Advances in Environmental Technology 2 (2021) 101-118

Iranian Research Organization for Science and Technology (IROST)

Advances in Environmental Technology

Journal home page: https://aet.irost.ir/

Source, geochemical spreading and risks of trace metals in particulate matter 2.5 within a gas flaring area in Bayelsa State, Nigeria

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ARTICLE INFO

Article history:
Received 7 July 2021
Received in revised form
9 November 2021
Accepted 13 November 2021

Keywords:
Air quality
Source of air trace metals
Metal enrichment
Ecological risk
Environmental health

ABSTRACT

The study investigated the source, geochemical spreading and risks assessment of trace metals in particulate matter 2.5 ($PM_{2.5}$) within a gas flaring area in Bayelsa State, Nigeria. $PM_{2.5}$ was measured using Geintek Particulate matter sampler APM131 monitor. Seven locations within 3000 m of the gas flaring area were sampled, with a control location established at about 7000 m from flare stark. The trace metals trapped in the $PM_{2.5}$ were analyzed using flame atomic absorption spectrometry. The mean level of trace metals ranged from 2.75 – 7.56 $\mu g/m^3$, 0.03 – 2.82 $\mu g/m^3$, 0.16 – 1.11 $\mu g/m^3$, 0.32 – 1.02 $\mu g/m^3$, 1.32 – 3.34 $\mu g/m^3$, and 0.15 – 2.07 $\mu g/m^3$ for iron, manganese, nickel, lead, zinc and vanadium, respectively. There was statistical dissimilarity ($P < 0.05$) across study stations for nickel, iron and zinc, and no significant variation ($P>0.05$) for manganese, vanadium and lead. Pollution indices and index of geoaccumulation showed low to moderate contamination. The overall risk index reveals a low hazard. The enrichment factor and principal components analysis showed the metals are from anthropogenic and natural sources. Zinc correlates strongly with iron, manganese and nickel, an indication that these metals are from similar sources. The carcinogenic and non - carcinogenic hazards were within the threshold limits of 10^{-6} to 10^{-4} and <1, respectively. Based on the result, there are no hazardous health effects resulting from the inhalation of trace metals in $PM_{2.5}$ for the age bracket being studied. However, there is a need to constantly monitor the level of these metals in the air via routine emission monitoring to forestall possible health risks.

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DOI: 10.22104/AET.2021.5053.1368

1. Introduction

Nigeria is a key crude oil-producing country with its oil and gas operations predominantly executed in the Niger Delta region. Bayelsa state is one of the core oil and gas explorations and producing states in the country. A substantial amount of gas produced is flared into the atmosphere, where they negatively impact the quality of air and the environment in general [1]. Trace metals are found in crude oil. Hence, traces of the metals tend to occur in produced gas and flares. In many regions of the world, air pollution reduction policies have not been met, especially in developing nations. The air quality guideline provided by World Health Organization (WHO) showed a threshold for health effects associated with air contamination [2]. The report further revealed that about 91% of the world population resides in regions where the air quality guidelines are inadequate as of 2016. Air pollution is associated with both indoor and outdoor pollutants in urban and rural areas. Poor air quality is a contributing factor to some critical human diseases which have led to the loss of lives. According to WHO ambient (outdoor) air contamination [2], a decline in air contaminants could lead to a decrease in the disease burden, especially cardiovascular and respiratory diseases, on both short and long term basis. In 2016, about 4.2 million untimely deaths were related to outdoor air contamination across the world, with 91% of deaths occurring mainly in low and middle-income nations and a significant number occurring in South-East Asia and Western Pacific regions of WHO ranked areas [2]. Particulate matters are particles (solid) and droplets (liquid) that can be dispersed into the air [3]. They enter the air directly through human activities and the chemical transformation of gaseous pollutants (natural processes) [3]. According to Chen and Kan [4], scientific evidence shows that particulates can lead to case mortality, especially in patients with cardiovascular and respiratory problems, and morbidity leading to hospital admissions, respiratory infection etc. Among the various particulates, $PM_{2.5}$ microns or less in diameter) and PM_{10} (10 micrometres in diameter) are the most important. The quantitative relationship associated with these particulates and their potential to increase mortality has been established [2]. Studies have shown that trace metals (metalloids of about five times denser than water) [5,6] are found in different environmental components, including surface water [6], soil [7], air [8], vegetables [9], beverages [10], fishes [11-16], meat [17] among others. Essential trace metals play useful roles in living organisms at specific concentrations, whilst they become deleterious to consumer health at excessive levels. Also, the non-essential metals possess no biological functions, thereby portending toxicity even at low concentrations. The roles and health hazards associated with some trace metals have been extensively documented by Izah et al. [5], Prashanth et al. [18], and Muhammad et al. [19]. The concentration of atmospheric $PM_{2.5}$ has been studied in many regions of the world including Nigeria. For instance, a daily average concentrations range of 15.30 - 70.20 $\mu g/m^3$ was reported within the Abuja metropolis [20], 14.4 – 986.5 $\mu g/m^3$ in an industrial area along with Ife–Ibadan highway [21]. Also, concentrations of 30 - 100 $\mu g/m^3$ were reported in some major cities in Nigeria [22], while some industrial sites in Northern Nigeria recorded ranges between 11.71 and 45.11 $\mu g/m^3$ [23]. In addition, concentrations ranging from 5 - 248 $\mu g/m^3$ have been reported in some areas in Nigeria between 1985 and 2015 [24]. Furthermore, waste dumpsites in Bayelsa, Delta, Abia and Rivers states have recorded levels between 26.44 and 40.10 $\mu g/m^3$ [25]. $PM_{2.5}$ levels recorded in Nigeria often exceeds the WHO and NAAQS limits of 25 $\mu g/m^3$ and 35 $\mu g/m^{3,}$ respectively. Metalloids concentrations in $PM_{2.5}$ have not been extensively documented in the same way as $PM_{2.5}$ particulate amounts have been reported in developing countries like Nigeria. In few instances that trace metals have been studied in $PM_{2.5}$, the values are only compared with regulatory limits. These comparative studies mainly were inadequate as they were unable to provide vital information concerning the hazard level of the respective metals of concern [6,26]. Hence, studies have developed a risk assessment approach for trace metals in the environment, as well as its predictable health effect on humans that are exposed to the toxicants. In addition, information on the Source of trace metals in $PM_{2.5}$ is scanty in the literature. Several statistical tools, including

Hierarchical cluster analysis (HCA), principal component analysis (PCA) and correlational analysis (CA) are useful tools used in determining trace metals in an environmental component. The focus of the study is to determine the Source, geochemical spreading, ecological and human health risks of trace metals in $PM_{2.5}$ around a gas flaring area in Bayelsa State, Nigeria. The findings of this study will provide information about the concentration of trace metals in $PM_{2.5,}$ as well as estimating the potential human health risks associated with exposure to atmospheric trace metals. It will be helpful to residents of the area and appropriate government agencies who will rely on this information to improve their regulatory duties.

2. Materials and methods

2.1. Study area

The study was carried out around a gas production and flaring gas area in Yenagoa local government area of Bayelsa State. Also, a control station was established within a tertiary institution in Ogbia local government area of the same State. The study region is a tropical rainforest region that is surrounded by a plethora of water bodies. The land surface area is seasonally flooded from overflowing or encroaching surface water bodies, mainly from the tributaries of a lower Niger River. Like other parts of the Niger, there are two distinctive seasons, viz wet and dry. The relative humidity and temperature range from 50.0 – 95.0 % and 28 ± 8°C throughout the year [7]. In addition, fishing, small scale farming and petty trading are the primary occupations of the indigenous people of this area.

2.2. Sample design

The sampling stations are numbered AQ1 to AQ8, with AQ1 to AQ7 being in the area around the gas flaring vicinity (approximately within 3000 m from the flaring station), while AQ8 (tagged as control) is located at over 10,000 m from the gas flaring station (Figure 1). In each of the stations, triplicate values (triplicate values from each stations were denoted as a, b and c) were obtained. Hence, a total of 24 samples were obtained from the eight (8) sampling locations (stations). The sampling was done between January to May 2019.

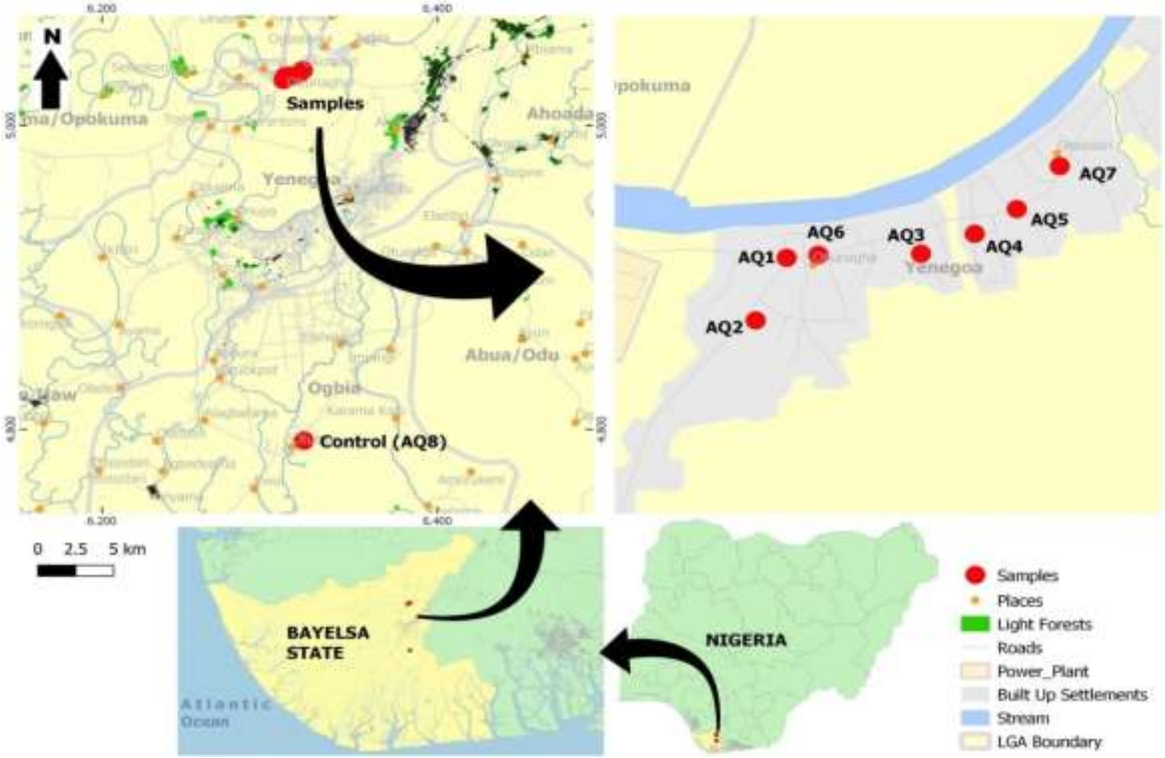

Fig. 1. Map of a gas flaring area in Bayelsa State, Nigeria, showing the sampling locations.

2.3. Sample collection and trace metal analysis

The particulate matter of the study area was measured at ambient atmospheric conditions using Geintek particulate matter sampler (model APM131). The sample was measured at the height of ≥ 3 m from the soil level. Samples were collected, prepared and trace metal analysis was carried out following the method comprehensively documented by Uzoekwe et al. [27].

2.4. Environmental Risk of trace metals in $PM_{2.5}$

Different background or baseline data have been used to estimate the environmental risk of trace metals in the environment. However, in many parts of the world, pre-industrial or baseline data are unavailable. As such, many studies have applied several data as background values, including the control (an area designated as uncontaminated within the same study location). Geometric mean value of a set of data is now commonly used as background values when calculating risk assessment of trace metals in soil [7], groundwater [28], surface water [29], sediment [29,30] and air [27]. Hence, the use of geometric mean was adopted for the environmental risk assessment in this study. In few instances where the concentration of metals is zero, 50% of the mean metal values for the remaining locations were the assumed values [28]. This was done prior to assessing the environmental risks. The scheme provided by Hakanson [31], and applied by Uzoekwe et al. [27] was used to estimate the contamination factor (CF*i*), degree of contamination (CD*i*) and ecological Risk (ER*i*) and risk index (ERI*i*). For the ER*i* calculation, the toxic factor used were Mn = 1, Ni=5 [32 – 34], Pb =5 and Zn = 1 [31]. Other indices applied in this study followed the description of the authors. For instance, pollution load index (PLI*i*) described by Tomlinson et al. [35] and applied by Bhutiani et al. [28] , index of geoaccumulaton (I-GEO*i*) as developed by Muller [36] and applied by Bhutiani et al. [28], as well as enrichment factor (EF*i*) estimated following descriptions previously applied by Bhutiani et al. [28], Kowalska et al. [37]. For EF*i* computation, iron was used as the normalization metal [27].

2.5. Human health risk assessment

The human health risk of trace metals in $PM_{2.5}$ was computed for carcinogenicity (for nickel) and non-carcinogenicity (for manganese, nickel, zinc and lead). The risk was computed under two scenarios viz: adult (with bodyweight of 70kg; inhalation rate = $0.9 m^3$/hour, exposure time =24 hours/day) and child (with bodyweight of 15kg, inhalation rate = $0.7 m^3$/hour, exposure time =24 hours/day) [38,39]. The carcinogenic and non - carcinogenic hazard (risk) of trace metals in $PM_{2.5}$ reported by Vaio et al. [39], and simplified by Uzoekwe et al. [27]was applied for this study.

Carcinogenic risk = $\frac{EFi*EDi*Ci*IUR*1000}{AT*365}$

Non-carcinogenic hazard (target hazard quotients) = $\frac{EFi*EDi*Ci}{AT*365*RFCi}$

Where Ci is the level of the metals in mg/m^3, EFi is the exposure frequency = 350 day/year for both adult and child; exposure duration (EDi) for adult and child were 24 years and 6 years, respectively [38], average lifetime (AT) non-carcinogenic risk is ED x 365 days/year, and carcinogenic risk is 70 (for both adult and child) x 365 day/year [39]. The reference concentration (RFCi) were 5.00×10^{-5} mgm^{-3} (manganese and nickel) [39,40], 1.00×10^{-4} mgm^{-3} (vanadium) [39], 3.50×10^{-3} mgm^{-3} (lead) [41], and inhalation unit risk (IUR) is 2.40×10^{-4} $(\mu gm^{-3})^{-1}$ and 8.00×10^{-5} $(\mu gm^{-3})^{-1}$ for nickel and lead respectively [40]. The carcinogenic hazard (risk) ranged from 10^{-6} to 10^{-4} [6,27,39,42]. Thus, the values lesser than 10^{-6} for individual and combined trace metals indicate insignificant cancer risk. Also, when the non-carcinogenic hazard value exceeds 1 it depicts a potential non-carcinogenic hazard, whilst values < 1 reflects no possible adverse health implication [6,27,39,42].

2.6. Statistical analysis

The statistical analysis was done using SPSS version 20. Descriptive statistics (mean, standard deviation, minimum (MIN) and maximum (MAX) was computed, and the values were presented as a box plot. One-way analysis of variance (ANOVA) is used to determine whether there are any statistically significant differences between the means values of the different locations. Where statistical dissimilarity occurred, Waller-Duncan test statistics were used to discern the Source of the variations. The CA, HCA and PCA was carried out to show the Source of the trace metals. For the PCA, Factor ≥ 0.5 indicates the level of significance [39,43].

3. Results and discussion

3.1. Concentration of trace metals in atmospheric $PM_{2.5}$

Figure 2 shows the concentration of trace metals in atmospheric $PM_{2.5}$ around flaring area in Bayelsa state, Nigeria. The mean concentration for iron ranged from 2.75 – 7.56 μg/m^3. The MIN (0.23 μg/m^3) and MAX (16.12 μg/m^3) concentration were recorded in AQ2. Statistically, there was no discrepancy ($p > 0.05$) across the different locations. Manganese concentration ranged from 0.03 – 2.82 μg/m^3. The MIN (0.00 μg/m^3) and MAX (3.55 μg/m^3) concentration were recorded in two location clusters (AQ1 and AQ2) and AQ7, respectively. Apart from AQ7, there was no significant variation ($P > 0.05$) among the various locations. The mean nickel level ranged from 0.16 – 1.11 μg/m^3. The MIN (0.09 μg/m^3) and MAX (2.03 μg/m^3) were recorded in AQ8 and AQ1, respectively. There was no statistical dissimilarity ($p > 0.05$) in the mean values across the different locations. The mean concentration of lead ranged from 0.32 – 1.02 μg/m^3. The MIN (0.00 μg/m^3) and MAX (1.09 μg/m^3) occurred in AQ3 and two other locations (AQ3 and AQ6), respectively. There was statistical discrepancy ($p < 0.05$) among the locations. However, multiple comparisons showed that location AQ5 was the predominant Source of observed variations. Mean zinc level was within the range of 1.32 – 3.34 μg/m^3. The MIN (0.02 μg/m^3) and MAX (6.91 μg/m^3) concentration were recorded in AQ1 and AQ7, respectively. There were no significant variations in mean values of iron, nickel and zinc, an indication that that similar activity is influencing their concentration in the different locations (AQ1 – AQ8). Furthermore, statistical variation exists in the mean concentration of manganese, lead and vanadium across study locations. Multiple comparisons revealed that the mean values of most sampling stations were not significantly different. Thus, the observed significance variations suggest diverging human activities within the study locations. For locations around the gas flaring stations (AQ1 – AQ7), 85.71%, 85.71% and 100.00% of the sites for manganese, vanadium and lead concentration showed no significant variation with the control station (AQ8). This further suggests that gas flaring is not the primary cause of trace metals in $PM_{2.5}$ within the study area. Among the 6 test metals, iron appears to be most predominantly distributed in atmospheric $PM_{2.5}$. This pattern has been reported in PM_{10} in Bayelsa State [8,27], Acerra city in Italy [39]. Some of the metals, including nickel and lead studied, have been reported to possess varying degrees of carcinogenicity [6,26,44]. Among the carcinogenic metals, nickel is classified as group 1 carcinogen [45], which suggest the availability of adequate information on its carcinogenic status. This may be in the form of some compounds containing nickel. For instance, nickel refinery dust and nickel sub-sulfide are potential carcinogenic substances in humans [46]. In addition, some inorganic forms of lead compounds may be carcinogenic to humans. Hence, they have been classified as Group 2A carcinogens [47]. This is an indication of the inadequate evidence of their human carcinogenicity. Other trace metals such as iron, manganese, zinc and vanadium possess varying levels of toxicity when their concentration exceeds threshold limits. Some of the ill-health associated with these toxic metals have been comprehensively discussed by Kim et al. [45], Sall et al. [48], Prashanth et al. [18] and Izah et al. [5,10]. The values recorded in this study have some similarities with the concentration of trace metals in $PM_{2.5}$ across different areas in Nigeria. Anake et al. [49] studied trace metals in $PM_{2.5}$ in Ewekoro, Nigeria, using the four-stage sequential extraction method, reporting bio-available levels of lead (4.05 μg/m^3) at value exceeding the World Health Organization allowable limits of 0.5 μg/m^3. Also, Owoade et al. [21] reported trace metals in $PM_{2.5}$ within the range of 3.00 – 3.30 μg/m^3 (iron), 0.16 – 0.31 μg/m^3 (manganese), 0.045 – 0.078 μg/m^3 (nickel), 2.40 – 6.00 μg/m^3 (lead), 31.10 – 58.00 μg/m^3 (zinc) and 0.0018 – 0.003 μg/m^3 (vanadium) around industrial area along the Ife–Ibadan highway, Nigeria. Variations are attributed to prevailing anthropogenic activities across the study area.

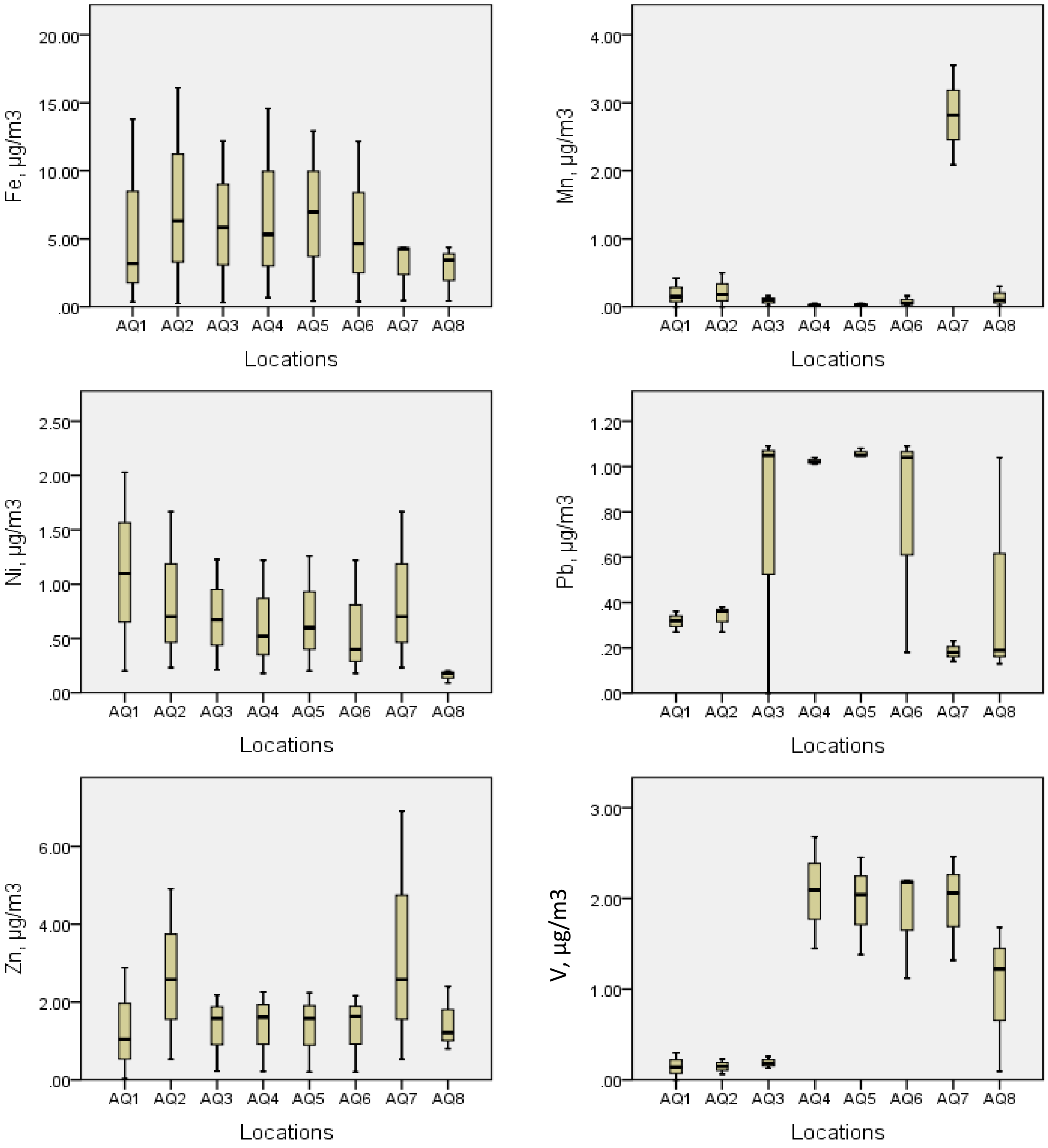

Fig. 2. Distribution of trace metals in $PM_{2.5}$ around a gas flaring area in Bayelsa State, Nigeria.

3.2. Correlation, cluster and principal component analyses of the trace metals

Table 1 shows the Pearson correlation of trace metals in $PM_{2.5}$ around the gas flaring area in Bayelsa State, Nigeria. Iron showed strong positive significant relationship with nickel (r = 0.826) and zinc (r = 0.572) at $p < 0.01$. Manganese showed positive significant relationship with zinc (r = 0.581), while Nickel correlates with zinc (r = 0.760) at $p < 0.01$. The CA revealed a very strong positive relationship between zinc and iron, manganese and nickel, and between iron and nickel at $p < 0.01$ (Table 1). This suggests that the trace metals are from similar sources, showing identical behaviour during transport. The sources may be from anthropogenic and natural effects. The HCA of atmospheric $PM_{2.5}$ based on locations and trace metals is shown in Figures 3 and 4, respectively.

Two main clusters were formed. Within each of the clusters, several sub-clusters were formed with varying distances. Whereas, AQ1c, AQ2c, AQ3c, AQ4c, AQ5c and AQ6c formed one sub-cluster, the other samples AQ7c, AQ8c, and AQ1-AQ8a, b were in a different major sub-cluster (Figure 3). Based on the individual trace metals, two main clusters were formed viz: iron in clusters 1, while nickel, lead, manganese, vanadium and zinc belonged in cluster 2. Under major cluster 2, zinc was grouped in sub-cluster 1, while nickel, lead, manganese and vanadium were categorized under sub-cluster 2 (Figure 4). From the HCA, close clusters are an indication of statistical relationship and close association between trace metals (Figure 2), as well as close association between different sampling locations/points (Figure 3). Conversely, distant clusters designate a degree of disassociation [7]. The difference in cluster level suggests variation in activities influencing the concentration of trace metals in atmospheric $PM_{2.5}$ in the area.

Table 1. Pearson correlation of trace metals in $PM^{2.5}$ around gas flaring area in Bayelsa State, Nigeria.

Parameters	Fe	Mn	Ni	Pb	Zn	V
Fe	1.000					
Mn	-0.079	1.000				
Ni	$.826^{**}$	0.268	1.000			
Pb	0.338	-0.386	0.078	1.000		
Zn	0.572^{**}	0.581^{**}	0.760^{**}	-0.073	1.000	
V	0.216	0.318	0.118	0.382	0.287	1.000

**. Indicate statistical correlation at p= 0.01 level (2-tailed).

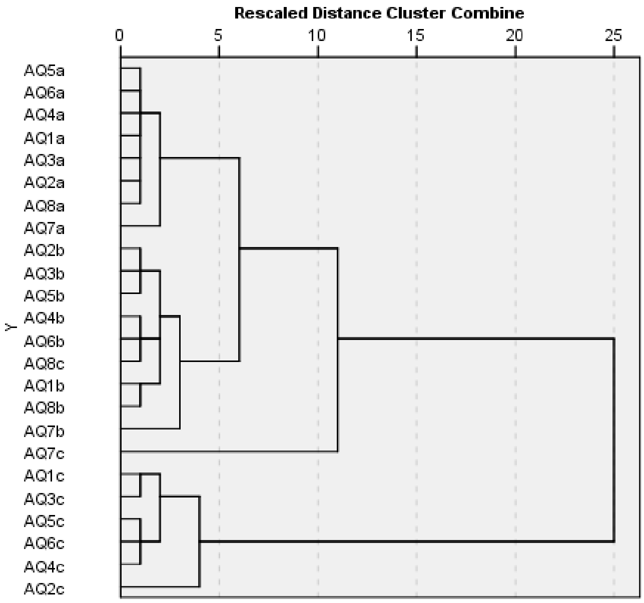

Fig.3. Cluster analysis of trace metals in $PM_{2.5}$ around gas flaring area in Bayelsa State, Nigeria (relationship among sampling stations).

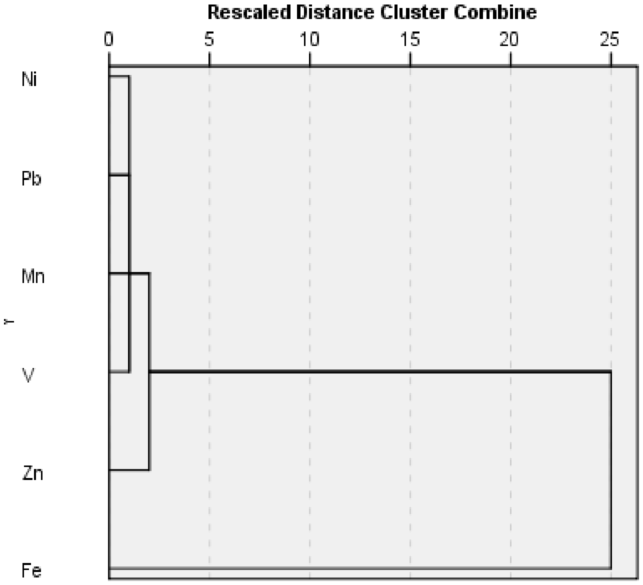

Fig. 4. Cluster analysis of trace metals in $PM_{2.5}$ around gas a flaring area in Bayelsa State, Nigeria (relationship among trace metals).

Table 2 summarizes the principal components (PCs) analysis of trace metals in atmospheric $PM_{2.5}$ around a gas flaring area in Bayelsa State, Nigeria. Total variance of 91.03% was obtained for the three components. PC-1 contributed 45.012% to the total variance, and correlates with nickel (r = 0.903), zinc (r = 0.899) and iron (r = 0.806). PC-2 contributed 26.873% to the total variance, and correlates with lead (r = 0.862), while PC-3 contributed 19.146% to the total variance, and correlates with vanadium (r = 0.834).

Table 2. Principal components of trace metal in atmospheric $PM_{2.5}$ around a gas flaring area in Bayelsa State, Nigeria.

Trace metals	PC -1	PC -2	PC -3
Fe	0.806	0.431	-0.304
Mn	0.458	-0.757	0.372
Ni	0.903	0.045	-0.346
Pb	0.157	0.862	0.318
Zn	0.899	-0.281	-0.031
V	0.438	0.173	0.834
Total	2.701	1.612	1.149
% of Variance	45.012	26.873	19.146
Cumulative %	45.012	71.884	91.03

The analysis showed that three principal components (PCs) with eigenvalue > 1. This is because the principal components with higher eigenvalues explain the variation in the data set [43]. The three principal components account for 91% of the total variance in the area. The level of trace metals in the study area emanates from multiple sources, including vehicular or traffic emissions and natural sources. In component 1, iron, nickel and zinc may be from vehicular emission, combustion due to the flare gas and natural effects, while components 2 and 3 are likely from fuel combustion, vehicular emissions and natural Source. Previous studies have indicated that lead, manganese and vanadium can emanate from natural sources and automobile exhaust in $PM_{2.5}$ within some areas in Nanjing City, China [41]. In addition, Vaio et al. [39] have reported nickel and vanadium to emanate from oil combustion, while zinc can be released from industrial emissions. Iron in PM_{10} from urban-industrial site in Acerra, Italy, was of crustal origin. Also, Niu et al. [50] reported that iron, zinc and manganese could emanate from the earth's crust. Lead, zinc and manganese can be from transportation processes, while manganese, lead and nickel result from fuel combustion.

3.3. Environmental risk assessment

Table 3 shows the contamination factor (CF*i*) of trace metals in $PM_{2.5}$ around a gas flaring area in Bayelsa State, Nigeria. The CF*i* ranged from low uncleanness (contamination) to very high uncleanness contamination. For iron, all mean and MIN showed moderate and low contamination, respectively. This being across the various locations, while 75% and 25% of the MAX values showed considerable and moderate contamination, respectively. For manganese, 37.5%, 50% and 12.5% showed moderate, low and very high contamination, respectively, for its mean values, with MIN values showing low, moderate and very high contamination of 62.5%, 25% and 12.5%, respectively. In addition, MAX values reflected 25%, 37.5%, 25% and 12.5% for low, moderate, considerable and very high uncleanness respectively. For nickel, mean values recorded 12.5% and 87.5% for low and moderate contamination respectively, while MIN values depicted 100% for low contamination, with MAX values reflecting 12.5%, 50% and 37.5% for low, moderate and considerable contamination respectively. For lead, mean values showed 50% and 50% for low and moderate contamination, respectively, with MIN values showing 75% and 25% for low and moderate contamination, respectively. At the same time, MAX values depicted 62.5% and 37.5% for moderate and low contamination, respectively. For zinc, there was 100% moderate and low *CFI* for mean and MIN values, while MAX values reflected 75% and 25% for moderate and very high contamination, respectively. For vanadium, mean values showed 62.5% and 37.5% for moderate and low contamination, respectively, while MIN values recorded 50% and 50% for moderate and low contamination, respectively. Whereas, MAX values recorded 37.5%, 12.5% and 50% for low, moderate and considerable contamination respectively. Table 4 shows the pollution load index (PLI*i*) and degree of contamination (CD*i*) of trace metals in $PM_{2.5}$ around a gas flaring area in Bayelsa State, Nigeria. The PLI*i* ranged from no to extremely trace pollution. Approximately 75%, 12.5% and 12.5% showed moderate, low and trace pollution for mean values; 100% no pollution for MIN values, and 25%, 62.5% and 12.5% for moderate, trace and extremely trace pollution respectively, for MAX values. Hence, the CD*i* ranged from low to very high Risk. Approximately 62.5%, 12.5% and 25% for moderate, very high and low Risk respectively, for the mean value, 87.5% and 12.5% for low and considerable Risk respectively, for MIN values; and 50% and 50% for moderate and considerable Risk respectively, for the MAX values.

Table 3. Contamination factor (CF*i*) of trace metals in $PM_{2.5}$ around a gas flaring area in Bayelsa State, Nigeria.

Metals	Statistics	Sampling stations							
		AQ1	AQ2	AQ3	AQ4	AQ5	AQ6	AQ7	AQ8
Fe	Mean	2.14	2.80	2.26	2.54	2.51	2.12	1.13	1.02
	Min	0.13	0.09	0.12	0.26	0.16	0.14	0.18	0.16
	Max	5.11	5.97	4.51	5.40	4.79	4.50	1.62	1.61
Mn	Mean	1.73	2.06	0.82	0.24	0.27	0.73	25.64	1.24
	Min	1.18	1.18	0.09	0.09	0.09	0.27	19.00	0.09
	Max	3.82	4.55	1.45	0.45	0.45	1.45	32.27	2.73
Ni	Mean	2.31	1.81	1.47	1.33	1.43	1.25	1.81	0.33
	Min	0.42	0.48	0.44	0.38	0.42	0.38	0.48	0.19
	Max	4.23	3.48	2.56	2.54	2.63	2.54	3.48	0.42
Pb	Mean	0.65	0.69	1.46	2.09	2.16	1.57	0.37	0.93
	Min	0.55	0.55	0.45	2.06	2.14	0.37	0.29	0.27
	Max	0.73	0.78	2.22	2.12	2.20	2.22	0.47	2.12
Zn	Mean	1.27	2.57	1.28	1.31	1.29	1.28	3.21	1.41
	Min	0.02	0.51	0.21	0.20	0.19	0.19	0.51	0.77
	Max	2.77	4.72	2.10	2.17	2.15	2.08	6.64	2.31
V	Mean	0.21	0.21	0.28	3.00	2.84	2.66	2.82	1.44
	Min	0.58	0.09	0.19	2.10	2.00	1.62	1.91	0.13
	Max	0.43	0.33	0.38	3.88	3.55	3.19	3.57	2.43

Note: contamination factor (CF*i*): low uncleanness (CF*i* < 1); moderate uncleanness (1 ≤ CF*i* < 3); considerable uncleanness (3 ≤ CF*i* < 6); very high uncleanness (CF*i* ≥ 6).

The CF*i*, CD*i* and PLI*i* showed some varying levels of contamination using the mean, MIN and MAX values for each of the sample locations. The trend report in this study had some similarities with values recorded in trace metals in atmospheric PM_{10} at Bayelsa State [27], and some other environmental components such as groundwater [28] and soil [51]. Table 5 presents the index of geoaccumulation (I-GEO*i*) of trace metals in $PM_{2.5}$ around a gas flaring area in Bayelsa State, Nigeria. The values ranged from no contamination to trace to extreme contamination. For mean values of iron, 75% and 25% showed 0 < I-GEO*i* ≤ 1 and I-GEO*i* ≤ 0, respectively, with MIN values showing 100% I-GEO*i* ≤ 0; and 75% and 25% for 1 < I-GEO*i* ≤ 2 and I-GEO*i* ≤ 0 respectively, for MAX values. For mean values of manganese, 25%, 62.5% and 12.5% showed I-GEO*i* ≤ 0, 1 < I-GEO*i* ≤ 2 and 4 < I-GEO*i* < 5 respectively, with MIN values showing 87.5% and 12.5% for I-GEO*i* ≤ 0 and 4 < I-GEO*i* < 5 respectively. Whereas, MAX values depicted 50%, 12.5% 25% and 12.5% for I-GEO*i* ≤ 0, 0 < I-GEO*i* ≤ 1, 1 < I-GEO*i* ≤ 2 and 4 < I-GEO*i* < 5 respectively. For nickel, 62.5% and 37.5% showed I-GEO*i* ≤ 0 and 0 < I-GEO*i* ≤ 1, respectively for mean values, while 100% showed I-GEO*i* ≤ 0 for MIN values, and 12.5%, 50%, 35.5% for I-GEO*i* ≤ 0, 0 < I-GEO*i* ≤ 1 and 1 < I-GEO*i* ≤ 2 respectively for MAX values. For lead, 62.5% and 37.5% showed I-GEO*i* ≤ 0 and 0 < I-GEO*i* ≤ 1, respectively for mean values; 75% and 25% showed I-GEO*i* ≤ 0 and 0 < I-GEO*i* ≤ 1, respectively for MIN values, and 37.5% and 62.5% showed I-GEO*i* ≤ 0 and 0 < I-GEO*i* ≤ 1, respectively for MAX values. For zinc, 87.5% and 12.5% showed I-GEO*i* ≤ 0 and 0 < I-GEO*i* ≤ 1, respectively for mean values; 100% for MIN values; and 75%, 12.5%, 12.5% showed $0 < \text{I-GEO}i \leq 1$, $1 < \text{I-GEO}i \leq 2$ and $2 < \text{I-GEO}i < 3$, respectively for MAX values. For vanadium, 50% and 50% showed $\text{I-GEO}i \leq 0$ and $0 < \text{I-GEO}i \leq 1$, respectively for mean and MIN values; and 37.5%, 12.5% and 50% for $\text{I-GEO}i \leq 0$, $0 < \text{I-GEO}i \leq 1$ and $1 < \text{I-GEO}i \leq 2$, respectively for MAX values. The I-GEO*i* showed positive values for some of the mean, MIN and MAX statistical considerations. The positive values revealed contamination due to both anthropogenic activities and natural effects [52]. Basically, positive CF*i* and I-GEO*i* indicate contamination results from anthropogenic activities [52]. The pattern recorded in this study is in accordance with a previous report on groundwater [28] and soil [52].

Table 6 shows the enrichment factor (EF*i*) of trace metals in $PM_{2.5}$ around gas a flaring area in Bayelsa State, Nigeria. The EF*i* ranged from background rank to very high enrichment. For manganese, 75%, 12.5% and 12.5% showed $EFi \leq 1$, $20 < EFi < 40$ and $1 < EFi < 2$, respectively for the mean values; , 75%, 12.5% and 12.5% showed $EFi \leq 1$, $1 < EFi < 2$ and $5 < EFi < 20$, respectively for the MIN values; and 50%, 12.5%, 25% and 12.5% showed $EFi \leq 1$, $1 < EFi < 2$, $5 < EFi < 20$ and $EFi > 40$, respectively for the MAX values. For nickel, 75% and 25% showed $EFi \leq 1$ and $1 < EFi < 2$, respectively for the mean values; 87.5% and 12.5% showed $EFi \leq 1$ and $2 < EFi < 5$, respectively for the MIN values; and 25%, 62.5% and 12.5% showed $1 < EFi < 2$, $2 < EFi < 5$ and $5 < EFi < 20$, respectively for the MAX values. For lead, 100% were $EF \leq 1$ for the mean values; 87.5% and 12.5% showed $EFi \leq 1$ and $1 < EFi < 2$, respectively for the MIN values; and 25%, 37.5% and 37.5% showed $1 < EFi < 2$, $2 < EFi < 5$ and $5 < EFi < 20$, respectively for the MAX values. For zinc, 75%, 12.5% and 12.5% showed $EFi \leq 1$, $1 < EFi < 2$ and $2 < EFi < 5$, respectively for the mean values; 75%, 12.5% and 12.5% showed $EFi \leq 1$, $1 < EFi < 2$ and $2 < EFi < 5$, respectively for the MIN values; and 25%, 37.5%, 25% and 12.5% showed $EFi \leq 1$, $1 < EFi < 2$, $2 < EFi < 5$ and $5 < EFi < 20$, respectively for the MAX values.

The EF*i* revealed background rank to extreme high enrichment. However, background rank to moderate enrichment was predominant. The values observed in consonance with the previous study on atmospheric PM_{10} in Bayelsa State [27] Based on the criteria of $EFi < 10$ (enrichment from crustal origin) and $EFi > 10$ (enrichment due to human activities) presented by Vaio et al. (2018), the enrichment values in this study mainly reflected crustal origin ($EFi < 10$), except for MAX values at AQ2, and MAX and MIN values at AQ7 for manganese, and MAX values of lead at AQ5 for which enrichment was due to anthropogenic activities ($EF > 10$). Again, only the MAX value of AQ7 for manganese exceeded $EFi > 100$ (high enrichment), an indication that anthropogenic activities were the Source of atmospheric $PM_{2.5}$. This trend is in consonance with values in atmospheric PM_{10} around Bayelsa State, as previously reported by Uzoekwe et al. [27].

Table 4. Pollution load index (PLI*i*) and degree of contamination (CD*i*) of trace metals in $PM_{2.5}$ around a gas flaring area in Bayelsa State, Nigeria.

Locations	Pollution load index (PLI*i*)			Degree of contamination (CD*i*)		
	Mean	Min	Max	Mean	Min	Max
AQ1	1.07	0.27	2.04	8.31	2.88	17.10
AQ2	1.25	0.33	2.20	10.14	2.89	19.82
AQ3	1.06	0.21	1.76	7.55	1.50	13.23
AQ4	1.37	0.44	2.19	10.52	5.09	16.58
AQ5	1.40	0.41	2.14	10.50	5.00	15.77
AQ6	1.48	0.34	2.50	9.60	2.97	15.99
AQ7	2.37	0.88	3.56	34.97	22.37	48.05
AQ8	0.96	0.20	1.67	6.37	1.61	11.62

Note: degree of contamination (CD*i*): low hazard or hazard ($CDi < 8$); moderate hazard ($8 \leq CDi < 16$); considerable hazard ($16 \leq CDi < 32$); very high hazard ($CDi > 32$); for pollution load index (PLI*i*): no pollution ($PLIi < 1$); moderate pollution ($1 < PLIi < 2$); trace pollution ($2 < PLIi < 3$); extremely trace pollution ($3 < PLIi$).

Table 5. Index of geoaccumulation (I-GEO*i*) of trace metals in $PM_{2.5}$ around gas a flaring area in Bayelsa State, Nigeria.

Metals	Statistics	Locations							
		AQ1	**AQ2**	**AQ3**	**AQ4**	**AQ5**	**AQ6**	**AQ7**	**AQ8**
Fe	Mean	0.51	0.90	0.59	0.76	0.74	0.50	-0.41	-0.56
	MIN	-3.49	-4.14	-3.66	-2.55	-3.24	-3.41	-3.08	-3.20
	MAX	1.77	1.99	1.59	1.85	1.67	1.59	0.11	0.11
Mn	Mean	0.20	0.46	-0.87	-2.63	-2.46	-1.04	4.10	-0.27
	MIN	-0.34	-0.34	-4.04	-4.04	-4.04	-2.46	3.66	-4.04
	MAX	1.35	1.60	-0.04	-1.72	-1.72	-0.04	4.43	0.86
Ni	Mean	0.62	0.27	-0.03	-0.17	-0.07	-0.26	0.27	-2.20
	MIN	-1.85	-1.65	-1.78	-2.00	-1.85	-2.00	-1.65	-3.00
	MAX	1.50	1.21	0.77	0.76	0.81	0.76	1.21	-1.85
Pb	Mean	-1.21	-1.13	-0.04	0.48	0.53	0.07	-2.00	-0.70
	MIN	-1.44	-1.44	-1.74	0.46	0.51	-2.03	-2.39	-2.50
	MAX	-1.03	-0.95	0.57	0.50	0.56	0.57	-1.68	0.50
Zn	Mean	-0.24	0.78	-0.23	-0.20	-0.22	-0.23	1.10	-0.09
	MIN	-6.29	-1.56	-2.83	-2.89	-2.96	-2.96	-1.56	-0.96
	MAX	0.88	1.65	0.48	0.53	0.52	0.47	2.15	0.62
V	Mean	-2.82	-2.82	-2.45	1.00	0.92	0.82	0.91	-0.05
	MIN	-1.37	-4.11	-2.99	0.49	0.42	0.11	0.35	-3.52
	MAX	-1.79	-2.17	-1.99	1.37	1.24	1.09	1.25	0.70

Note: I-GEO*i* ≤ 0 (no uncleanness or contamination), 0 < I-GEO*i* ≤ 1 (no uncleanness to moderate uncleanness), 1 < I-GEO*i* ≤ 2 (moderate uncleanness), 2 < I-GEO*i* < 3 (moderate to trace uncleanness), 3 < I-GEO*i* < 4 (trace uncleanness), 4 < I-GEO*i* < 5 (trace to extreme uncleanness), I-GEO*i* ≥ 5 (extreme uncleanness).

Table 6. Enrichment factor (EF*i*) of trace metals in $PM_{2.5}$ around gas flaring area in Bayelsa State, Nigeria.

Metals	Statistics	Sampling stations							
		AQ1	**AQ2**	**AQ3**	**AQ4**	**AQ5**	**AQ6**	**AQ7**	**AQ8**
Mn	Mean	0.81	0.74	0.36	0.10	0.11	0.34	22.77	1.22
	MIN	0.75	0.76	0.32	0.08	0.09	0.32	19.89	1.69
	MAX	8.86	13.87	0.77	0.36	0.57	1.94	106.88	0.56
Ni	Mean	1.08	0.65	0.65	0.52	0.57	0.59	1.60	0.32
	MIN	0.83	0.58	0.57	0.47	0.55	0.56	2.14	0.26
	MAX	3.13	5.63	3.69	1.47	2.62	2.66	2.70	1.15
Pb	Mean	0.30	0.25	0.64	0.82	0.86	0.74	0.33	0.91
	MIN	0.14	0.13	0.49	0.39	0.46	0.49	0.29	1.31
	MAX	4.13	6.47	3.79	8.07	13.46	2.61	1.61	1.63
Zn	Mean	0.59	0.92	0.56	0.51	0.51	0.60	2.85	1.39
	MIN	0.54	0.79	0.46	0.40	0.45	0.46	4.10	1.43
	MAX	0.14	5.98	1.78	0.79	1.21	1.37	2.87	4.72

Note: background rank (EF*i* ≤ 1), minimal enrichment (1< EF*i* < 2), moderate enrichment (2< EF*i* < 5), significant enrichment (5 < EF*i* < 20), very high enrichment (20 < EF*i* < 40), extremely high enrichment (EF*i* > 40).

The Source of these metals in the atmosphere may be from anthropogenic activities. Apart from gas flaring, bush burning, open waste dump incineration, artisanal refining of crude oil/illegal bunkering, among others, contribute significantly to the release of trace/trace metals in the environment. Table 7 shows the ecological Risk of trace metals in $PM_{2.5}$ around a gas flaring area in

Bayelsa State, Nigeria. The ecological risk (ER*i*) values showed low Risk (Er < 40) for test metals across study locations using the various statistical approaches (mean, MIN and MAX). The risk hazard (ERI*i*) was low (ERI < 150) across various locations for the test statistics (mean, MIN and MAX). The ER*i* of manganese, nickel, lead and zinc, and overall risk index across all study locations revealed low risks. The values were lower when compared to the criteria of low to considerable Risk recorded for ER*i*, and low to moderate Risk for risk index earlier recorded by Uzoekwe et al. [27]. The values recorded had some similarities with values recorded in some environmental components such as soil [32] and groundwater [28].

Table 7. Ecological Risk (ER*i*) and risk index (ERI*i*) of trace metals in $PM_{2.5}$ around a gas flaring area in Bayelsa State, Nigeria.

Metals	Statistics	Sampling stations							
		AQ1	AQ2	AQ3	AQ4	AQ5	AQ6	AQ7	AQ8
Mn	Mean	1.73	2.06	0.82	0.24	0.27	0.73	25.64	1.24
	MIN	1.18	1.18	0.09	0.09	0.09	0.27	19.00	0.09
	MAX	3.82	4.55	1.45	0.45	0.45	1.45	32.27	2.73
Ni	Mean	11.56	9.03	7.33	6.67	7.15	6.25	9.03	1.63
	MIN	2.08	2.40	2.19	1.88	2.08	1.88	2.40	0.94
	MAX	21.15	17.40	12.81	12.71	13.13	12.71	17.40	2.08
Pb	Mean	3.23	3.44	7.28	10.44	10.82	7.86	1.87	4.63
	MIN	2.76	2.76	2.24	10.31	10.71	1.84	1.43	1.33
	MAX	3.67	3.88	11.12	10.61	11.02	11.12	2.35	10.61
Zn	Mean	1.27	2.57	1.28	1.31	1.29	1.28	3.21	1.41
	MIN	0.02	0.51	0.21	0.20	0.19	0.19	0.51	0.77
	MAX	2.77	4.72	2.10	2.17	2.15	2.08	6.64	2.31
Potential Ecological Risk index	Mean	17.79	17.09	16.71	18.66	19.53	16.12	39.75	8.91
	MIN	6.04	6.84	4.73	12.47	13.08	4.17	23.33	3.12
	MAX	31.41	30.54	27.48	25.94	26.75	27.36	58.65	17.74

Note: low hazard or risk (ER*i* < 40); moderate hazard (40 ≤ ER*i* < 80); considerable (80 ≤ ER*i* < 160); high 160 ≤ ER*i* < 320); very high (ER*i* ≥ 320); low hazard (ERI*i* < 150); moderate hazard (150 ≤ ERI*i* < 300); considerable hazard (300 ≤ ERI*i* < 600); very high hazard (ERI*i* ≥ 600); potential ecological risk hazard (ERI*i*); Ecological risk (ER*i*).

3.4. Human risk assesment

Table 8 showed the inhalation risk of non-carcinogenic hazard of trace metals of adults and children around a gas flaring area in Bayelsa State, Nigeria. Under the categories (adult and child), the different statistical approaches (mean, MIN and MAX) for test metals (manganese, nickel, lead and vanadium) were < 1. The total non-carcinogenic hazard of trace metals was also < 1. Table 9 shows the carcinogenic risk of nickel and lead via inhalation in adults and children around the gas flaring area. For adults, nickel values were in the range of 10^{-8} - 10^{-7} for mean and MAX, and 10^{-8} for MIN values. For children, the values were in the range of 10^{-9} - 10^{-8} for mean and MIN values and 10^{-8} - 10^{-7} for MAX values. Meanwhile, lead values were in the order of 10^{-8} for mean and MAX values, and 10^{-9} - 10^{-8} for MIN values (adult), and 10^{-9} - 10^{-8} for mean, MIN and MAX values, except for few instances where the values were 0.00E+00.

Table 8. Inhalation risk of non-carcinogenic hazard of trace metals in adult and children inhabiting gas flaring area in Bayelsa State, Nigeria.

Metals	Locations	Adult			Child		
		Mean	MIN	MAX	Mean	MIN	MAX
Mn	AQ1	9.98E-03	0.00E+00	2.21E-02	9.98E-03	0.00E+00	2.21E-02
	AQ2	1.19E-02	0.00E+00	2.63E-02	1.19E-02	0.00E+00	2.63E-02
	AQ3	4.73E-03	5.25E-04	8.41E-03	4.73E-03	5.25E-04	8.41E-03
	AQ4	1.40E-03	5.25E-04	2.63E-03	1.40E-03	5.25E-04	2.63E-03
	AQ5	1.58E-03	5.25E-04	2.63E-03	1.58E-03	5.25E-04	2.63E-03
	AQ6	4.20E-03	1.58E-03	8.41E-03	4.20E-03	1.58E-03	8.41E-03
	AQ7	1.48E-01	1.10E-01	1.87E-01	1.48E-01	1.10E-01	1.87E-01
	AQ8	7.18E-03	5.25E-04	1.58E-02	7.18E-03	5.25E-04	1.58E-02
Ni	AQ1	5.83E-02	1.05E-02	1.07E-01	5.83E-02	1.05E-02	1.07E-01
	AQ2	4.55E-02	1.21E-02	8.77E-02	4.55E-02	1.21E-02	8.77E-02
	AQ3	3.70E-02	1.10E-02	6.46E-02	3.70E-02	1.10E-02	6.46E-02
	AQ4	3.36E-02	9.46E-03	6.41E-02	3.36E-02	9.46E-03	6.41E-02
	AQ5	3.61E-02	1.05E-02	6.62E-02	3.61E-02	1.05E-02	6.62E-02
	AQ6	3.15E-02	9.46E-03	6.41E-02	3.15E-02	9.46E-03	6.41E-02
	AQ7	4.55E-02	1.21E-02	8.77E-02	4.55E-02	1.21E-02	8.77E-02
	AQ8	8.23E-03	4.73E-03	1.05E-02	8.23E-03	4.73E-03	1.05E-02
Pb	AQ1	2.38E-04	2.03E-04	2.70E-04	2.38E-04	2.03E-04	2.70E-04
	AQ2	2.53E-04	2.03E-04	2.85E-04	2.53E-04	2.03E-04	2.85E-04
	AQ3	5.35E-04	0.00E+00	8.18E-04	5.35E-04	0.00E+00	8.18E-04
	AQ4	7.68E-04	7.58E-04	7.81E-04	7.68E-04	7.58E-04	7.81E-04
	AQ5	7.96E-04	7.88E-04	8.11E-04	7.96E-04	7.88E-04	8.11E-04
	AQ6	5.78E-04	1.35E-04	8.18E-04	5.78E-04	1.35E-04	8.18E-04
	AQ7	1.38E-04	1.05E-04	1.73E-04	1.38E-04	1.05E-04	1.73E-04
	AQ8	3.40E-04	9.76E-05	7.81E-04	3.40E-04	9.76E-05	7.81E-04
V	AQ1	3.85E-03	0.00E+00	7.88E-03	3.85E-03	0.00E+00	7.88E-03
	AQ2	3.85E-03	1.58E-03	6.04E-03	3.85E-03	1.58E-03	6.04E-03
	AQ3	4.99E-03	3.42E-03	6.83E-03	4.99E-03	3.42E-03	6.83E-03
	AQ4	5.45E-02	3.81E-02	7.04E-02	5.45E-02	3.81E-02	7.04E-02
	AQ5	5.14E-02	3.63E-02	6.44E-02	5.14E-02	3.63E-02	6.44E-02
	AQ6	4.82E-02	2.94E-02	5.78E-02	4.82E-02	2.94E-02	5.78E-02
	AQ7	5.11E-02	3.47E-02	6.46E-02	5.11E-02	3.47E-02	6.46E-02
	AQ8	2.62E-02	2.36E-03	4.41E-02	2.62E-02	2.36E-03	4.41E-02
Zn	AQ1	1.15E-05	1.75E-07	2.52E-05	1.15E-05	1.75E-07	2.52E-05
	AQ2	2.34E-05	4.64E-06	4.30E-05	2.34E-05	4.64E-06	4.30E-05
	AQ3	1.16E-05	1.93E-06	1.91E-05	1.16E-05	1.93E-06	1.91E-05
	AQ4	1.19E-05	1.84E-06	1.98E-05	1.19E-05	1.84E-06	1.98E-05
	AQ5	1.17E-05	1.75E-06	1.96E-05	1.17E-05	1.75E-06	1.96E-05
	AQ6	1.16E-05	1.75E-06	1.89E-05	1.16E-05	1.75E-06	1.89E-05
	AQ7	2.92E-05	4.64E-06	6.05E-05	2.92E-05	4.64E-06	6.05E-05
	AQ8	1.29E-05	7.01E-06	2.10E-05	1.29E-05	7.01E-06	2.10E-05
Total non-carcinogenic hazard	AQ1	7.24E-02	1.07E-02	1.37E-01	7.24E-02	1.07E-02	1.37E-01
	AQ2	6.15E-02	1.39E-02	1.20E-01	6.15E-02	1.39E-02	1.20E-01
	AQ3	4.73E-02	1.49E-02	8.07E-02	4.73E-02	1.49E-02	8.07E-02
	AQ4	9.03E-02	4.88E-02	1.38E-01	9.03E-02	4.88E-02	1.38E-01
	AQ5	8.99E-02	4.81E-02	1.34E-01	8.99E-02	4.81E-02	1.34E-01
	AQ6	8.45E-02	4.06E-02	1.31E-01	8.45E-02	4.06E-02	1.31E-01
	AQ7	2.45E-01	1.57E-01	3.40E-01	2.45E-01	1.57E-01	3.40E-01
	AQ8	4.20E-02	7.72E-03	7.12E-02	4.20E-02	7.72E-03	7.12E-02

Table 9. Inhalation risk of carcinogenic hazard of trace metals in adult and child around a gas flaring area in Bayelsa State, Nigeria.

Metals	Locations	Adult Mean	Adult MIN	Adult MAX	Child Mean	child MIN	Child MAX
Ni	AQ1	2.40E-07	4.32E-08	4.39E-07	6.00E-08	1.08E-08	1.10E-07
	AQ2	1.87E-07	4.97E-08	3.61E-07	4.68E-08	1.24E-08	9.03E-08
	AQ3	1.52E-07	4.54E-08	2.66E-07	3.80E-08	1.13E-08	6.65E-08
	AQ4	1.38E-07	3.89E-08	2.64E-07	3.46E-08	9.73E-09	6.59E-08
	AQ5	1.48E-07	4.32E-08	2.72E-07	3.71E-08	1.08E-08	6.81E-08
	AQ6	1.30E-07	3.89E-08	2.64E-07	3.24E-08	9.73E-09	6.59E-08
	AQ7	1.87E-07	4.97E-08	3.61E-07	4.68E-08	1.24E-08	9.03E-08
	AQ8	3.39E-08	1.95E-08	4.32E-08	8.47E-09	4.86E-09	1.08E-08
Pb	AQ1	2.28E-08	1.95E-08	2.59E-08	4.28E-09	3.65E-09	4.87E-09
	AQ2	2.43E-08	1.95E-08	2.74E-08	4.55E-09	3.65E-09	5.14E-09
	AQ3	5.14E-08	0.00E+00	7.85E-08	9.65E-09	0.00E+00	1.47E-08
	AQ4	7.37E-08	7.28E-08	7.49E-08	1.38E-08	1.37E-08	1.41E-08
	AQ5	7.64E-08	7.57E-08	7.78E-08	1.43E-08	1.42E-08	1.46E-08
	AQ6	5.55E-08	1.30E-08	7.85E-08	1.04E-08	2.43E-09	1.47E-08
	AQ7	1.32E-08	1.01E-08	1.66E-08	2.48E-09	1.89E-09	3.11E-09
	AQ8	3.27E-08	9.37E-09	7.49E-08	6.13E-09	1.76E-09	1.41E-08

The health risks depicted by the carcinogenic hazard of nickel and non-carcinogenic hazard of all other test metals (manganese, nickel, lead, vanadium and zinc) for the two groups of persons (adults and children), particularly considering exposure due to inhalation showed no adverse health effects according to the mean, MIN and MAX values obtained. The carcinogenic hazard of nickel and lead were lesser than the threshold values of 10^{-4} - 10^{-6} for both body weights considered (adult and children) [6,27,42]. The values were lesser than ($< 10^{-6}$) classified shallow risk (totally acceptable) classification category by Adeyemi and Ojekunle [53], and Joel et al. [54]. This suggests that individuals exposed to atmospheric $PM_{2.5}$ in the study area may not experience carcinogenic effects resulting from the test metals. However, the values had some similarity with an average carcinogenic hazard of some trace metals such as arsenic (2.25E–09), cadmium (2.09E–12) and chromium (2.05E–11) in $PM_{2.5}$ in urban air of Tehran, Iran [55], range of 10^{-8} - 10^{-7} (arsenic), 10^{-7} - 10^{-6} (cobalt) and 10^{-8} - 10^{-6} (cadmium) in atmospheric PM_{10} in Bayelsa State, Nigeria [27] . The non-carcinogenic hazard of all trace metals studied was < 1 for the different categories of body weight (adult and child). This is an indication that there is no potential adverse health effect. Values observed for (non-carcinogenic and carcinogenic hazards) is consistent with the values recorded for the non-carcinogenic threat of trace metals in atmospheric PM_{10} in Bayelsa State, as reported by Uzoekwe et al. [27]. Hence, the human Risk (carcinogenic and non-carcinogenic hazards) is within the acceptable range for both age groups. The trend in carcinogenic and non-carcinogenic hazards for the individual trace metals showed some resemblance with the report of Vaio et al. [37] in Acerra city in Italy, and Uzoekwe et al. [27]in Bayelsa State, Nigeria.

4. Conclusions

$PM_{2.5}$ has the tendency to penetrate into the alveoli, causing obstruction in the respiratory tract system. This study investigated the concentration, Source, environmental and human health risk of trace metals in atmospheric $PM_{2.5}$ around a gas flaring area in Bayelsa state, Nigeria. The study showed that there is no statistical dissimilarity ($p > 0.05$) in mean values of iron, nickel and zinc, while significant variations ($p < 0.05$) exist in the various study locations for manganese, lead and vanadium. CF*i*, CD*i* and PLI*i* revealed contamination ranging from low to high Risk. The EF*i* and I-GEO*i* revealed that the metals emanate from human activities and geologic sources. The ecological Risk and risk index depicts low Risk, while the health risk (carcinogenic and non-carcinogenic hazard) showed no adverse health concern due to inhalation of these trace metals in atmospheric $PM_{2.5}$. Therefore, there is a need to include $PM_{2.5}$ as part of ambient air monitoring parameters, especially when considering ambient air quality.

References

[1] Seiyaboh, E. I., Izah, S. C. (2017). A Review of impacts of gas flaring on vegetation and water resources in the Niger Delta Region of Nigeria. *International journal economy, energy and environment, 2*(4), 48–55.

[2] World Health Organization (WHO) (2018). Ambient (outdoor) air pollution fact sheet. https://www.who.int/news-room/fact-sheets/detail/ambient-(outdoor)-air-quality-and-health (Accessed December 2020).

[3] Popoola, L. T., Adebanjo, S. A., Adeoye, B. K. (2018). Assessment of atmospheric particulate matter and heavy metals: a critical review. *International journal of environmental science and technology, 15,* 935–948.

[4] Chen, B., Kan, H. (2008). Air pollution and population health: a global challenge. *Environmental health and preventive medicine, 13,* 94–101.

[5] Izah, S. C., Chakrabarty, N., Srivastav, A. L. (2016). A Review on heavy metal concentration in potable water sources in Nigeria: Human health effects and mitigating measures. *Exposure and health, 8,* 285–304.

[6] Ogamba, E. N., Charles, E. E., Izah, S. C. (2021). Distributions, pollution evaluation and health risk of selected heavy metal in surface water of Taylor creek, Bayelsa State, Nigeria. *Toxicology and environmental health sciences, 13*(2), 109–121.

[7] Izah, S. C., Bassey, S. E., Ohimain, E. I. (2017). Assessment of heavy metal in cassava mill effluent contaminated soil in a rural community in the Niger Delta region of Nigeria. *EC pharmacology and toxicology, 4*(5), 186–201.

[8] Uzoekwe, S. A., Ajayi, E. D. (2018). Trace metals concentration assessment in Urban particulate matter in Yenagoa and it's environ. *Journal of applied sciences and environmental management, 22*(1), 134–140.

[9] Izah, S. C., Aigberua, A. O. (2017). Comparative Assessment of selected heavy metals in some common edible vegetables sold in Yenagoa metropolis, Nigeria. *Journal of biotechnology research, 3*(8), 66 – 71.

[10] Izah, S. C., Inyang, I. R., Angaye, T. C. N., Okowa, I. P. (2017). A review of heavy metal concentration and potential health implications in beverages consumed in Nigeria. *Toxics, 5* (1): 1–15.

[11] Ogamba, E. N., Ebere, N., Izah, S. C. (2017). Levels of lead and cadmium in the bone and muscle tissues of *Oreochromis niloticus* and *Clarias camerunensis. EC nutrition, 7*(3), 117–123.

[12] Ogamba, E. N., Izah, S. C., Isimayemiema, F. (2016). Bioaccumulation of heavy metals in the gill and liver of a common Niger Delta wetland fish, *Clarias garepinus*. *British journal of applied research, 1*(1), 17–20.

[13] Ogamba, E. N., Izah, S. C., Ofoni-Ofoni AS. (2016). Bioaccumulation of chromium, lead and cadmium in the bones and tissues of Oreochromis niloticus and clarias camerunensis from Ikoli creek, Niger Delta, Nigeria. *Advanced science journal of zoology, 1*(1), 13–16.

[14] Ogamba, E. N., Izah, S. C., Ebiowe, R. G. (2015). Bioconcentration of Mercury, Lead and Cadmium in the bones and muscles of *Citharinus citharus* and *Synodontis clarias* from the Amassoma Axis of River Nun, Niger Delta, Nigeria. *Research journal of pharmacology and toxicology, 1*(1), 21–23.

[15] Aghoghovwia, O. A., Ohimain, E. I., Izah, S. C. (2016). Bioaccumulation of Heavy metals in different tissues of some commercially important fish species from Warri River, Niger Delta, Nigeria. *Biotechnology research, 2*(1), 25–32.

[16] Kigigha, L. T., Ebieto, L. O., Izah, S. C. (2017). Health risk assessment of heavy metal in smoked Trachurus trachurus sold in Yenagoa, Bayelsa state, Nigeria. *International Journal of healthcare and medical sciences, 3*(9), 62–69.

[17] Seiyaboh, E. I., Kigigha, L. T., Aruwayor, S. W., Izah, S. C. (2018). Level of selected heavy metals in liver and muscles of cow meat sold in Yenagoa Metropolis, Bayelsa State, Nigeria. *International journal of public health and safety, 3,* 154.

[18] Prashanth, L., Kattapagari, K. K., Chitturi, R. T., Baddam, V. R. R., Prasad, L. K. (2015). A review on role of essential trace elements in health and disease. *Journal of Dr. NTR university of health sciences, 4*(2), 75–78.

[19] Muhammad, I., Ashiru, S., Ibrahim, I. D., Salawu, K., Muhammad, D. T., Muhammad, N. A. (2014). Determination of some heavy metals in wastewater and sediment of artisanal gold local mining site of Abare Area in Nigeria. *Journal of environmental treatment techniques, 1*(3), 174–182.

[20] Wambebe, N. M., Duan, X. (2020). Air quality levels and health risk assessment of particulate matters in Abuja Municipal Area, Nigeria. *Atmosphere, 11*, 817,

[21] Owoade, K. O., Hopke, P. K., Olise, F. S., Ogundele, L. T., Fawole, O. G., Olaniyi, B. H., Jegede, O. O., Ayoola, M. A., Bashiru, M. I. (2015). Chemical compositions and source identification of particulate matter. (PM2.5 and PM2.5–10). from a scrap iron and steel smelting industry along the Ife–Ibadan highway, Nigeria. *Atmospheric pollution research, 6,* 107–119.

[22] Obioh, I. B., Ezeh, G. C., Abiye, O. E., Alpha, A., Ojo, E. O., Ganiyu, A. K. (2013). Atmospheric particulate matter in Nigerian megacities. *Toxicological and environmental chemistry, 95*(3), 379–385.

[23] Ayua, T. J., Tyovenda, A. A., Sombo, T., Tikyaa, E. V., Igbawua, T. (2020). Fine particulate matter and heavy metals pollution status in ambient air of some selected industrial sites in Northern Nigeria. *Journal of geoscience and environment protection, 8*, 1–13.

[24] Offor, I. F., Adie, G. U., Ana, G. R. E. E. (2016). Review of particulate matter and elemental composition of aerosols at selected locations in Nigeria from 1985-2015. *Journal of health pollution, 10,* 1–18.

[25] Richard, G., Nwagbara, M. O., Weli, V. E. (2019). Seasonality in particulates distribution from dumpsites in the Niger Delta Region of Nigeria: A health risk assessment approach. *International journal of research in environmental science, 5*(2), 7–15.

[26] Mohammadi, A. A., Zarei, A., Majidi, S., Ghaderpoury, A., Hashempour, Y., Saghi, M. H., Ghaderpoori, M. (2019). Carcinogenic and non-carcinogenic health risk assessment of heavy metals in drinking water of Khorramabad, Iran. *MethodsX*, *6*, 1642–1651.

[27] Uzoekwe, S. A., Izah, S. C., Aigberua, A. O. (2021). Environmental and human health risk of heavy metals in atmospheric particulate matter. (PM10). around gas flaring vicinity in Bayelsa State, Nigeria. *Toxicology and environmental health Sciences,7*(3), 34–38.

[28] Bhutiani, R., Kulkarni, D. B., Khanna, D. R., Gautam, A. (2017). Geochemical distribution and environmental risk assessment of heavy metals in groundwater of an industrial area and its surroundings, Haridwar, India. *Energy, ecology and environment, 2*(2), 155–167.

[29] Uzoekwe, S. A., Aigberua, A. O. (2019). Heavy metal distribution and assessment of ecological risk in surface waters and sediment within the flow station in Kolo Creek, Nigeria. *Journal of chemical society of Nigeria, 44*(5), 809–824.

[30] Aghoghovwia, O. A., Izah, S. C., Miri, F. A. (2018). Environmental risk assessment of heavy metals in sediment of Nun River around Gbarantoru and Tombia Towns, Bayelsa State, Nigeria. *Biological evidence, 8*(3), 21–31.

[31] Hakanson, L. (1980). An ecological risk index for aquatic pollution control. A sedimentological approach. *Water research, 14,* 975–1001.

[32] Izah, S. C., Bassey, S. E., Ohimain, E. I. (2018). Ecological risk assessment of heavy metals in cassava mill effluents contaminated soil in a rural community in the Niger Delta Region of Nigeria. *Molecular soil biology, 9*(1), 1–11.

[33] Xu, Z. Q., Ni, S. J., Tuo, X. G. (2008). Calculation of heavy metals toxicity coefficient in the evaluation of potential ecological risk index. *Environmental science and technology, 31,* 112–115.

[34] Soliman, N. F., Nasr, S. M., Okbah, M. A. (2015). Potential ecological risk of heavy metals in sediments from the Mediterranean coast, Egypt. *Journal of environmental health science and engineering*, *13*(1), 1–12.

[35] Tomlinson, D., Wilson, J., Harris, C., Jeffrey, D. (1980). Problems in the assessment of heavy-metal levels in estuaries and the formation of

a pollution index. *Helgolander meeresunters, 33,* 566–575.

[36] Muller, G. (1969). Index of geo-accumulation in sediments of the Rhine River, *Geo journal*, *2*(3), 108–118.

[37] Kowalska, J., Mazurek, R., Ga̧siorek, M., Setlak, M., Zaleski, T., Waroszewski, J. (2016). Soil pollution indices conditioned by medieval metallurgical activity - a case study from Krakow. (Poland). *Environmental pollution ,218*, 1023–1036.

[38] Cerón Bretón, J. G., Cerón Bretón, R. M., Espinosa Guzman, A. A., Guarnaccia, C., Martínez Morales, S., Lara Severino, R. D. C., Espinosa Fuentes, M. D. L. L. (2019). Trace metal content and health risk assessment of PM10 in an urban environment of León, Mexico. *Atmosphere*, *10*(10), 573,

[39] Di Vaio, P., Magli, E., Caliendo, G., Corvino, A., Fiorino, F., Frecentese, F., Perissutti, E. (2018). Heavy metals size distribution in PM10 and environmental-sanitary risk analysis in Acerra (Italy). *Atmosphere*, *9*(2), 58.

[40] Liu, K., Shang, Q., Wan, C. (2018). Sources and health risks of heavy metals in PM2. 5 in a campus in a typical suburb area of Taiyuan, North China. *Atmosphere*, *9*(2), 46,

[41] Wu, L., Luo, X. S., Li, H., Cang, L., Yang, J., Yang, J., Tang, M. (2019). Seasonal levels, sources, and health risks of heavy metals in atmospheric PM2. 5 from four functional areas of Nanjing city, eastern China. *Atmosphere*, *10*(7), 419,

[42] Izah, S. C., Aigberua, A. O. (2020). Microbial and heavy metal hazard analysis of edible tomatoes (Lycopersicon esculentum) in Port Harcourt, Nigeria. *Toxicology and environmental health sciences*, *12*(4), 371–380.

[43] Shabanda, I. S., Koki, I. B., Raof, S. F. A., Lee, Y. H., Mainal, A., Bakar, N. K. A., Khor, S. M. (2019). Distribution of heavy metals in roadside dust of petaling Jaya, Malaysia with multivariate and correlation analyses for source identification. *International journal of environmental analytical chemistry 101*(2), 184–207.

[44] Rezeai, H., Zaei, A., Kamarehie, B., Jafari, A., Fakhri, Y., Bidarpoor, F., Karami, M. A., Farhang, M., Ghaderpoori, M., Sadeghi, H., Shalyari, N. (2019). Levels, distributions and health risk assessment of lead, cadmium and arsenic found in drinking groundwater of Dehgolan's villages, Iran. *Toxicology and environmental health sciences, 11*(1), 54–62.

[45] Kim, H. S., Kim, Y. J., Seo, Y. R. (2015). An overview of carcinogenic heavy metal: Molecular toxicity mechanism and prevention. *Journal of cancer prevention, 20*(4), 232–240.

[46] US Department of Health and Human services. (1999). Agency for toxic substances and disease registry-ATSDR.

[47] Muhle, H., Steenland, K. (2006). Lead and lead compounds. *Internatinal Agancy for Research on Cancer (IARC) Monographs,* 87, 12–16.

[48] Sall, M. L., Diaw, A. K. D., Gningue-Sall, D., Aaron, S. E., Aaron, J-J. (2020). Toxic heavy metals: impact on the environment and human health, and treatment with conducting organic polymers, a review. *Environmental science and pollution research, 27*, 29927–29942.

[49] Anake, W. U., Benson, N. U., Theophilus Tenebe, I., Emenike, P. C., RE E Ana, G., Zhang, S. (2020). Chemical speciation and health risks of airborne heavy metals around an industrial community in Nigeria. *Human and ecological risk assessment: An international journal, 26*(1), 242-254.

[50] Niu, Y., Wang, F., Liu, S., Zhang, W. (2021). Source analysis of heavy metal elements of PM2.5 in cateen in a university in winter. *Atmospheric environment, 244,* 117879.

[51] Izah, S. C., Bassey, S. E., Ohimain, E. I. (2017). Assessment of pollution load indices of heavy metals in cassava mill effluents contaminated soil: a case study of small-scale cassava processing mills in a rural community of the Niger Delta region of Nigeria. *Bioscience methods, 8*(1), 1-17.

[52] Izah, S. C., Bassey, S. E., Ohimain, E. I. (2017). Geo-accumulation index, enrichment factor and quantification of contamination of heavy metals in soil receiving cassava mill effluents in a rural community in the Niger Delta region of Nigeria. *Molecular soil biology, 8*(2), 7-20.

[53] Adeyemi, A. A., Ojekunle, Z. O. (2021). Concentrations and health risk assessment of industrial heavy metals pollution in

groundwater in Ogun state, Nigeria. *Scientific African, 11,* e00666.

[54] Joel, E. S., Maxwell, O., Adewoyin, O. O., Ehi-Eromosele, C. O., Embong, Z., Oyawoye, F. (2018). Assessment of natural radioactivity in various commercial tiles used for building purposes in, Nigeria. *MethodsX, 5,* 8–19.

[55] MohseniBandpi, A., Eslami, A., Ghaderpoori, M., Shahsavani, A., Jeihooni, A. K., Ghaderpoury, A., Alinejad, A. (2018). Health risk assessment of heavy metals on PM2.5 in Tehran air, Iran. *Data brief, 17,* 347–355.