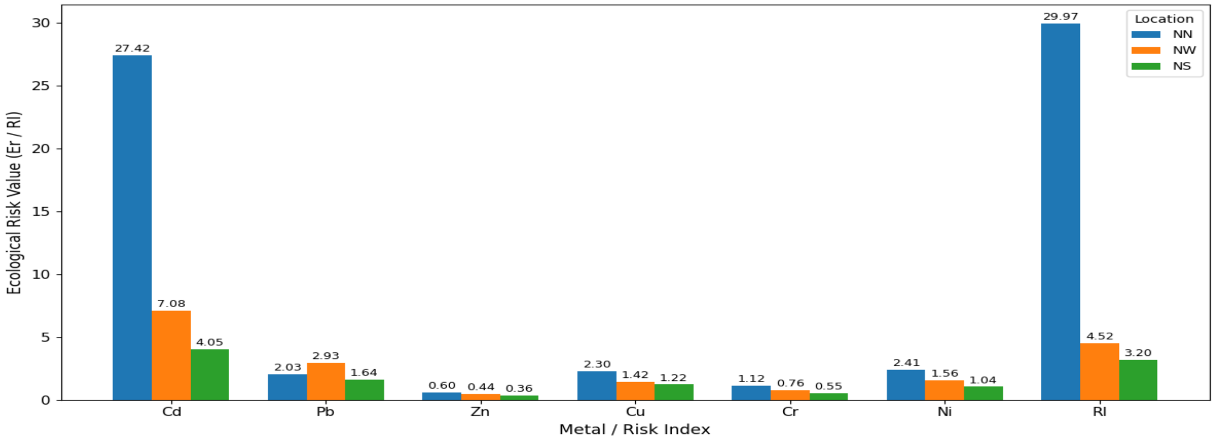

Figure 4: potential ecological risk index (ER and RI) across locations

Table 5. Potential ecological risk index (RI) and individual risk factors (Er).

Metal	Er (NN)	Er (NW)	Er (NS)
Cd	27.42	7.08	4.05
Pb	2.03	2.93	1.64
Zn	0.60	0.44	0.36
Cu	2.30	1.42	1.22
Cr	1.12	0.76	0.55
Ni	2.41	1.56	1.04
RI	**29.97**	**4.52**	**3.20**

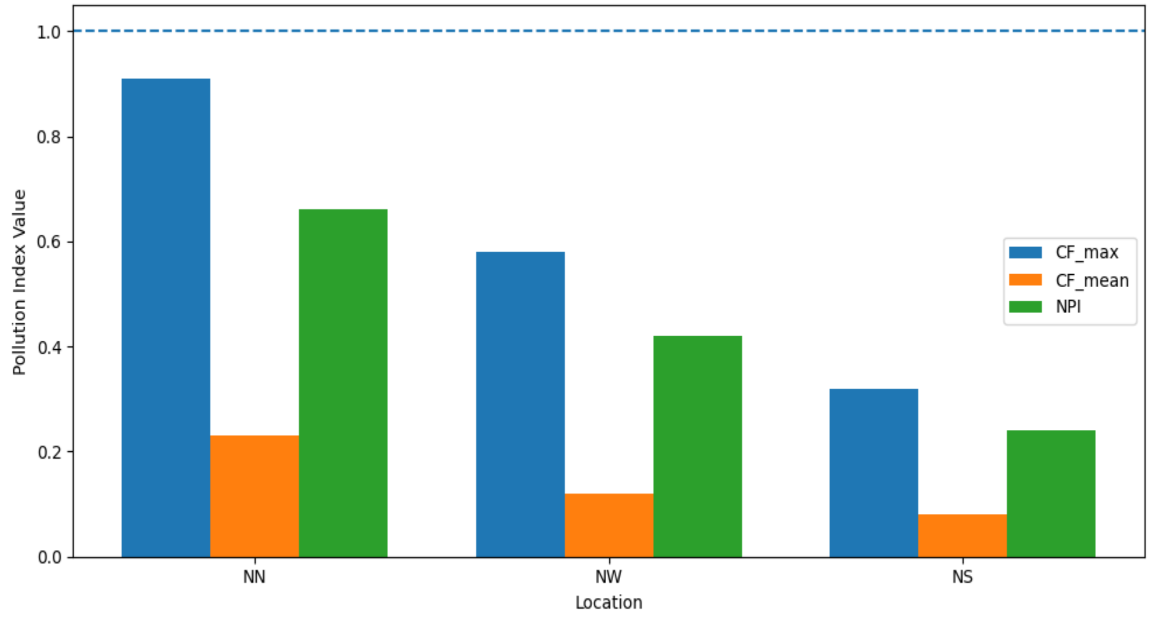

Figure 5: illustrates the Nemerow Pollution Index (NPI) values across the three locations: NN, NW, and NS.

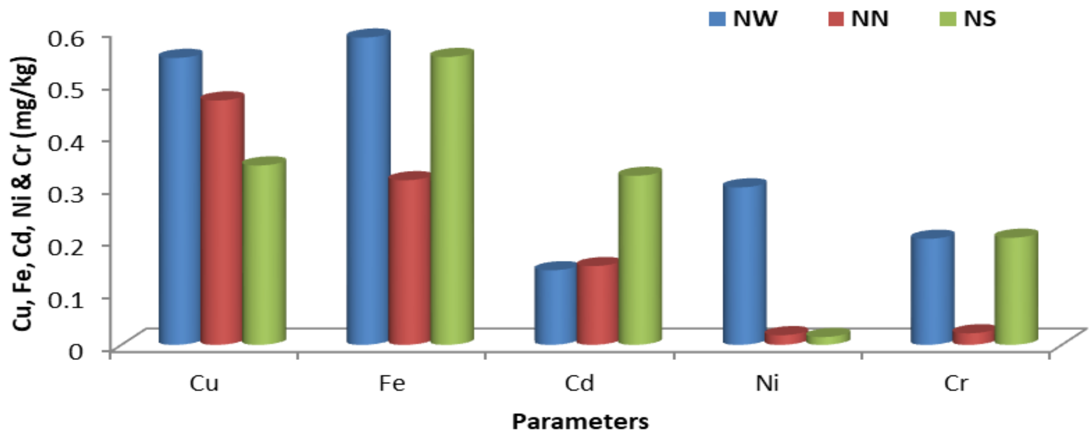

Figure 6: Spatial Distributions of Heavy Metals Across Sampling Areas

Table 6. Principal component analysis loadings for metals.

Metal	Component 1	Component 2
Cd	0.86	0.12
Pb	0.24	0.81
Zn	0.32	0.74
Cu	0.58	0.42
Cr	0.79	0.28
Ni	0.68	0.36
Fe	0.82	0.15
Variance (%)	56.2	22.2

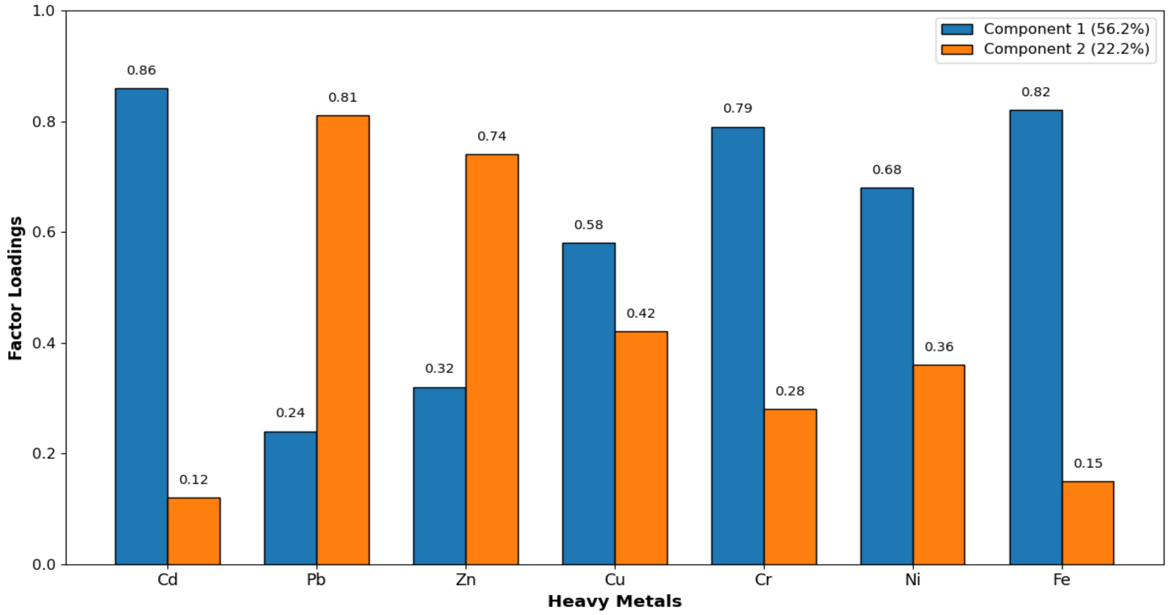

Figure 7: PCA component loadings of Heavy Metals