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Assessment of the Climatic Conditions and Health Risk of Potentially Toxic Elements in Ambient Air of Port Harcourt, Rivers State, Nigeria

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Abstract

Air pollution has become a global phenomenon and of great concern. This study investigated the influence of climatic conditions on potentially toxic elements (PTEs – Ni, Cd, As, Cr, Pb) and the associated health risks posed by the elements in selected locations within Port Harcourt, Nigeria. The research spanned from September 2014 to February 2025 covering both dry and wet season and focused on Eleme-Akpajo, Trans-Amadi and GRA-Port Harcourt serving as a control location. Meteorological factors (Temperature, wind speed, relative humidity and wind direction) and PTEs were measured at geolocated stations using air 4250 Kestrel weather trackers and Kanomax 3900 portable counter high volume sampler and Atomic absorption spectrophotometer respectively based on ASTM D1971/4691 standard method. The results indicated that the industrial areas had significantly higher PTE concentrations ($P < 0.05$), influenced by climate conditions and anthropogenic activities, posing serious health concerns. Eleme-Akpajo showed the high average temperature (34.68°C dry season) and correspondingly elevated PTEs concentrations. Average concentrations of Pb, Cd, and Cr exceeded WHO ambient air quality standards in Eleme-Akpajo and Trans-Amadi, particularly during the dry season. There were extremely high EF values for Cadmium in both locations, particularly at Eleme-Akpajo (EF > 3000 in wet season), indicating significant anthropogenic input. Lead and Arsenic also showed elevated EF values above 10, particularly in the wet season, signifying non-crustal sources. Chromium, on the other hand, consistently recorded EF < 1 in both sites and seasons, suggesting a natural origin (crustal). Non-Carcinogenic Risk revealed that HQ for children and adults was >1 in Eleme-Akpajo and Trans-Amadi, indicating a potential for adverse health effects. Cd and Pb were the major contributors. Carcinogenic Risks, CR values for Cr and Cd ranged from 1.2×10^{-4} to 3.4×10^{-4} in Eleme-Akpajo, exceeding the acceptable limit. GRA recorded CR values below 10^{-5}, posing negligible risk. At Eleme-Akpajo, all PTEs loaded equally and positively on PC1, suggesting a strong shared source, most likely industrial emissions. At Trans-Amadi, although PC1 still captured all the variance, the more varied loading patterns indicate the possibility of multiple, less uniformly distributed sources. The nearly equal and opposite values of PC2 at both sites reflect minor influence or variability across the sample matrix, but do not significantly. Continuous monitoring, pollution control, and policy interventions are essential to mitigate environmental health hazards in the city.

Keywords: Assessment, potentially toxic elements, health risk, inhalation, climate weather, Port Harcourt

Introduction

Urbanization and industrialization have both been major contributors to the decline in environmental quality in recent years [1,2]. The increase in population and development in urban areas has led to a rise in pollution, deforestation, and loss of habitat for various species. With industrialization comes an increase in carbon emissions, water pollution, and other harmful by-products of production. The combination of these two factors has resulted in a significant negative impact on the environment. Through careful analysis and citing relevant research, this study delves into the various ways in which urbanization and industrialization have affected environmental quality [3].

The growing impact of urbanization and industrialization on environmental quality has led to increased concerns over air pollution. Urban air pollution remains a growing concern, especially in industrial cities within developing countries. Port Harcourt is a major industrial hub in Nigeria, especially in developing cities in Rivers States [1,2]. Major contributors include petrochemical industries, gas flaring, and vehicular emissions, which release potentially-toxic-elements (PTEs) such as lead (Pb), cadmium (Cd), chromium (Cr), and nickel (Ni) into the atmosphere. These pollutants are persistent, non-biodegradable, and can cause severe health effects upon prolonged exposure [4,5]. Potentially toxic elements are crucial contributors to fine particulate matter ($PM_{2.5}$) and also affect atmospheric chemistry, and climate variation [6,7,8]. Climatic weather conditions such as temperature, humidity, wind speed and wind direction play a vital role in the dispersion, accumulation, transformation of air pollutants [9]. Atmospheric elements are widely present and pose serious risks to human health through inhalation, skin exposure, and ingestion of pollutants [10 - 12]. In particular, heavy metals have received more concern because of their damage to the respiratory, nervous, and cardiovascular systems [13]. Elements such as Sb, Ni, Cr (VI), Cd, Pb, As, and their compounds have been classified as carcinogenic by the International Agency for Research on Cancer of the World Health Organization [14].

In view of the Agency for Toxic Substances and Disease Registry (ATSDR) [15], Ni and Co can harm the respiratory system; Pb can impair children's intelligence and harm fetal development; Cd and As can cause human malformation.

Therefore, atmospheric elements have gained increasing concern recently [16-18].

Understanding the influence of meteorological variables is essential for identifying pollution trends and managing health risks.

This study evaluates PTE levels in selected locations in Port Harcourt, with emphasis on the role of climate and human activities. Enrichment factor analysis and health risk assessments are employed to identify pollution sources and evaluate potentially toxic element risks. The Government Reserved Area (GRA) in Port Harcourt serves as a residential control site for comparison with Eleme-

Akpajo (an industrial and commercial zone) and Trans-Amadi (an industrial and commercial zone).

Materials and Methods

Study Area

Eleme-Akpajo Axis is nn industrial zone that hosts petrochemical plants and the Port Harcourt Refinery. High emissions from industrial activities and gas flaring characterize this area.

Trans-Amadi: A commercial and industrial hub with a mix of manufacturing facilities, moderate traffic, and limited vegetation.

Government Residential Area (GRA**),** Port Harcourt: A low-traffic, well-planned residential area with no industrial activity was selected as a control site.

Sample Collection

Between September 2014 and February 2025, particulate matter ($PM_{2.5}$ and PM_{10}) samples were collected monthly using high-volume samplers positioned at strategic points in each study area. Meteorological data (temperature, wind speed, humidity, and rainfall) were obtained using 4250 Kestrel weather tracker thermometers. All equipment and instruments were calibrated prior to use for quality assurance in order to ascertain the accuracy of the results obtained.

Sample Analysis

Potentially Toxic Elements (Cd, Ni, Cr, As, Cu and Pb) from Study Area

A mini kanomax 3900 portable counter high volume sampler equipment was used to collect total suspended particulate (TSP) on a filter paper. The sampler consists of a

vacuum system and filter housed in a shelter and operates on the same principle as a vacuum cleaner. A known volume of air was drawn through a pre-weighed TSP filter for a 2-hour period.

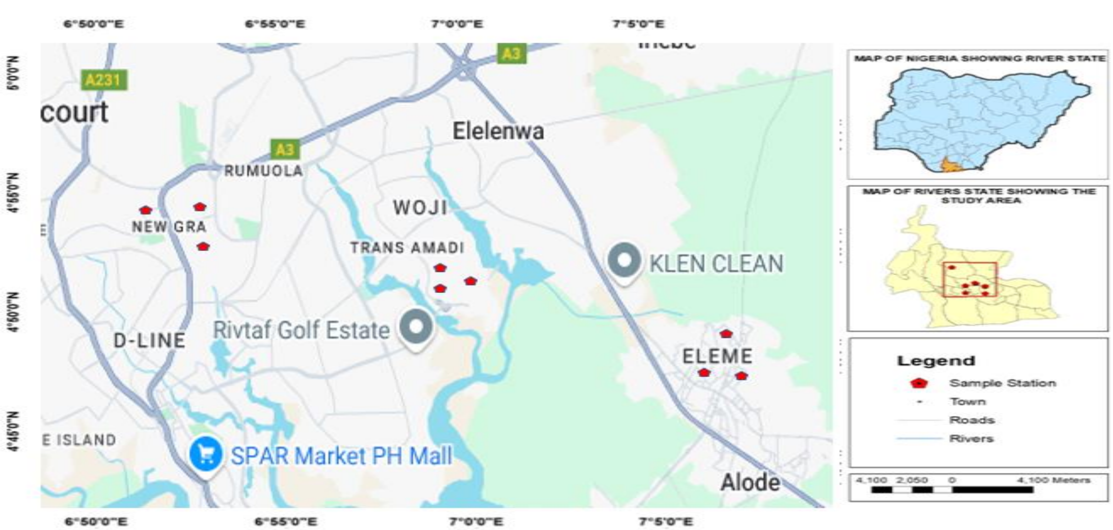

Fig. 1: Map of the study area

The filter is then re-weighed to determine the mass of the particles collected. Whenever the filter is handled, clean forceps were used with disposable gloves. At each station a new TSP filter is used. For better identification; the sampling location was labeled on the outside of the glass petri dish which contains each filter paper. The TSP filters were then taken to Jaros Inspection Services Limited, where it was extracted and analyzed.

The TSP filters were extracted using hot acid digestion. These were done by cutting a 1 × 8 strip from the exposed filter paper. The filter paper was placed in a 250mL quartz beaker. 30mL of the 10% nitric acid were poured onto the filter. It was then reflux gently for 30 minutes at 95 ºC. After refluxing, 10mL of clean deionized water were added and allowed to cool for 30 minutes. The extract was filtered using Whatman 541 filter paper. The samples were diluted with 20mL clean deionized water. The samples were then analyzed using an Atomic Absorption Spectrometer (Perkins Elmer A Analyst 400). Metal concentration was calculated as follows;

$$C = (M_s - M_b) \times V_e \times \frac{F_a}{V} \times F_t \quad (1$$

Where, C = concentration, µg metal/m^3.

M_s = metal concentration, µg/mL

M_b = blank concentration µg/mL

V_e = total volume of extraction in mL

F_a = total area of exposed filter in cm^2

V = Volume of air sampled in m^3

F_t = Area of filter taken for digestion in cm^2

Data Analysis

Enrichment Factor Analysis

Enrichment factor (EF) was used to determine the influence of anthropogenic activities and crustal sources of metal concentrations, ‘Crust” denotes element concentrations in the Earth’s upper crust. Fe, Al, and Si, abundant and stable in the crust, are commonly chosen as reference elements [19]. The EF were calculated using Fe as the reference element [20]:

$$EF = \left(\frac{C_{metal}/C_{Fe}}{(C_{metal}/C_{Fe})_{crust}} \right)$$

EF values close to 1 indicate that elements primarily originate from natural sources with minimum enrichment; values between 1 and 10 suggest mixed sources, with natural sources dominating and slight enrichment from anthropogenic activities; and values ranging from 10 to 100 reflect a more substantial impact of anthropogenic emissions with moderate enrichment, while values exceeding 100 denote a dominance of anthropogenic sources with high enrichment [21, 22].

Health Risk Assessment

Inhalation risk assessment is performed using United States Environmental Protection Agency (USEPA) guidelines [23]. The key metrics evaluated include:

Non-Carcinogenic Risk:

Daily Dose (ADD) and Hazard Quotient (HQ) were calculated for each metal.

HQ > 1 indicates potential health concern.

$$HQ = \frac{ADD}{RfD}$$

Where:

ADD = Average Daily Dose (mg/kg-day)

RfD = Reference Dose for inhalation (mg/kg-day)

Carcinogenic Risk

Cancer risk (CR) was estimated using slope factor (SF):

$$CR = ADD \times SF$$

Where:

SF = Slope Factor $(mg/kg\text{-}day)^{-1}$

Acceptable CR values range from 10^{-6} to 10^{-4} [23].

Table 1: Exposure Guidelines

Parameter	Children	Adults
Inhalation Rate (IR)	10 m³/day	20 m³/day
Exposure Frequency (EF)	350 days/year	350 days/year
Exposure Duration (ED)	6 years	24 years
Body Weight (BW)	15 kg	70 kg
Averaging Time (AT) - Non-cancer	2190 days	8760 days
Averaging Time (AT) - Cancer	25550 days	25550 days

[24]

Statistical Analysis

Pearson correlation *assessed relationships between PTEs and weather conditions.*

T-test *compared pollutant levels across sites.*

Factor analysis and Principal Component Analysis *were used to identify pollution sources and reduce data dimensionality.*

Table 2: Toxicological Parameters

Element	RfD (mg/kg/day)	Slope Factor (SF) $[(mg/kg/day)^{-1}]$
Copper	0.04	Not classified
Cadmium	0.00001	6.1
Lead	0.0008	0.0085
Chromium(VI)	0.0001	41.0
Arsenic	0.0003	15.1
Nickel	0.0002	0.91

[23 ,24].

Results and Discussion

Potentially Toxic Elements Levels

Eleme-Akpajo: The concentration of potentially-toxic-elements (PTEs) in Eleme-Akpajo Table 3 was significantly higher during the dry season compared to the wet season. Copper increased from 0.069 mg/kg to 0.602 mg/kg ($p = 0.01$), cadmium from 0.394 mg/kg to 0.876 mg/kg ($p = 0.01$), and lead from 0.569 mg/kg to 1.145 mg/kg ($p = 0.03$). These increases are statistically significant, indicating intensified emissions or decreased atmospheric dispersion in the dry period. The increase could be attributed to reduced dilution from rainfall and possible increased anthropogenic activities such as open burning or industrial discharge during the dry period [25].

Dry season accumulation of dust particles may also increase airborne metal deposition [26]. Chromium also increased significantly from 0.105 mg/kg to 0.375 mg/kg, ($p = 0.05$), whereas arsenic and nickel did not show significant changes ($p > 0.05$). These patterns suggest the dominance of industrial emissions especially from petrochemical plants and gas flaring that may intensify in drier conditions due to lack of atmospheric scavenging.

Table 3: Levels of PTEs and Meteorological Characteristics at Eleme-Akpajo Location

	Eleme--Akpajo E Wet Season			Eleme--Akpajo Dry- Season			
PTEs (mg/kg)	Mean	Min	Max	Mean	Min	Max	P-Value
Copper	0.069	0.00	0.24	0.602	0.22	1.22	0.01
Cadmium	0.394	0.07	0.88	0.876	0.49	1.26	0.01
Lead	0.569	0.14	0.96	1.145	0.43	2.32	0.03
Chromium	0.105	0.01	0.34	0.375	0.22	0.56	0.05
Arsenic	0.024	0.00	0.05	0.026	0.00	0.09	0.25
Nickel	0.353	0.03	0.84	0.513	0.04	0.98	0.16
		Meteorological Parameters					
Temp (0C)	31.550	27.60	33.90	34.683	29.40	42.70	0.06
Rel.H (%)	76.933	61.20	86.00	65.133	51.10	74.00	0.05
WS (km/hr)	7.773	1.50	14.80	7.217	5.00	9.40	0.43
Wind Direction		WSW- SW			WSW - SW		

$P < 0.05$ is significant

Table 4: Levels of PTEs and Meteorological Characteristics at Trans-Amadi Location

	Trans-Amadi Wet Season			Trans-Amadi Dry Season			
PTEs (mg/kg)	Mean	Min	Max	Mean	Min	Max	P-Value
Copper	0.015	0.01	0.02	0.043	0.01	0.08	0.25
Cadmium	0.028	0.01	0.06	0.178	0.00	0.55	0.08
Lead	0.078	0.07	0.09	0.121	0.03	0.18	0.06
Chromium	0.010	0.01	0.01	0.033	0.01	0.06	0.29
Arsenic	<0.001	0.00	0.00	<0.001	0.00	0.00	NA
Nickel	0.030	0.01	0.06	0.108	0.02	0.21	0.07
		Meteorological Parameters					
Temp (0C)	34.533	32.70	38.80	37.783	34.10	44.70	0.10
Rel.H (%)	66.900	48.60	79.40	47.133	30.80	57.00	0.03
WS (km/hr)	6.150	2.20	13.00	4.833	3.00	8.60	0.27
Wind Direction		SW			N		

$P < 0.05$ is significant

The meteorological parameters reinforce this interpretation: the average temperature rose from 31.55°C to 34.68°C, while relative humidity dropped significantly from 76.93% to 65.13% ($p = 0.03$). Wind speed remained relatively stable ($p = 0.41$), while wind direction consistently blew from WSW-SW, indicating potential pollutant transport from nearby industrial zones.

This aligns with previous findings that dry seasons exacerbate the accumulation of heavy metals due to low rainfall and limited atmospheric cleansing [1]. Additionally, the increased temperature can enhance volatilization and chemical reactivity of airborne pollutants [2].

Table 5: Levels of PTEs and Meteorological Characteristics at GRA-Port Harcourt Location

	GRA Wet Season			GRA Dry Season			
PTEs (mg/kg)	Mean	Min	Max	Mean	Min	Max	P value
Copper	ND	ND	ND	ND	ND	ND	NA
Cadmium	ND	ND	ND	ND	ND	ND	NA
Lead	ND	ND	ND	ND	ND	ND	MA
Chromium	ND	ND	ND	ND	ND	ND	NA
Arsenic	ND	ND	ND	ND	ND	ND	NA
Nickel	ND	ND	ND	ND	ND	ND	NA
		Meteorological Parameters					
Temp (0C)	31.22	29.60	33.40	35.68	32.10	37.80	0.00
Rel.H (%)	68.72	59.50	72.00	55.52	47.00	73.60	0.01
WS (km/hr)	8.50	5.00	13.00	5.70	4.00	8.60	0.04
Wind Direction	SW - NW			S - NW			

$P < 0.05$ is significant

Table 6: Correlation Coefficient Matrix of Eleme-Akpajo Location for Wet Season

Eleme-Akpajo Wet Season Correlations

	Copper	Cadmium	Lead	Chromium	Arsenic	Nickel	Temp	Rel.H	W.Speed
Copper	1								
Cadmium	-0.115	1							
Lead	-0.898	0.709	1						
Chromium	0.015	**.992****	0.538	1					
Arsenic	**-1.000****	**-1.000****	**1.000****	**-1.000****	1				
Nickel	0.139	**.979****	0.580	**.987****	**-1.000****	1			
Temp	0.400	0.712	0.560	0.597	**-1.000****	0.757	1		
Rel. H	0.364	-0.385	-0.480	0.183	**1.000****	-0.417	-0.587	1	
W. Speed	-0.210	-0.069	-0.184	-0.506	**-1.000****	-0.011	-0.237	-0.541	1

**. Correlation is significant at the 0.01 level (2-tailed).

Table 7: Correlation Coefficient Matrix of Eleme-Akpajo Location for Dry Season

Eleme-Akpajo Dry Season Correlations									
	Copper	Cadmium	Lead	Chromium	Arsenic	Nickel	Temp	Rel.H	W.Speed
Copper	1								
Cadmium	0.625	1							
Lead	-0.538	-0.141	1						
Chromium	-0.138	0.168	0.479	1					
Arsenic	-0.487	-0.192	0.946	**1.000****	1				
Nickel	0.690	**.932****	-0.402	0.174	-0.446	1			
Temp	0.250	0.667	-0.385	0.387	**-0.906**	**.814***	1		
Rel.H	0.003	-0.263	0.431	0.408	0.646	-0.402	-0.434	1	
W.Speed	-0.123	-0.585	-0.512	-0.784	-0.557	-0.419	-0.396	-0.437	1

**. Correlation is significant at the 0.01 level (2-tailed).
*. Correlation is significant at the 0.05 level (2-tailed).

Table 8: Correlation Coefficient Matrix of Trans-Amadi Location for Wet Season

Trans-Amadi Wet Season Correlations									
	Copper	Cadmium	Lead	Chromium	Arsenic	Nickel	Temp	Rel. H	W. Speed
Copper	1								
Cadmium	**-1.000****	1							
Lead	**-1.000****	0.725	1						
Chromium	.[b]	.[b]	.[b]	.[b]					
Nickel	.[b]	-0.719	-0.272	.[b]	.[b]	1			
Temp	**-1.000****	-0.156	-0.074	.[b]	.[b]	-0.614	1		
Rel.H	**1.000****	0.209	0.145	.[b]	.[b]	0.478	**-.936****	1	
W. Speed	**-1.000****	-0.508	-0.570	.[b]	.[b]	0.298	-0.097	0.172	1

**. Correlation is significant at the 0.01 level (2-tailed).
b. Cannot be computed because at least one of the variables is constant.

Table 9: Correlation Coefficient Matrix of Trans-Amadi Location for Dry Season

Trans-Amadi Dry Season Correlations

	Copper	Cadmium	Lead	Chromium	Arsenic	Nickel	Temp	RH	W. Speed
Copper	1								
Cadmium	0.887	1							
Lead	0.862	0.267	1						
Chromium	0.770	**.965***	0.521	1					
Arsenic	.[a]	.[a]	.[a]	.[a]	.[a]				
Nickel	.[a]	-0.919	0.544	.[a]	.[a]	1			
Temp	-0.478	0.026	-0.481	0.151	.[a]	-0.363	1		
RH	0.596	0.065	0.667	-0.034	.[a]	0.375	**-.952****	1	
W. Speed	-0.319	0.275	-0.512	0.358	.[a]	-0.596	**.942****	**-.892***	1

*. Correlation is significant at the 0.05 level (2-tailed).
**. Correlation is significant at the 0.01 level (2-tailed).
a. Cannot be computed because at least one of the variables is constant.

Trans-Amadi

Trans-Amadi also exhibited higher dry season concentrations for most elements (Table 4), although fewer differences were statistically significant. Copper increased from 0.015 mg/kg to 0.043 mg/kg, cadmium from 0.028 mg/kg to 0.178 mg/kg, and lead from 0.078 mg/kg to 0.121 mg/kg, with p-values close to significance thresholds (0.08 and 0.06). Nickel also rose from 0.030 mg/kg to 0.108 mg/kg (p = 0.07). Chromium increased modestly, while arsenic remained below detection limits in both seasons. The modest increases in PTEs and borderline p-values suggest a potential seasonal effect, but the relatively lower concentrations compared to Eleme-Akpajo point to less intense sources of pollution, possibly from mixed-use traffic and smaller-scale industry. Meteorologically, temperature increased from 34.53°C to 37.78°C (p = 0.05), while relative humidity dropped significantly from 66.90% to 47.13% (p = 0.01). Wind speed slightly reduced but not significantly (p = 0.23). These conditions likely contributed to decreased atmospheric dispersion and higher pollutant accumulation, as seen in other studies linking low humidity to elevated PM-bound metal concentrations (3).

GRA Port Harcourt (Control Site)

No potentially toxic elements were detected in GRA (Table 5) during either season (marked as ND, not detected). This supports the hypothesis that GRA, being a low-industrial and low-traffic residential area, is minimally impacted by anthropogenic emissions. However, there were significant differences in climatic variables between seasons. Temperature increased from 31.22°C to 35.68°C (p = 0.00), relative humidity dropped from 68.72% to 55.52% (p = 0.01), and wind speed decreased from 8.50 km/h to 5.70 km/h (p = 0.04). The wind direction shifted slightly from SW–NW to S–NW. Despite these changes, the absence of detectable PTEs suggests a cleaner atmosphere, validating the use of GRA Port Harcourt as a control.

Comparing the three locations: Eleme-Akpajo consistently recorded the highest concentrations of PTEs, especially during the dry season, with significant increases in copper, cadmium, lead, and chromium. This reinforces its classification as a high-pollution industrial site. Trans-Amadi, while also showing increased dry season concentrations, had generally lower levels and fewer statistically significant differences, reflecting moderate industrial and vehicular emissions. GRA displayed no detectable PTEs, indicating negligible pollution load and affirming its status as a residential control.

The consistent seasonal trend of higher PTE concentrations in the dry season across Eleme-Akpajo and Trans-Amadi can be attributed to lower rainfall and humidity, reducing pollutant scavenging, and to increased dry season industrial activity, as corroborated in similar urban-industrial studies [4,5].

Correlation Analysis

Correlation analysis provides insight into the strength and direction of relationships among potentially toxic elements (PTEs) and meteorological parameters across Eleme-Akpajo (Tables 6, 7) and Trans-Amadi (Tables 8, 9) during wet and dry seasons. Significant relationships ($p < 0.01$ and $p < 0.05$) are highlighted, offering possible shared sources, synergistic effects, or environmental behaviour patterns.

The Eleme-Akpajo wet season recorded strong negative correlations: between Copper–Lead ($r = -0.898$) and Copper–Arsenic ($r = -1.000$) suggesting antagonistic relationships or different anthropogenic sources. A perfect correlation (positive and negative) was observed between Lead–Arsenic ($r = 1.000$) and Cadmium–Arsenic ($r = -1.000$): with arsenic pointing to a deterministic association likely due to common emissions, possibly from industrial activities or combustion processes. A strong positive correlation existed between Cadmium–Chromium ($r = 0.992$), Cadmium–Nickel ($r = 0.979$), and Chromium–Nickel ($r = 0.987$) indicating that these metals may originate from similar sources such as waste incineration or metallurgical processes [7]. The meteorological revealed that Arsenic shows perfect negative correlation with temperature ($r = -1.000$) and positive with Relative Humidity ($r = 1.000$), suggesting its concentration decreases as temperature rises, with potentially due to volatilization or dispersion [26]. The Eleme-Akpajo dry season shows significant positive correlations between Cadmium–Nickel ($r = 0.932$) and Arsenic–Chromium ($r = 1.000$). This suggests common industrial sources such as petrochemical discharge, welding, or smelting. There was a strong inverse correlation between

Arsenic–Temperature (r = -0.906). This again suggests arsenic concentrations decline with rising temperatures, consistent with wet season trends. Wind Speed–Chromium (r = -0.784) Wind may facilitate dispersion of airborne chromium particles.

At Trans-Amadi during wet season, a perfect negative correlation was observed between Copper–Cadmium, Copper–Lead, Copper–Temp, Copper–Wind Speed (r = -1.000) implying a uniform inverse relationship, possibly from vehicular or industrial pollution under similar environmental conditions. Also observed was a perfect positive association between Copper–Relative humidity (r = 1.000): Copper levels may rise with higher humidity, possibly due to reduced dispersion.

Chromium values were constant ("b" entries), so correlations could not be computed, which limits interpretation for that element. At dry season, a strong positive relationship was recorded between Cadmium–Chromium (r = 0.965) and Chromium–Copper (r = 0.770). This reflects similar sources in dry conditions, possibly industrial emissions re-suspended by dust [27]. Meteorological interactions revealed strong associations between wind speed and Temp (r = 0.942) and wind speed and Relative humidity (r = -0.892). This suggests that wind disperses metals more when temperature is high and relative humidity is low. Strong positive correlations among Cd, Ni, Cr across seasons and sites suggest consistent industrial or combustion sources [28].

Influence of meteorology with negative correlations of metals with temperature and wind speed imply dispersion and dilution in dry and hot conditions, while higher relative humidity may increase metal retention in the atmosphere [29].

Enrichment Factor (EF) Analysis

The Enrichment Factor (EF) is an important indicator for distinguishing the origin of potentially toxic elements (PTEs) in the atmosphere. EF values <1 suggest crustal or natural sources, values between 1–10 indicate mixed sources, while values >10 imply significant anthropogenic influence.

Table 10: Enrichment Factor (EF) of PTEs in Wet and Dry Seasons

(a) Eleme-Akpajo

Element	EF (Wet)	EF (Dry)
Cadmium	3140.58	800.33
Lead	26.68	6.15
Chromium	0.84	0.34
Arsenic	12.75	1.58
Nickel	3.75	0.62

(b) Trans-Amadi

Element	EF (Wet)	EF (Dry)
Cadmium	1026.67	2276.74
Lead	16.82	9.10
Chromium	0.37	0.42
Arsenic	12.22	4.26
Nickel	1.47	1.84

The Enrichment Factor analysis (Tables 10) reveals extremely high EF values for Cadmium in both locations, particularly at Eleme-Akpajo (EF > 3000 in wet season),

indicating significant anthropogenic input, likely from industrial activities such as oil refining and petrochemical operations. Lead and Arsenic also showed elevated EF values above 10, particularly in the wet season, signifying non-crustal sources. Chromium, on the other hand, consistently recorded EF < 1 in both sites and seasons, suggesting a natural origin (crustal) [30].

Principal Component Analysis (PCA)

Principal Component Analysis (PCA) was conducted to identify common source patterns and simplify the complexity of PTE relationships. At Eleme-Akpajo (Table 11), all PTEs loaded equally and positively on PC1, suggesting a strong shared source, most likely industrial emissions. At Trans-Amadi, although PC1 still captured all the variance, the more varied loading patterns indicate the possibility of multiple, less uniformly distributed sources. The nearly equal and opposite values of PC2 at both sites reflect minor influence or variability across the sample matrix, but do not significantly [31].

Table 11: PCA Loadings and Variance Explained

(a) Eleme-Akpajo

Component	Copper	Cadmium	Lead	Chromium	Arsenic	Nickel
PC1	0.408	0.408	0.408	0.408	0.408	0.408
PC2	0.913	-0.183	-0.183	-0.183	-0.183	-0.183

Explained Variance: PC1 = 100.00%, PC2 = ~0%

(b) Trans-Amadi

Component	Copper	Cadmium	Lead	Chromium	Arsenic	Nickel
PC1	-0.447	-0.447	-0.447	-0.447	-0.000	-0.447
PC2	-0.894	0.224	0.224	0.224	0.000	0.224

Explained Variance: PC1 = 100.00%, PC2 = ~0%

Table 12: Non-Carcinogenic Risk (Hazard Quotient - HQ) of PTEs by Inhalation

Site	Element (Season)	Child HQ	Adult HQ
Eleme-Akpajo	Copper (Wet)	0.0022	0.0001
	Copper (Dry)	0.0192	0.0010
	Cadmium (Wet)	50.37	2.70
	Cadmium (Dry)	112.00	6.00
	Lead (Wet)	0.91	0.05
	Lead (Dry)	1.83	0.10
	Chromium (Wet)	1.34	0.07
	Chromium (Dry)	4.79	0.26
	Arsenic (Wet)	0.10	0.005
	Arsenic (Dry)	0.11	0.006
	Nickel (Wet)	2.26	0.12
	Nickel (Dry)	3.28	0.18
Trans-Amadi	Copper (Wet)	0.0005	0.00003
	Copper (Dry)	0.0014	0.00007
	Cadmium (Wet)	3.58	0.19
	Cadmium (Dry)	22.76	1.22
	Lead (Wet)	0.12	0.007
	Lead (Dry)	0.19	0.01
	Chromium (Wet)	0.13	0.007
	Chromium (Dry)	0.42	0.02
	Nickel (Wet)	0.19	0.01
	Nickel (Dry)	0.69	0.037

Table 13: Carcinogenic Risk (CR) of PTEs by Inhalation

Site	Element (Season)	Child CR	Adult CR
Eleme-Akpajo	Cadmium (Wet)	2.63×10^{-4}	5.64×10^{-5}
	Cadmium (Dry)	5.86×10^{-4}	1.25×10^{-4}
	Lead (Wet)	5.30×10^{-7}	1.14×10^{-7}
	Lead (Dry)	1.07×10^{-6}	2.29×10^{-7}
	Chromium (Wet)	4.72×10^{-4}	1.01×10^{-4}
	Chromium (Dry)	1.68×10^{-3}	3.61×10^{-4}
	Arsenic (Wet)	3.97×10^{-5}	8.51×10^{-6}
	Arsenic (Dry)	4.30×10^{-5}	9.22×10^{-6}
	Nickel (Wet)	3.52×10^{-5}	7.54×10^{-6}
	Nickel (Dry)	5.12×10^{-5}	1.10×10^{-5}
Trans-Amadi	Cadmium (Wet)	1.87×10^{-5}	4.01×10^{-6}
	Cadmium (Dry)	1.19×10^{-4}	2.55×10^{-5}

Site	Element (Season)	Child CR	Adult CR
	Lead (Wet)	7.27×10^{-8}	1.56×10^{-8}
	Lead (Dry)	1.13×10^{-7}	2.42×10^{-8}
	Chromium (Wet)	4.49×10^{-5}	9.63×10^{-6}
	Chromium (Dry)	1.48×10^{-4}	3.18×10^{-5}
	Nickel (Wet)	2.99×10^{-6}	6.41×10^{-7}
	Nickel (Dry)	1.08×10^{-5}	2.31×10^{-6}

Non-carcinogenic and Carcinogenic Health Risk Assessment

The results (Table 12) revealed alarming non-carcinogenic risks (HQ > 1) associated primarily with cadmium (Cd) at Eleme-Akpajo during both wet and dry seasons. Inhalation exposure to cadmium, especially among children, significantly exceeded the safety threshold, indicating a potential for kidney dysfunction, bone demineralization, and pulmonary damage [23, 27]. Similarly, lead (Pb) also demonstrated moderate HQ values >1 during the dry season, particularly for children. Lead exposure is notorious for its neurodevelopmental toxicity in children, affecting cognitive function, behaviour, and learning abilities.

Carcinogenic risks (CR) (Table 13) were also prominently high, with cadmium presenting values well above the acceptable regulatory limit of 1.0E-04 in Eleme-Akpajo [23,33]. Chronic exposure to cadmium via inhalation has been linked to lung cancer and damage to the respiratory system [34]. Arsenic (As), although present in lower concentrations, showed CR values above the threshold in both children and adults, posing a risk for cancers of the lung, bladder, and skin [14]. The presence of CR values above safe levels for other metals like nickel (Ni) and chromium (Cr) further raises concerns, as these elements are associated with increased risks of respiratory illnesses, allergic reactions, and cancer with prolonged exposure [15].

The elevated values of both HQ and CR in Eleme-Akpajo, particularly during the dry season, indicate a significant health threat to nearby residents. Children appear to be at greater risk due to their higher breathing rates and susceptibility to toxicants. This calls for immediate policy and environmental intervention strategies, including emission regulation and public health monitoring. While Trans-Amadi exhibited comparatively lower risk values, the presence of measurable CRs and HQs still warrants proactive surveillance and mitigation strategies.

Conclusion

The Eleme-Akpajo axis is a hotspot for both carcinogenic and non-carcinogenic risks, primarily due to emissions from petrochemical and industrial activities. Seasonal variation exacerbates risks, with dry season conditions (high temperature, low humidity, low wind) favoring accumulation of potentially toxic elements (PTEs). Trans-Amadi exhibits lower but non-negligible risks, whereas GRA remains clean and serves as a valid control.

Recommendation

Continuous monitoring, pollution control, and policy interventions are essential to mitigate environmental health hazards in the city.

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