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Cancer and non-cancer risks potentials of metals in transformer-impacted soils in Nigeria

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Abstract: Electricity power generation and transmission have been an integral aspect of human existence globally. Nevertheless, power transmission installations have been one of the sources of soil contamination by metals from their metallic components. This research investigated the concentrations of metals and their related health hazards on electricity workers in transformer-impacted soils within Itiam-Ewet Housing Estate, Uyo, and South-South of Nigeria. Topsoil samples collected from transformer-impacted soils and a control plot were treated with standard methods and analyzed using spectrophotometer for their total Cd, Cr, Cu, Fe, Ni, and Pb. Results revealed that concentrations of all the metals except Cu were within their recommended limits in soil by international bodies. Pollution indices models revealed high levels of soil contamination by metals at all the studied locations. Multivariate analyses revealed the transformer, transformer oil, and vehicular emissions as the major contributors of these metals to the studied soils. The estimated daily intake rates of the metals indicated low levels of metal toxicity. The target hazard quotient and total hazard index of the metals showed minimal non-carcinogenic risks associated with the exposure by electricity workers. The incremental lifetime cancer risk and total cancer risks indicated low cancer-causing potentials of the metals in electricity workers. Based on the outcome of the study, other transformer-impacted soils should be investigated and regular assessment of locations studied is highly recommended.

1. Introduction

Metals from anthropogenic and natural sources are stored in the soil environment (Ebong and Ekong, 2015, Soltani-Gerdefaramarzi *et al*., 2021). Nonetheless, research has shown that human activity is the primary cause of increasing metal concentrations (Shangguan *et al*., 2018, Briffa *et al*., 2020; Ebong *et al*., 2023). According to (Tianlik *et al*. (2016), soil contamination and subsequent pollution are turning into a major issue that affects all living things, including human cells, worldwide. Human health and the worth of the ecosystem are both impacted by pollution (Islam *et al.* (2019). According to (Ebong *et al*. (2015) and (Offiong *et al*. (2021), metals can bioaccumulate, remain in biological cells throughout the food chain, and appear in a variety of detrimental ways. Persistent exposure to high levels of metals may result in both cancer and cancer-related health hazards in humans (Yang *et al*., 2019, Aliyu *et al*., 2022). Reports have shown that electricity power installations, including transformers, have the potential to elevate the concentrations of metals in the environment, mostly soil (Ikechukwu and Pauline, 2015, Akhigbe *et al*., 2019, Ogunlana *et al*., 2020, Mitra *et al*., 2022). Previous studies revealed that Cd, Cr, Cu, Fe, Ni, and Pb are the major metallic components of the transformer and its oil (Idowu and Iwuoha, 2021, Tiwari *et al*., 2024). Consequently, electricity workers and allied workers may be exposed to these metals and their related health problems. Thus, a periodic evaluation of soils around power transformers will provide insight into the concentrations of metals and their attendant health hazards for electricity workers.

The pollution status of metals in a contaminated environment has been identified by assessing models such as contamination factor, degree of contamination, ecological risk factor, and potential ecological risk index (Xiao *et al*., 2019, Islam *et al*., 2020, Yang *et al*., 2020, Ebong *et al*., 2022). The cancer and non-cancer health risks related to exposure to metals have also been studied with the estimated daily intake rate, and carcinogenic and non-carcinogenic health assessment models (Salihu *et al*., 2019, Alsafran *et al*., 2021, Hassan *et al*., 2022, Ain *et al*., 2023).

According to (Jomova *et al*. 2022), some metals are essential for the normal enzymetic, metabolic, and growth activities in human, lower animals, and fish. However, metals even the essential ones are useful within their normal limits while others are not useful at all to the human system and are generally referred to as toxic metals. Hence, both the essential and toxic metals can impact negatively on living organisms (Belbachir *et al*. 2013; Karim *et al*. 2016 & 2019).

High levels of toxic metal in human can cause damage the bones, lungs, renal dysfunction, cause diarrhea, and stomach irritation, mental retardation, weight loss, and psychosis, cancer, birth defects, dermal, and neurological problem. It can also cause skin, brain, and kidney problems, asthma, respiratory, gastrointestinal, and cardiovascular diseases, headache, hypertension, edema, renal dysfunction, and loss of appetite. Vertigo, sleeplessness, hallucination, and arthritis dyslexia, paralysis, autism, hyperactivity, weakness of muscles, and death could be experienced by the victim as well (AbdElnabi *et al*., 2023, Obasi and Akudinobi, 2020, Ohiagu *et al*., 2022).

High levels of metals in animals can cause some negative issues such as hydrothorax, hemoglobinuria, head pushing, opisthotonus, aimless roaming, bruxism, circling, and ataxia, haemolytic disease, anorexia, thirst, sadness, jaundice, haemolytic anemia, and hemoglobinuria, heartbeat, sadness, blindness, ascites etc (Newcomer *et al*., 2021, Acheampong, 2023)

Metal toxicity can damage the nervous system of fish, stimulates cytotoxicity and can lead to degenerative changes in essential organs of the fish. Metals can alter the levels of blood parameters and affects the oxygen- carrying capacity in fish (Garai *et al*., 2021, *Ahmed et al*., 2022, Shahjahan *et al*., 2022).

This research investigated the influence of power transformers in Itiam-Ewet Housing on the metal concentrations in the host soil environment and their potential health risks for electricity workers. The work assessed the pollution status of transformer-impacted soils at Itiam-Ewet Housing Estate and established the source of metal contaminants in the studied soils using multivariate analyses. The assessment of metal loads in soils around power transformers and their associated health risks for electricity workers has not been carried out before in Akwa Ibom State. Hence, the results obtained from this study will serve as baseline data for future researchers in the study area. The outcome of this investigation will be useful to both the electricity staff and the power generating companies. The outcome of this study will forestall the health problems associated with prolonged exposure to soil particles from transformer-impacted soils by electricity workers.

2. Materials and Methods

2.1. Study Area

The research was carried out within Itiam-Ewet Housing Estate in Uyo, Akwa Ibom State, and the South-South Region of Nigeria. Akwa Ibom State lies in the oil-producing section of Nigeria; the state has been affected negatively by the activities of oil companies. This study was conducted within latitudes 5° 00' 35"N and 5° 01' 24′′N and longitudes 7° 56' 31" E and 7° 56' 53"E (Table 1). The study has wet and dry seasons as the major seasons, with abundant rainfall during the wet season. The mean rainfall and temperature of the area range from 2,000 to 3,000 mm and 25 to 29 °C, respectively. Itiam-Ewet Estate is a major housing estate in Akwa Ibom State where a greater number of inhabitants from Uyo Metropolis are accommodated. The majority of power transformers in Uyo Metropolis are installed in Ewet Housing; hence, most electricity workers perform their duties in the location. Consequently, if there is an incidence of health problems associated with power supply in Itiam-Ewet Housing Estate, it will affect many electricity workers in the state. The studied locations, control site, and their respective coordinates are in Table 1.

Table 1: Sample locations, Control, and their coordinates

LOCATION	LATITUDE	LONGITUDE
A-LINE	5° 00' 35" N	7° 56' 49"
B-LINE	5° 01' 21" N	7° 56' 30"
C-LINE	5° 01' 16" N	7° 56' 21"
D-LINE	5° 00' 41" N	7° 56' 38"
F-LINE	5° 01' 09" N	7° 56' 48"
G-LINE	5° 00' 55" N	7° 56' 42"
E-LINE (CONTROL)	5° 01' 24" N	7° 56' 53"

2.2. Sample Collection and Treatment

Surface soil samples were obtained randomly within the neighborhood of electric power transformers at A, B, C, D, F, and G Lines in Itiam-Ewet Housing Estate, Uyo, Nigeria, and using Auger. Soil samples were also collected from a location without transformer and other sources of soil contaminants along the E-Line and used as the Control. The samples and control were dried in the sun for seventy-two (72) hours, homogenized, and sieved using a 2mm stainless steel mesh. One gram (1g) of the sieved sample was placed in a conical flask, 10 ml of Aqua regia was added, and the mixture was placed on a hot plate. Later, the mixture was cooled, and 20 ml of distilled water was added to the digest. The conical flask was then stirred vigorously and filtered. The filtrates were stored in clean sample containers and preserved at 4°C before analysis for trace metals using an atomic absorption spectrophotometer.

2.3. Evaluation of Pollution Indices of the Studied Soils

2.3.1. Contamination Factor (CF)

The contamination factor was employed for the evaluation of the toxicity status of each metal at each of the locations examined (Saha *et al*. (2022). The contamination factor was calculated using Eqn. 1 as proposed by Tomczyk *et al*. (2023).

$$CF = \frac{Cm}{Bm} \quad \textbf{Eqn. 1}$$

Where CF denotes the contamination factor, Cm is the level of metals in soils examined, and Bm symbolizes the concentration of trace metal in the control site, correspondingly. Based on Contamination factor is grouped into (i) CF < 1 = low contamination (ii) 1 ≤ CF < 2 = Low to moderate contamination (iii) $2 \leq CF \leq 3$ = moderate contamination (iv) $3 \leq CF < 4$ = Moderate to high contamination (v) $4 \leq CF < 5$ = High contamination (vi) $5 \leq CF < 6$ = High to very high contamination and (vii) $CF \leq 6$ = Extreme contamination (Papadimou *et al.* (2023).

2.3.2. Degree of Contamination (DC)

The degree of contamination (DC) was determined to assess the environmental hazards associated with the studied soils caused by the various metals (Hou *et al*., 2013, Essien *et al*., 2019). In this work, CD was computed using Eqn. 2 according to Håkanson (1980).

$$CD = \Sigma Cd + \Sigma Cr + \Sigma Cu + \Sigma Fe + \Sigma Ni + \Sigma Pb \qquad \textbf{Eqn. 2}$$

Where DC is the degree of contamination, $\Sigma Cd+\Sigma Cr+\Sigma Cu+\Sigma Fe+\Sigma Ni+\Sigma Pb$ indicates the summation of all the trace metals determined in the studied soils. According to (Håkanson (1980), the degree of contamination is categorized into the following classes: $DC \leq 6$ is the low degree of contamination, $6 < DC \leq 12$ indicates a moderate degree of contamination, $12 < DC \leq 24$ denotes considerable degree of contamination, and $24 > DC$ very high degree of contamination.

2.3.3. Ecological Risk Factor (ERF)

This research utilized ecological risk factors to evaluate the hazards associated with the accumulation of metals in the studied soils by Eqn. 3 according to (Håkanson (1980) and (Ebong *et al*. (2018):

$$ERF = Tr \times CF \qquad \textbf{Eqn. 3}$$

Where ERF is the ecological risk factor, Tr shows the toxic-response factor and CF denotes the contamination factor of metals. Toxic response factors of the metals are Cd (30.0), Cr (2.00), Cu (5.00), Fe (6.00), Ni (5.00), and Pb (5.00) (Ouchir *et al*., 2016, Mavakala *et al*., 2022). According to the classifications by (Rostami *et al*. (2021), ERF is categorized into (i) $ERF < 40$ = low ecological risk, $40 \leq ERF < 80$ = moderate potential risk, $80 \leq ERF < 160$ = considerable potential risk, $160 \leq ERF < 320$ = high potential risk, and $ERF \geq 320$ = significantly very high risk.

2.3.4. Potential Ecological Risk Index (PERI)

The potential ecological risk index (PERI) was used to assess the ecological hazards of the trace metals in the studied impacted soils comprehensively (Tisha *et al*. (2020). This study used Eqn. 4 to determine the PERI of metals at the studied locations (Håkanson, 1980, Saha *et al*., 2022).

$$PERI = \Sigma(ERF) \qquad \textbf{Eqn. 4}$$

Where PERI is the potential ecological risk index and $\Sigma(ERF)$ indicates the summary of the ecological risk factor of trace metals for each location. (Kang *et al*. (2020) grouped PERI as (i) $RI < 150$ = low ecological risk class, $150 \leq RI < 300$ = moderate ecological risk class, $300 \leq RI < 600$ = considerable ecological risk class, and $RI \geq 600$ = high ecological risk class.

2.4. Appraisal of Health Risks

Appraisal of non-cancer human health hazards related to the exposure to trace metal through studied soil particles from the studied locations was done through the estimation of daily intake rate (Hassan *et al*. (2022); target hazard quotient (Udiba *et al*. (2022); total hazard index (Ain *et al*. (2023). The cancer and cancer-related risks linked to the carcinogens in soil particles from the studied locations were assessed with incremental lifetime cancer risk and total cancer risks (Salihu *et al*., 2019, Alsafran *et al*., 2021).

2.4.1. Estimated daily intake (EDI) of Trace Metals

The estimated daily intake rate of the metals was determined to evaluate the level at which these metals were ingested by electricity and allied workers via exposure to soil particles from the studied locations (Hassan *et al*. (2022). The estimated daily intake rate of the trace metals through exposure to soil particles from the studied locations by electricity workers was computed using Eqn. 5 below.

$$\text{EDI} = \frac{CxRI}{BW} \qquad \textbf{Eqn.5}$$

EDI in Equation is the estimated daily intake rate, C denotes the concentration of trace metals in the studied soils, RI signifies the daily intake rate of metals via the studied soils, and BW indicates the body weight. In this study, RI = 0.0001 day-1 and BW = 70 kg (USEPA, 2011, Dan *et al*., 2023).

2.4.2. Target Hazard Quotients (THQ) of Trace Metals

The target hazard quotient of trace metals through exposure to soil particles from the studied locations by electricity workers was assessed using Eqn. 6.

$$\text{THQ} = \frac{EDI}{Rfd} \qquad \textbf{Eqn. 6}$$

Where THQ is the target hazard quotient, EDI denotes the estimated daily intake rate of the metals, and Rfd signifies the recommended oral reference dose of the metals. The Rfd for the metals are 0.001, 1.50, 0.04, 0.7, 0.02, and 0.004 mg/kg/day for Cd, Cr, Cu, Fe, Ni, and Pb, respectively (USEPA (2015).

2.4.3. Total Hazard Index (THI) of Trace Metals

The total hazard index of the metals via exposure to soil particles from the locations examined by electricity workers was calculated with Eqn. 7.

$$\text{THI}=\Sigma\text{THQ}=\text{THQCd}+\text{THQCr}+\text{THQCu}+\text{THQFe}+\text{THQNi}+\text{THQPb} \qquad \textbf{Eqn. 7}$$

In Equation 7 above, THI is the total hazard index and ΣTHQ is the summation of the target hazard quotient for all the metals determined.

2.4.4. Incremental Lifetime Cancer Risk (ILCR) of Carcinogens

Incremental lifetime cancer risk (ILCR) of the carcinogens through exposure to soil particles from the studied locations by electricity workers was assessed using Eqn. 8 below.

$$\text{ILCR}=\text{CSF x EDI} \qquad \textbf{Eqn. 8}$$

Where CSF = Cancer slope factor of the metals and EDI indicates the calculated estimated daily intake rate of the carcinogens. CSF values for Cd, Cr, Ni, and Pb are 5.00E-01, 5.00E-01, 1.70, and 8.50E-03, respectively (USEPA IRIS, 2011, Mohammadi *et al*., 2019).

2.4.5. Total Cancer Risk (TCR) of the Carcinogens

The total cancer risk (TCR) of the cancer-causing metals via exposure to soil particles from the studied soils by electricity workers was computed based on Eqn. 9.

$$\text{TCR}=\Sigma\text{ILCR}=\text{ILCRCd}+\text{ILCRCr}+\text{ILCRNi}+\text{ILCRPb} \qquad \textbf{Eqn. 9}$$

Where ΣILCR shows the summation of the entire incremental lifetime cancer risk (ILCR) of trace metals determined in the studied soils.

2.5. Analysis of Data

Results obtained were subjected to statistical analysis by the use of IBM SPSS Statistic 20 Software. The Principal Component Analysis (PCA) was performed with Varimax Factor analysis on six (6) metals and values lower than 0.506 were not considered. Hierarchical Cluster Analysis (HCA) was done on the results obtained using Dendrograms using average linkage.

3. Results and Discussion

3.1. The results of trace metals in transformer-impacted soils

The results of trace metals in soils impacted by transformer are in Table 2. The results obtained showed the following mean concentrations (mgkg-1) for Cd, Cr, Cu, Fe, Ni, and Pb: 0.76±0.21, 0.49±0.08, 38.12±3.15, 803.32±94.62, 1.21±0.29, and 9.47±1.25, respectively. These mean values are higher than their respective concentrations recorded at the control site, as shown in Table 2. This agrees with the results obtained by (Ogunlana *et al*. (2020) in soils around transformers. This indicates that transformers can increase the concentrations of metals in the surrounding soil environment as reported by (Stojić *et al*. (2014). The mean concentrations of all the metals reported are higher than the values obtained by (Akhigbe *et al*. (2019) and (Idowu and Iwuoha (2021) in transformer-impacted soils. However, the mean values of Cu, Fe, and Pb obtained are lower than the values reported by (Ogunlana *et al*. (2020) in a similar study. Of all the metals determined, Fe showed the highest mean concentration, as previously reported by (Akhigbe *et al*. (2019).

Table 2: Concentrations of Trace Metals in Soils around Transformers

	Cd	Cr	Cu	Fe	Ni	Pb
A-LINE	0.57	0.53	33.20	642.04	1.13	8.57
B- LINE	0.68	0.49	40.15	758.26	0.87	11.53
C- LINE	0.83	0.62	38.56	890.61	1.17	8.04
D- LINE	0.61	0.39	42.07	855.80	1.28	10.20
F- LINE	1.14	0.46	35.92	791.15	1.09	9.36
G- LINE	0.75	0.42	38.84	882.07	1.74	9.11
MIN	0.57	0.39	33.20	642.04	0.87	8.04
MAX	1.14	0.62	42.07	890.61	1.74	11.53
RANGE	0.57	0.23	8.87	248.57	0.87	3.49
MEAN	0.76	0.49	38.12	803.32	1.21	9.47
SD	0.21	0.08	3.15	94.62	0.29	1.25
CONTROL	0.02	0.04	3.28	126.05	0.07	0.62

Generally, the mean values of all the metals except Cu were within their recommended limits by (FEPA (1999) and (WHO (1996). Based on the results obtained, Cd, Cr, Fe, Ni, and Pb may not pose immediate health problems to the electricity workers exposed to soil particles from areas investigated, but as metals, they can bio-accumulate over time and exhibit their harmful tendencies. The results also revealed that, prolonged exposure to soil particles from the transformer-impacted soils by electricity workers might result in problems associated with copper toxicity. Thus, regular monitoring of their concentrations is highly recommended. Nonetheless, consistent exposure to soil particles by electricity workers and others can cause Cu toxicity and related human health problems (Konadu *et al*., 2023).

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3.2. The results of contamination factor of trace metals in transformer-impacted soils

The results of the contamination factors (CF) of trace metals determined in the impacted soils are shown in Figure 1. The CF results obtained indicated the following mean values: 57.0, 15.5, 12.8, 7.1, 24.9, and 18.6 for Cd, Cr, Cu, Fe, Ni, and Pb, respectively. The results revealed that contamination factors of the entire metals belong to the extreme contamination category according to (Papadimou *et al*. (2023) classifications. The CF of the metals followed a decreasing order as Cd > Ni > Pb > Cr > Cu > Fe. Consequently, Cd showed the highest level of soil contamination, while Fe exhibited low soil contamination potential. This is in agreement with the results obtained by (Emmanuel *et al*. (2014). The high CF values of toxic metals reported call for concern because they can be very hazardous, even at very low concentrations.

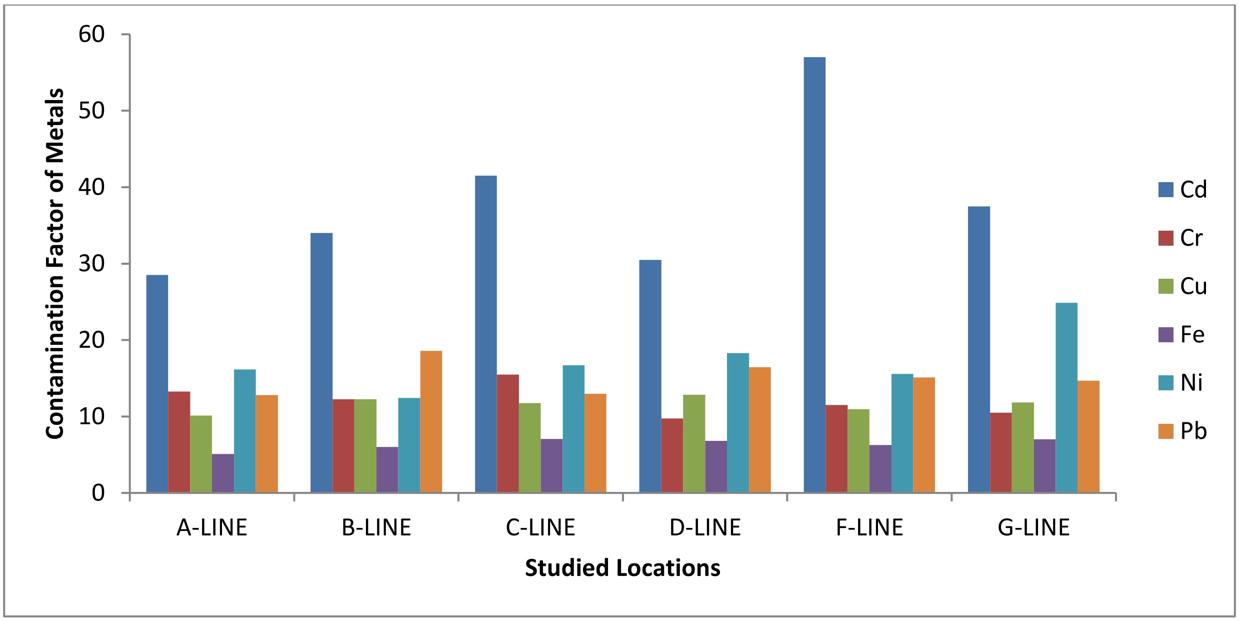

Figure 1: Contamination Factor of Metals in Soils from the Studied Locations

3.3. The results of degree of contamination of the transformer-impacted soils by trace metals

The results of the degree of contamination (DC) are shown in Figure 2. The CD values obtained at the A, B, C, D, F, and G lines were 85.9, 94.5, 105.5, 94.6, 116.4, and 106.4, respectively. According to (Hakanson (1980), all the studied locations belong to the very high degree of contamination class. Consequently, all the locations were highly contaminated by these trace metals, which are very risky, mostly for the electrical workers. The CD of the various locations examined followed the sequence F-Line > G-Line > C-Line > D-Line > B-Line > A-Line. This corroborates the findings of PERI that the F-line has the highest potential risk while the A-line has the lowest.

3.4. The results of ecological risk factor of trace metals at the studied transformer-impacted soils

The results of the ecological risk factor (ERF) are in Table 3 and the results showed the following mean values: Cd (1145.0), Cr (24.3), Cu (58.1), Fe (38.3), Ni (86.7), and Pb (75.5). According to the groupings by (Fadlillah *et al*. (2023), Cd belongs to the significantly high-risk group, Cr and Fe are in the low ecological risk category, Cu and Pb belong to the moderate potential risk class, and Ni is in the considerable potential risk category. Consequently, Cd showed the highest level of enrichment and the potential to have a negative impact on the soils examined.

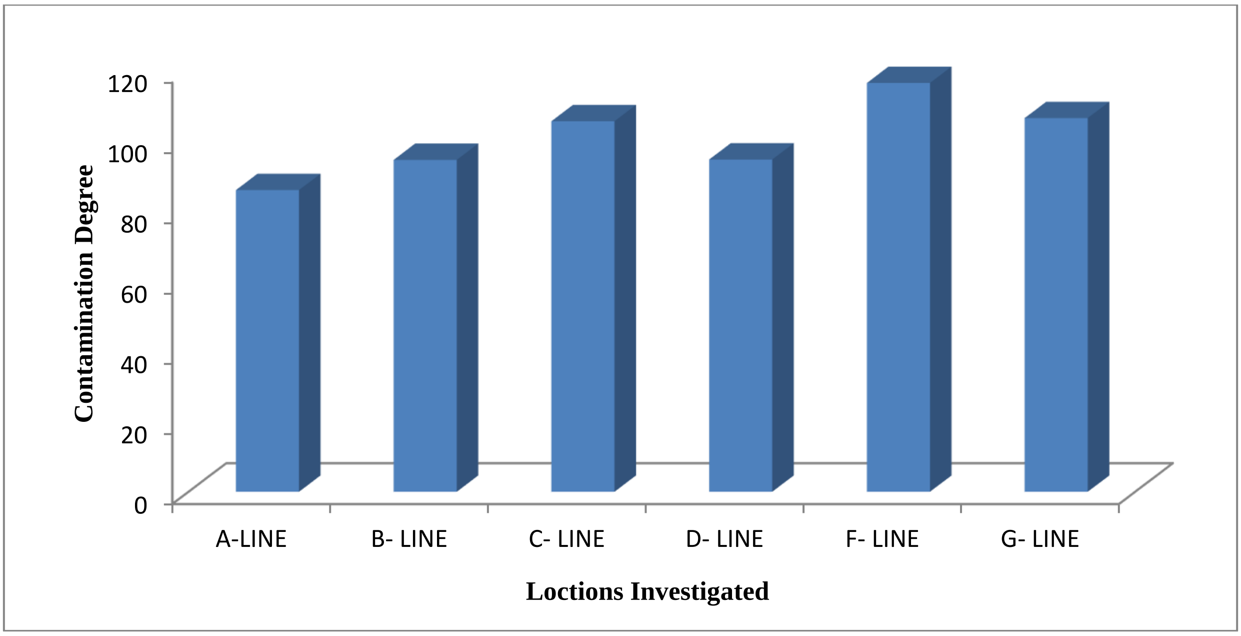

Figure 2: Contamination Degree of the Locations Examined

Table 3: Results of Ecological risk factor of trace metals at the studied soils

	Cd	Cr	Cu	Fe	Ni	Pb
A-LINE	855	26.5	50.6	30.54	80.7	64.1
B- LINE	1,020	24.5	61.2	36.12	62.15	93
C- LINE	1,245	31	58.8	42.42	83.55	64.85
D- LINE	915	19.5	64.15	40.74	91.45	82.25
F- LINE	1,710	23	54.75	37.68	77.85	75.5
G- LINE	1,125	21	59.2	42	124.3	73.45
MIN	855	19.5	50.6	30.5	62.2	64.1
MAX	1710	31	64.2	42.4	124.3	93
MEAN	1145	24.3	58.1	38.3	86.7	75.5

3.5. Results of potential ecological risk index of the studied transformer-impacted soils

The results of potential ecological risk index (PERI) are shown in Figure 3. The mean PERI values of the studied locations are as follows: A-Line (1107.4), B-Line (1,297), C-Line (1,526), D-Line (1,213.1), F-Line (1,979), and G-Line (1,445), respectively.

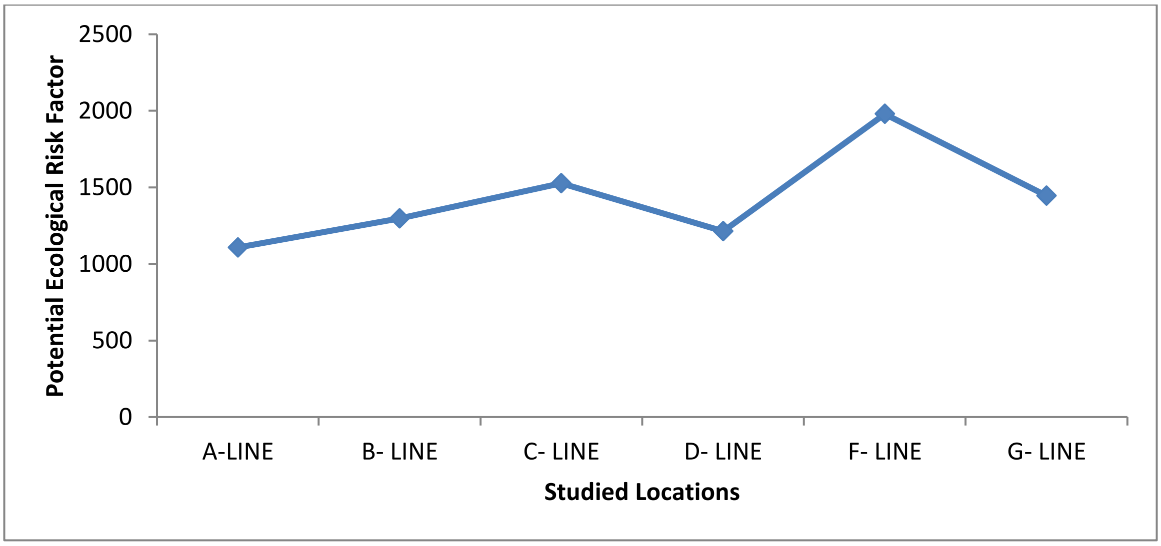

Figure 3: Potential Ecological Risk Factor of the Studied Locations

According to (Chen *et al*. (2019) classifications of PERI, all the studied locations belong to the high-risk class. Consequently, there are high risks associated with prolonged human exposure to the locations studied. This reveals the high risks associated with the exposure of electricity workers to soil particles at the studied locations. Although the class of PERI at all the studied locations belongs to the high category, it decreases in the order F-Line > C-Line > G-Line > B-Line > D-Line > A-Line.

3.6. Multivariate analyses

3.6.1. Results of Principal Component Analysis

Principal component analysis (PCA) revealed three (3) main factors accountable for the accumulation of these metals (Table 4). These factors have Eigenvalues higher than one (1) and a total variance of 84.6%. Factor 1 (PC1) has an Eigenvalue of 2.27 and a total variance of 37.8%, with a significant negative loading on Cr and strong positive loadings on Cu, Fe, and Pb. This could be the negative impact of the transformer oil on the soil quality (Tiwari *et al*. (2024). Factor 2 (PC2) has an Eigenvalue of 1.72 and a total variance of 28.7%, with strong positive loadings on Fe and Ni but significant negative loadings on Pb (Table 4). This factor may indicate the impact of the transformer on the studied soil environment (Idowu and Iwuoha (2021). Factor 3 (PC3) has an Eigenvalue (1.09, a total variance of 18.1%, and a strong positive loading on Cd and a significant negative loading on Ni (Table 4). This could be the negative impact of vehicular emissions on the studied soil as the locations are by the roadsides (Kubier *et al*. (2019).

Table 4: Results of Principal Component analysis (PCA) of Trace Metals in the studied soils

	Impacted Soil		
	PC1	PC2	PC3
Component			
Cd	-0.127	0.427	0.738
Cr	-0.718	0.195	0.263
Cu	0.891	-0.140	0.223
Fe	0.687	0.601	0.320
Ni	0.460	0.685	-0.525
Pb	0.506	-0.808	0.208
% Total Variance	37.8	28.7	18.1
Cumulative %	37.8	66.5	84.6
Eigen value	2.27	1.72	1.09

3.6.2. Results of Hierarchical cluster analysis of trace metals in the Studied Soils

Hierarchical cluster analysis (HCA) revealed two (2) key clusters (Figure 4). Cluster 1 puts Cd, Cr, Ni, Pb, and Cu in a common group, while Cluster 2 has Fe only. Cluster 1 shows that most of the metals determined in the studied soils might have originated mainly from the transformer and the oil (an anthropogenic source). However, cluster 2 indicates that Fe may have emanated largely from the natural source, as previously reported by (Ebong *et al*. (2018).

3.6.3. Results of Hierarchical cluster analysis of the studied transformer-impacted Soils

The HCA of the different studied locations in Figure 5 indicates three main clusters. The first cluster connects the C, D, and G lines. The second cluster links both the B and F lines as one, while the third cluster shows only the A- line. This indicates that the level of soil pollution by the transformers at C, D, and G Lines might have been the same. The degree of soil contamination by the transformers installed at B and F lines could have been identical. The extent of soil contamination by the transformer at A-Line might have been relatively different from others and the lowest as indicated by the results of contamination degree and potential ecological risk index of the studied locations.

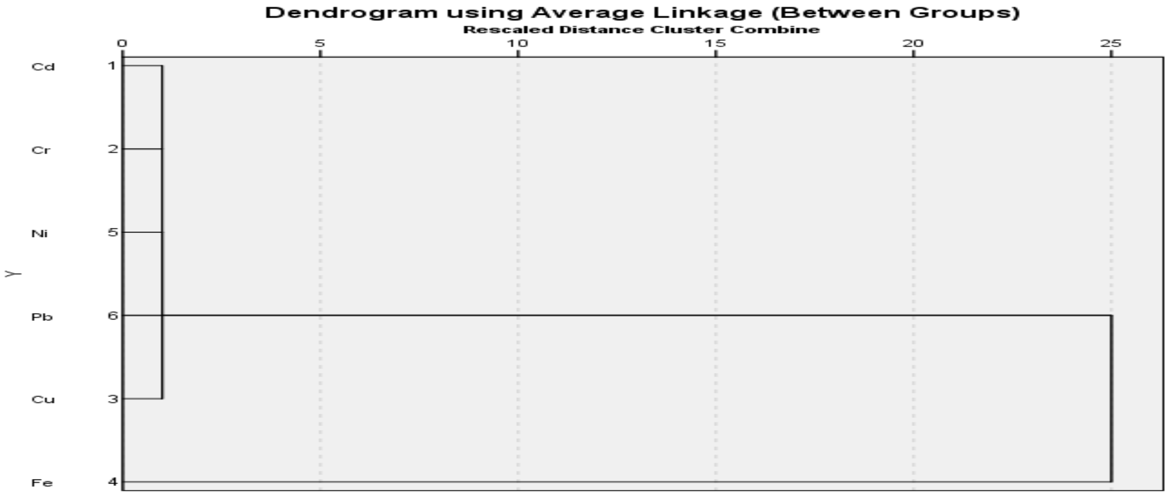

Figure 4: Hierarchical clusters of Trace Metals in the Studied Soils

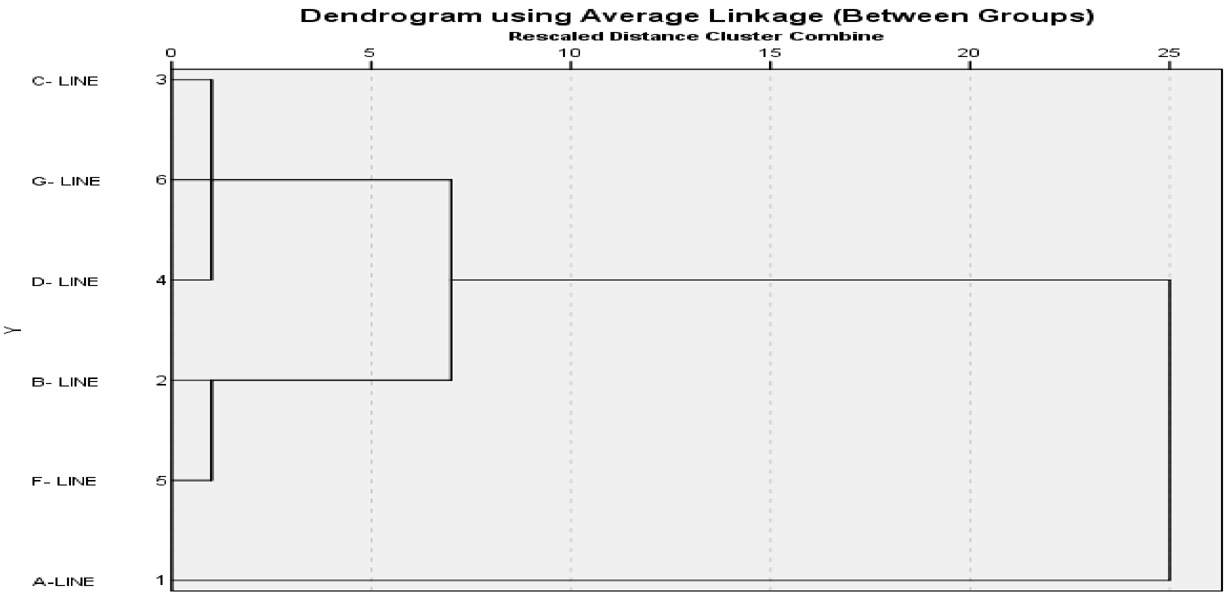

Figure 5: Hierarchical clusters of the Studied Locations

3.7. Evaluation of health risks associated with exposure to trace metals by electricity workers

3.7.1. Results of the estimated daily intake rate of trace metals by electricity workers

The results of estimated daily intake (EDI) rates of trace metals in the studied soils through ingestion of soil particles are in Table 5. Based on the results, the mean EDI values of Cd, Cr, Cu, Fe, Ni, and Pb were 1.09E-06, 6.93E-07, 5.45E-05, 1.46E-03, 1.57E-06, and 1.35E-05, respectively. Accordingly, the mean EDI values of all the metals were within their acceptable oral reference doses (RfDs), according to (USEPA (2000). This is in agreement with the results published by (Rakib *et al.* (2021) and (Begum *et al*. (2023) from their studies. Nevertheless, the average EDI values of Cr and Ni were within their ideal RfD limits. Hence, consistent exposure to soil particles from the studied location may result in minimal health problems associated with these metals in electricity workers (Adebiyi *et al.*, 2019, Meseret *et al.*, 2020). The mean EDI values of these metals followed a decreasing order of Fe < Cu < Pb < Ni < Cd < Cr. This indicates that Fe had the highest mean EDI value, similar to the results obtained by (Ebong *et al*. (2019) and (Rakib *et al*. (2021).

Table 5: Results of the estimated daily intake (EDI) rate of trace metals by electricity workers

	Cd	Cr	Cu	Fe	Ni	Pb
A-LINE	8.14E-07	7.57E-07	4.74E-05	9.17E-04	1.61E-06	1.22E-05
B- LINE	9.71E-07	7.00E-07	5.74E-05	1.08E-03	1.24E-06	1.65E-05
C- LINE	1.19E-06	8.86E-07	5.51E-05	1.27E-03	1.67E-06	1.15E-05
D- LINE	8.71E-07	5.57E-07	6.01E-05	1.22E-03	1.83E-06	1.46E-05
F- LINE	1.63E-06	6.57E-07	5.13E-05	1.13E-03	1.56E-06	1.34E-05
G- LINE	1.07E-06	6.00E-07	5.55E-05	1.26E-03	1.49E-06	1.30E-05
MEAN	1.09E-06	6.93E-07	5.45E-05	1.46E-03	1.57E-06	1.35E-05

3.7.2. Results of the target hazard quotient of trace metals on electricity workers

The average target hazard quotient (THQ) values of metals in the impacted soils are in Table 6. The mean THQ values obtained were 1.09E-03, 4.62E-07, 1.36E-03, 1.64E-03, 7.84E-05, and 3.39E-03 for Cd, Cr, Cu, Fe, Ni, and Pb, respectively. Thus, the mean THQ values of the metals were less than one (1). This is consistent with the results obtained by (Abdullahi and Musa (2023) and (Okorie *et al*. (2024). Consequently, these metals could exhibit low levels of non-carcinogenic hazards associated with exposure to soil particles at the studied locations by electricity workers. The mean THQ values of the metals followed the sequence: Pb > Fe > Cu > Cd > Ni > Cr. Hence, Pb had the highest mean THQ value, as previously reported by (Bambara *et al*. (2023) in their study.

Table 6: Results of target hazard quotient of metals on electricity workers

	Cd	Cr	Cu	Fe	Ni	Pb	THI
A-LINE	8.14E-04	5.05E-07	1.19E-03	1.31E-03	8.05E-05	3.05E-03	6.45E-03
B- LINE	9.71E-04	4.67E-07	1.44E-03	1.54E-03	6.20E-05	4.13E-03	8.14E-03
C- LINE	1.19E-03	5.91E-07	1.38E-03	1.81E-03	8.35E-05	2.88E-03	7.34E-03
D- LINE	8.71E-04	3.71E-07	1.50E-03	1.74E-03	9.15E-05	3.65E-03	7.85E-03
F- LINE	1.63E-03	4.38E-07	1.28E-03	1.61E-03	7.80E-05	3.35E-03	7.95E-03
G- LINE	1.07E-03	4.00E-07	1.39E-03	1.80E-03	7.45E-05	3.25E-03	7.59E-03
MEAN	1.09E-03	4.62E-07	1.36E-03	1.64E-03	7.84E-05	3.39E-03	7.55E-03

3.7.3. Results of the total hazard index of trace metals on electricity workers

The values of the total hazard index (THI) for all the locations assessed ranged from 6.45E-03 at A-Line to 8.14E-03 at B-Line (Table 6). This indicates that the THI of all the metals at all the studied locations was less than one (1), as reported by (Rezapour *et al*. (2022) and (Okorie *et al*. (2024). This indicates that exposure to these metals via the soil particles by the electricity workers from the studied locations could result in minimal non-carcinogenic health problems, as reported by (Karimyan *et al*. (2020) and (Khan *et al*. (2022). The THI values of the studied locations followed the following order: B-Line > F-Line > D-Line > G-Line > C-Line > A-Line. Hence, as the non-carcinogenic risks are directly proportional to the THI, the transformer-impacted soil at B-Line showed the highest potential for causing non-carcinogenic risks (Maigari *et al*., 2017, Gan *et al*., 2022). Based on the results in Table 6, it could be deduced that Pb and Cr contributed the highest and lowest proportions of THI at all the studied locations. This conforms to the findings reported by (Bassey and Chukwu (2019) in a related study.

3.7.4. Results of the **incremental lifetime cancer risk** *of carcinogens on electricity workers*

The results of the incremental lifetime cancer risk (ILCR) of the carcinogens (Cd, Cr, Ni, and Pb) at the studied locations are in Table 7. The ILCR values of the metals varied as follows: 4.07E-07 – 8.15E-07, 2.00E-07 – 4.43E-07, 2.11E-06 – 3.11E-06 and 9.78E-08 – 1.40E-07 for Cd, Cr, Ni, and Pb, respectively. Results in Table 7 indicate that Cd, Cr, and Pb belong to the negligible cancer risk category while Ni belongs to the low cancer risk group (Ramadan and Haruna, 2019, USEPA, 1999). Nevertheless, the ILCR values of all the carcinogens were within the acceptable range of 10^{-6}–10^{-4}, according to (USEPA (2011). However, relatively higher ILCR values were recorded for Ni at the studied locations. Consequently, electricity workers exposed to soil particles from the studied locations may experience minimal cancer risks associated with high Ni. The relatively high cancer risks of Ni reported in this study agree with the results obtained by (Tombere *et al*. (2023).

Table 7: Results of incremental lifetime cancer risk of carcinogens on Electricity Workers

	Cd	Cr	Cu	Fe	Ni	Pb	TCR
A-LINE	4.07E-07	3.79E-07	-	-	2.74E-06	1.04E-07	3.63E-06
B- LINE	4.86E-07	3.50E-07	-	-	2.11E-06	1.40E-07	3.09E-06
C- LINE	5.95E-07	4.43E-07	-	-	2.84E-06	9.78E-08	3.98E-06
D- LINE	4.36E-07	2.79E-07	-	-	3.11E-06	1.24E-07	3.95E-06
F- LINE	8.15E-07	3.29E-07	-	-	2.65E-06	1.14E-07	3.91E-06
G- LINE	5.35E-07	2.00E-07	-	-	2.53E-06	1.11E-07	3.38E-06
MIN	4.07E-07	2.00E-07	-	-	2.11E-06	9.78E-08	3.09E-06
MAX	8.15E-07	4.43E-07	-	-	3.11E-06	1.40E-07	3.98E-06

3.7.5. Results of the **total cancer risk** *of carcinogens on electricity workers*

The total cancer risks (TCR) of the carcinogens at all the locations examined varied from 3.09E-06 to 3.98E-06 between Lines B and C, respectively (Table 7). The values of TCR at all the locations were in the low cancer category and within the acceptable range (USEPA, 1999, USEPA, 2011). Hence, soil particles from all the locations investigated may have low-level health problems for the electricity workers. According to the results obtained, Ni was the main contributor to the TCR at each of the locations assessed. The results also showed a decreasing order for TCR as follows: C-Line > D-Line > F-Line > A-Line > G-Line > B-Line. Thus, the transformer-impacted soil at C-Line had the highest cancer-causing potentials, while soil particles at B-Line showed the lowest cancer-causing potentials, similar to the findings by (Aendo *et al*. (2022) and (Cheng *et al*. (2023).

Conclusion

Results obtained from this study revealed that the transformer and the oil could elevate concentrations of metals in the host soil environment. Pollution index models used indicated that all the studied locations were highly contaminated with metals. Multivariate analyses confirmed that the transformer and its oil were good sources of soil contamination by metals. Health risk evaluation revealed that the metals determined might result in low carcinogenic and non-carcinogenic risks for electricity workers exposed to soil particles from the studied locations. However, since metals can bioaccumulate in biological cells for a long time, regular assessments of metal loads in transformer-impacted soils and their related health problems for electricity workers should be performed. Transformers should be maintained properly to avoid leakages of oil into the soil, and unserviceable transformers should be disposed of effectively. Electricity workers should be conversant with the health problems associated with persistent exposure to high levels of metals through contaminated/polluted soil particles.

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