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Health Impact of Heavy Metals in Soil and Vegetables near a Gas-Powered Thermal Plant in Nigeria

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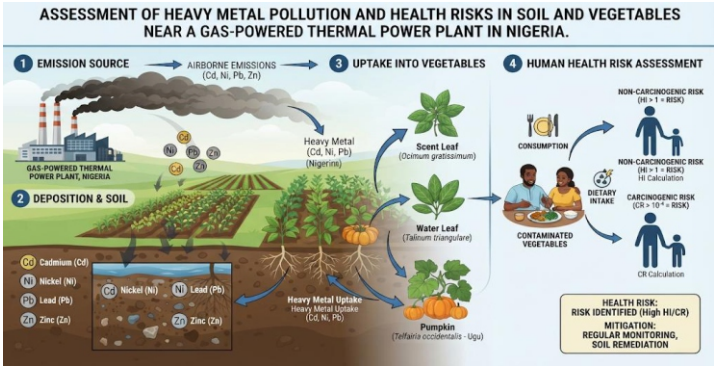
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ABSTRACT

This study assessed the ecological and human health risks of heavy metals in soil and vegetables near a gas-powered thermal power plant in Nigeria and their impact on public health. Levels of heavy metals were determined. Mean concentrations of Pb, Cr, Cd, Ni, Mn, Fe, Cu and Zn in the soil were 3.73, 0.16, 4.12, 7.10, 6.46, 1344.27, 10.84 and 12.81 mg/kg, respectively, while in vegetables (except for Pb) the respective values were 3.89, 0.05, 1.18, 5.77, 9.08, 1.21 and 1.78 mg/kg. These concentration values, except Cd, were below the safe limits. Results of the carcinogenic risk of combined pollution of HMs in soil varied from 9.31E-05 to 4.72E-04 in children and 5.16E-05 to 2.81E-04 in adults, while in vegetables, from 8.10E-08 to 1.31E-06 in children and 2.58E-07 to 4.22E-06 in adults. For the metals, Ni and Cd were the dominant metals and accounted for 96.99% of the total carcinogenic risk in soil. The Pearson correlation shows positive correlation in soil for Pb-Zn (r=0.71), Mn-Zn (r=0.76), in vegetable for Cr-Cd (r=0.81), Cr-Zn (r=0.81) and Fe-Cu (r=0.84) while others show weak correlation. Also, there was positive correlation between soil and vegetables HMs: soil-Scent leaf for Cr (r=0.89), soil-curry for Ni and Mn (r>0.90), soil-water leaf for Cd and Fe (r≥0.85), soil-flute pumpkin for Zn (r=0.88) and there was a strong positive correlation in soil-fluted pumpkin for Cd (r=0.84).

Keywords: *Heavy Metals, Soil, Edible Vegetables, Gas-powered, Thermal Plant, Pollution, Carcinogenic Risk.*

Graphical Abstract



Introduction

Heavy metal contamination poses a significant and growing threat to environmental and public health, especially in developing nations where industrial growth often outpaces effective regulatory oversight [1,2,3]. One of the major anthropogenic sources of heavy metal emissions is the combustion of fossil fuels in thermal power plants. Thermal power plants, whether gas- or oil-fired, release various pollutants, including heavy metals like lead (Pb), cadmium (Cd), chromium (Cr), and nickel (Ni), into the atmosphere and surrounding environment through ash, flue gas, and effluent discharges. These contaminants, which include known carcinogens and neurotoxins, are non-biodegradable and tend to accumulate in living organisms. They can enter the food chain through various pathways, including contaminated soil and water used for agriculture [4,5]. The accumulation of heavy metals from thermal power plants in the environment has severe consequences. In the soil, they can disrupt microbial activity, reduce fertility, and negatively impact plant growth. When heavy metals are present in the soil, plants can absorb them through their roots via bioaccumulation. This process creates a direct link to the human food chain, especially in agricultural areas where vegetables are grown for local consumption. Studies have confirmed this pathway, showing that vegetables grown near industrial sites are contaminated with heavy metals at concentrations that exceed permissible limits [6,7,8].

The Niger Delta region of Nigeria, and specifically Rivers State, is a hub of industrial activity, including thermal power generation, which has raised concerns about environmental pollution. Studies across Nigeria have already shown that areas near industrial sites, including a thermal station in Lagos, have elevated concentrations of heavy metals in their soil and vegetation, often exceeding international safety standards [9-12]. This is of particular concern in a state like Rivers State, where local communities often rely on subsistence farming and the consumption of locally grown vegetables.

A recent study on surface water in Rivers State confirmed that certain heavy metals exceeded national and international standards, leading to significant potential cancer and non-cancer risks [6]. Similarly, some reviews found that toxic metals had accumulated in edible plants in the South-South zone of Nigeria, confirming a widespread threat to public health. The presence of heavy metals in edible plants presents a direct health risk to humans [13, 14]. For instance, consuming crops contaminated with high levels of cadmium and lead has been linked to severe health issues, including kidney dysfunction, neurological disorders, and an increased risk of cancer [15]. Therefore, assessing the extent of heavy metal contamination in the soil and vegetables cultivated around a thermal plant in Rivers State is critical for understanding the potential ecological damage and the direct health risks faced by the local population. This research aims to provide a comprehensive assessment of these risks, which can inform environmental policies and public health interventions to protect the affected communities.

Methodology

Map of Study Area and Sample Locations

Afam IV Power Station is located in Afam, Okoloma, Oyigbo LGA, Rivers State, Nigeria, as shown in the satellite map of study area - Afam IV power station, Afam IV-V GT Power Plant Nigeria - GEO. globalenergyobservatory.org. Retrieved 2024-08-20 [16]. Sampling was done in the dry season. Detailed geographic locations for the Afam IV Power Station and sample locations are shown in Table 1. Four sample locations were selected in the area; locations SL1-SL4 were 100 m, 200 m, 300 m, and 400 m from the power plant perimeter fence, respectively.

Sample Collection and Pretreatment

Global Positioning System (GPS), measuring tape, field notebook, stainless-steel auger, digital camera, knife, marker/tape, and sample bags were used for sample collection. The sampling was carried out in November 2023. Four sample locations were selected in the area, namely SL1, SL2, SL3, and SL4 which were 100 m, 200 m, 300 m, and 400 m away from the power plant perimeter fence, respectively. The sample collection was based on a multi-point (5 points) mixed method, which consisted of randomly collecting five sub-samples at the same sample location and bulked together to form a composite sample. After the removal of the exposed surface, eight soil samples in triplicate were collected with a stainless-steel auger that had been pre-cleaned with concentrated nitric acid, to depths of 0-10 cm and 10-20 cm. Each soil sample (500 g), consisted of five sub-samples from five points 20 m away from each other within the same sampling location, collected randomly, pooled, and homogenized to form a representative sample. Before being transferred into acid-cleaned black polythene bottles, materials like rocks, gravels, and organic debris were removed manually from the soil samples, screened with a thin mesh and labelled (date of collection, sampling location code and GPS coordinates) properly.

Four species of edible vegetable samples [*Ocimum gratissimum,* (Scent Leaf), *Murraya koenigii,* (Curry Leaf), *Talinum fruticosum* (Waterleaf) and *Telfairia occidentalis* (Fluted pumpkin)] were collected from the same points of SL1 of soil sample collection, with the aid of a stainless-steel knife. Four replicates of each vegetable were collected from the sampling zone. The vegetable samples were placed in sterile polyethylene zip bags, then properly labelled and placed in the ice chest.

In total, ten samples (8 - soil and 4 - edible part of vegetables) collected were from the vicinity of the Afam IV Plant and conveyed to the laboratory.

In the laboratory, each screened soil sample was then dried at a temperature of 50 ^{0}C in an oven until a constant weight was obtained. The dried soil samples were then crushed and pulverised into fine powder, homogenized in a thoroughly cleaned agate mortar and pestle, sieved through a 2 mm mesh plastic sieve, demagnetized with a magnetic rod and kept in sealed vials labelled until chemical analysis was carried out. The homogenised soil sample were preserved in a refrigerator at 4^{o}C. The samples for the four vegetables species were carefully washed with running tap water and distilled water and the edible parts were shredded after discarding the non-edible portions and then oven-dried at 70–80 °C to attain constant weight. The dried vegetable samples were homogenised by grinding with a porcelain mortar and pestle and sieved through 2 mm nylon sieve. Both homogenised soil and vegetable samples were preserved in a refrigerator at 4 ^{o}C according to the US-EPA recommended sampling protocols (Method 8100) prior to analysis.

Sample Extraction, Digestion and Analysis of Heavy Metals

The soil and vegetable samples were digested using the aqua regia procedure of ISO (1995), Method 3050 [17]. The aliquots of the digestates were analysed for total Pb, Cr, Cd, Ni, Mn, Fe, Cu and Zn using Atomic Absorption Spectrophotometer (AAS) with an air/acetylene flame. The concentrations of the various heavy metals in the soil and vegetable samples were expressed in mg/kg dw (dry weight). The recovery was between 94.3 – 100.6% for all the analysed metals.

Instrumental Analysis, Quality Assurance and Quality Control

During the research, quality assurance and quality control methods were established to ensure accuracy and validity of the results. Vessels and containers were immersed in 5% nitric acid (HNO_3) for over than 24 hours, and were subsequently rinsed with distilled water and completely dried. Stock solutions of the working standards (Pb, Cr, Cd, Ni, Mn, Fe, Cu and Zn) were prepared by dissolving accurate weighing of the nitrate salts in standardised volumes of solution, yielding a working stock of concentration of 1000 mg/L in 0.01 mol/l HNO_3. Freshly prepared weekly, these working solutions were formed from the stock standard solutions by serial dilution in de-ionised water and stored at -4 °C in the dark. All flasks, plastic containers and glassware were rinsed with de-ionised water and soaked in 2 M nitric acid prior to use. Heavy metal (HMs) recovery was tested by spiking 1 g of sample with standardised aliquots of each HMs, and the concentrations were subsequently determined after the complete analysis of the spiked samples [18]. The recovery of heavy metals ranged between 94.3% and 100.6%. The limit of detection (LOD) and limit of quantification (LOQ) for the heavy metals were established as the lowest concentration of the specific metal in the spiked samples that produced a signal-to-noise (S/N) ratio greater than or equal to 3 and 10, respectively.

Health Risk Assessment

The last step in human health risk assessment is the risk characterisation. An individual at any age might be exposed to soil and vegetables contaminated through these exposure routes, where it is more relevant to generalise health risk assessment calculations for adults (from 18 years of age) and children (from 0-6 years of age) [19].

The term "adult" also represents both genders, hence using the same parameters for both. A wide variety of adverse health effects can be attributed to the presence of heavy metals in human, with carcinogenic risk being expressed by the total carcinogenic risk (TCR) [20]. These indices are an indicator for the potential development of carcinogenic diseases in humans and will arguably provide a more profound understanding of soil and vegetable pollution [21]. On the basis of the index values, categorisation as well as determination of the severity of danger to human health take place [22]. Moreover, potential results for additional treatment of the investigated soil can be acquired, should excess pollution exist.

Exposure Assessment

Exposure assessment of heavy metals can be carried out via accidental direct ingestion of the soil through the mouth, inhalation of suspended soil particulates and absorption of the soil through the skin, and oral intake of vegetables. The carcinogenic doses (lifetime average daily doses, LADDs) of HMs via the three main paths (ingestion, inhalation, and dermal contact) were calculated according to the equations (1)-(3) adapted from [23, 24, 25]:

$$LADDing = \frac{Csoil/veg \times IRsoil/veg \times EF \times ED \times CF}{BW \times ATca} \quad (1)$$

$$LADDinh = \frac{Csoil \times IRinh \times EF \times ET \times ED}{PEF \times 24 \times BW \times ATca} \quad (2)$$

$$LADDderm = \frac{Csoil \times SA \times AF \times ABSd \times EF \times ED \times CF}{BW \times ATca} \quad (3)$$

Parameters used for the dose estimation for children and adults are shown in Table 2.

Soil-to-human Health Risk Assessment (Carcinogenic Risk)

The cancer risk (CR) estimates of carcinogenic chemicals represent the incremental probability that an individual might develop cancer over a lifetime as a result of as a result of total exposure to the potential carcinogens. The health risk associated with carcinogenic contaminants was estimated based on three exposure pathways (accidental ingestion, inhalation and dermal contact for soil, and oral ingestion for vegetables) to HMs following an already established criteria [25]. In this study, the carcinogenic contaminants are Pb, Cr(VI), Cd, and Ni (defined as carcinogenic metals, cHMs), and the concentration of Cr(VI) was estimated as one seventh (1/7) of the total Cr concentration [26] and used for the computation of lifetime average daily dose (LADD). The cancer risks (CRs) for carcinogens (cHMs) were obtained as the products of carcinogenic doses and the corresponding cancer slope factors (SF), expressed by equation (4): The values of cancer slope factors of HMs used in this study are given in Table 3.

$CR_{i,x} = LADD_{i,x} \times SF_{i,x}$ (4)

The cancer risk of contaminant i is the sum of the cancer risks for the three exposure routes and expressed by equation (5):

$CR_{i,soil} = \sum CR_i = CR_{ing} + CR_{inh} + CR_{der}$ (5)

Vegetable-to-human Health Risk Assessment

$CR_{i,veg} = LADD_{ing} \times SF_{ing}$ (6)

$CR_{i,veg} = \sum CR_{i,ing}$ (7)

Soil-vegetable-to-human Health Risk Assessment

The overall accumulative cancer risk (TCR) for an individual, accounting for the combined contamination of all the cHMs in soil and vegetable samples and for all exposure pathways in the study area is the sum of the CR_{soil} and CR_{veg}, while the total cancer risk (TCR) was used to assess the effects of multiple carcinogenic elements, calculated by the summation of LCR.

Total cancer risk in soil (CR_{soil}) and vegetable (CR_{veg}) value represents the cumulative risk factor from exposure to the investigated HMs in both soil and vegetable, and is given by Equation (8):

$TCR = CR_{soil} + CR_{veg}$ (8)

The lifetime cancer risk (LCR) for an individual accounting is the sum of the total cancer risk for both age groups by Equation (9) [27]:

$LCR = TCR_{child} + TCR_{Adult}$ (9)

Possible Sources of Heavy Metals (Pearson Correlation Analysis)

Pearson correlation analysis is a multivariate statistical analysis commonly used to evaluate the possible sources of origin of contaminants (HMs) and is useful for establishing the value of the relationship among the investigated metals [28, 29].

Statistical Analysis

Descriptive statistical operations like minimum, maximum, mean, standard deviation and coefficient of variation were used to analyze the measured data. Descriptive statistics were calculated using the Microsoft Excel version 2010 (Microsoft Office, Microsoft, Redmond, WA, USA) and SPSS 25.0 (SPSS Inc., 2017). A Pearson correlation matrix was also used.

Results

Concentrations of Heavy Metals in Soil and Vegetables

The mean concentration of heavy metals in soil at the sample locations in comparison with international agencies' permissible limits is presented in Figure 1, while that of vegetables is presented in Figure 2. The trend of the heavy metal contents in soil on the basis of the average concentrations observed is followed as Fe > Zn > Cu > Cr > Ni > Mn > Cd > Pb. The concentrations of HMs in soil samples ranged from 2.03 to 5.70 mg/kg with mean of 3.73 mg/kg for Pb, 7.30 to 10.63 mg/kg with mean of 9.16 mg/kg for Cr, 1.61 to 7.59 mg/kg with mean of 4.12 mg/kg for Cd, 4.87 to 9.50 mg/kg with mean of 7.10 mg/kg for Ni, 4.38 to 9.18 mg/kg with mean of 6.46 mg/kg for Mn, 1148.43 to 1496.76 mg/kg with mean of 1344.27 mg/kg for Fe, 8.21 to 13.69 mg/kg with mean of 10.84 mg/kg for Cu and 11.05 to 16.99 mg/kg with mean of 12.81 mg/kg for Zn. Based on the mean concentrations found in vegetables, the abundance of heavy metals decreased in the sequence of Fe > Mn > Cr > Zn > Cu > Ni > Cd. Heavy metal concentration in vegetables samples varied from 2.60 to 5.12 mg/kg with an average of 3.89 mg/kg for Cr, < 0.012 to 0.12 mg/kg with an average of 0.05 mg/kg for Cd, 0.90 to 1.65 mg/kg with an average of 1.18 mg/kg for Ni, 4.65 to 7.95 with an average of 5.77 mg/kg for Mn, 2.07 to 12.80 mg/kg with an average of 9.08 for Fe, 0.91 to 1.79 mg/kg with an average of 1.21 mg/kg for Cu and 1.04 to 2.91 mg/kg with an average of 1.78 mg/kg for Zn. The content of Pb was below the instrument's limit of quantification (LOQ < 0.001 mg/kg) in the four species of vegetables.

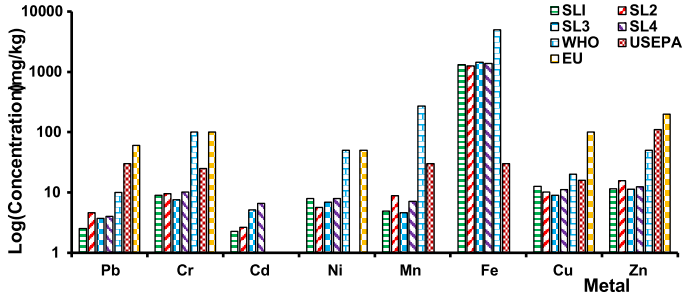


Figure 1. Mean concentrations of heavy metals in soil samples are represented in a logarithmic scale

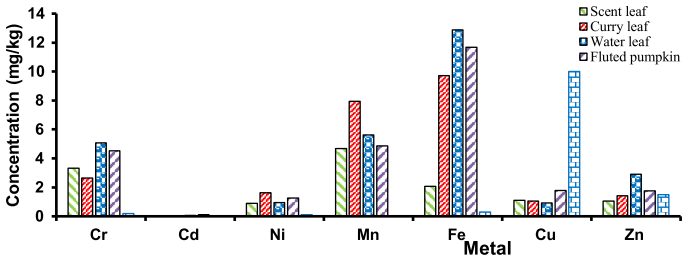


Figure 2. Mean concentrations of heavy metals in vegetable samples

The coefficient variations (CV%) of metals in vegetables ranged between 47.09 (Mn) and 191.46 (Cd), except Cd, which had 50.28, suggesting natural processes, while Cd shows human activities.

Human Health Risk Assessment

The descriptive statistical analysis of estimated carcinogenic risks associated with exposure through ingestion, inhalation and dermal contact of soil HMs are presented in Tables 4 and 5. This showed that the contributions of the exposure pathways in term of risks followed the same order of ingestion > dermal absorption > inhalation for both children and adults. The carcinogenic risks of HMs in soil and vegetables followed the patterns of Ni > Cd > Cr(VI) > Pb and Ni > Cr > Cd, respectively. The carcinogenic risk indices associated with HMs in soil for children and adults ranging from 5.54E-05 to 1.45E-04 to with an average of 9.57E-05, and 2.77E-05 to 7.40E-05, with a mean of 4.83E-05, respectively. Also, carcinogenic risk indices associated with vegetable HMs for children and adults range from 8.04E-08 to 1.83E-07 with an average of 1.20E-07, and 2.58E-07 to 5.88E-07 with a mean of 3.87E-07, respectively (Table 6). Based on the mean total cancer risk of soil HMs, Ni accounted for 60.10% for children and 57.39% for adults of the total cancer risk associated with HMs in soil. Similarly, Ni contributed 78.18% of the mean total cancer risk of vegetable HMs for both children and adults. For HMs in soil samples, the contributions of the exposure pathways to total carcinogenic risk, TCR_{soil}, for children and adults followed a trend of ingestion (55.52% and 58.86%) > dermal absorption (44.04% and 32.68%) > inhalation (0.44% and 8.46%) (Table 7). For the studied metals, Ni and Cd were the dominant metals and accounted for 96.99% of total carcinogenic risk due to soil HMs (TCR_{soil}) for both children and adults. The total carcinogenic risk due to soil HMs is moderate according to carcinogenic risk classification to the total carcinogenic risk (TCR_{soil}). Taking into consideration the results of ecological risk and health risk assessments, measures must be taken to reduce and/ or eliminate the buildup of Cd and Ni.

Pearson Correlation Matrix Analysis

Pearson correlation analysis was performed to explore the strength of the inter-relationships between HMs in soil and HMs in vegetables and shown in Tables 8 and 9. For the correlation analysis of HMs in soil (Table 8 down), there was significant positive correlation for Pb-Zn (r=0.71, p>0001) and Mn-Zn (r=0.76, p > 0.01). The rest four metals (Cr, Cd, Fe, and Cu) have very weak or no correlation. In vegetables (Table 8 up), the following HM pairs: Cr-Cd (r=0.81), Cr-Zn (r=0.81), Fe-Cu (r=0.84) showed significant positive correlation. The other metal pairs of Cr-Ni, Cr-Cu, Ni-Mn, Ni-Fe, Ni-Cu, Ni-Zn, Mn-Cu and Mn-Zn have less or no correlation. For HMs in soil and vegetables (Table 9), very strong, significant positive correlations were found between soil HMs and vegetable HMs as follows: soil-scent leaf for Cr ($r = 0.89$, $p < 0.001$), soil-curry for Ni and Mn ($r > 0.90$, $p < 0.001$), soil-water leaf for Cd and Fe ($r \geq 0.85$, $p < 0.001$), and soil-flute pumpkin Zn ($r = 0.88$, $p < 0.001$). Strong, significant positive correlation was found in soil-fluted pumpkin for Cd (r=0.84, p < 0.01).

Discussion

The concentrations of Pb, Cr, Ni, Mn, Fe, Cu, and Zn were observed under the safe limit of FAO/WHO as reported [30, 31, 32]. However, Cd concentration exceeded three safe limit standards. The coefficient of variation (CV) is an important indicator for determining the degree of interference of soil HM concentration distribution by anthropogenic activities. The degree of variability can be classified as weak variability (CV < 10%), moderate variability (10% ≤ CV < 100%), and strong variability (CV > 100%) [33]. The concentrations of the analysed eight metals in the four species of vegetables studied were compared with the permissible limit of the World Health Organisation [34] and found to be above, except for Cu. The coefficient of variations (CV%) of metals in soil (Table 4) ranged from 8.56% (Fe) and 50.28% (Cd), while that of vegetables (Table 5) ranged between 47.09% (Mn) and 191.46% (Cd). The CV for Cd in the vegetables shows a strong variability, which points to anthropogenic influences such as localized industrial activities and high vehicular movement in that vicinity.

Among the HM contaminants, based on the mean values of the potential ecological risk factor and potential ecological risk index, cadmium posed the highest risk of soil contamination and controlling metal, accounting for 99.5% of the ecological risk burden and toxicity of the soil. Other metals (Pb, Cr, Ni, Mn, Fe, Cu and Zn) accounted for about 0.5% of the ecological burden in the soil of the study area.

Ingestion is the dominant route of three exposure pathways for both children (94.04%) and adults (95.06%) of eight metals. This aligns with other reports that the route of exposure can affect the degree of potential health hazards [35]. It is revealed that the HQ due to ingestion (HQ_{ing}) is the main route of exposure to metals in soil, which leads to a higher risk for children and adults, which aligns with previous reports [36, 37]. The total HI of the combined pollution of HMs in the soil and vegetables was less than unity, indicating no non-carcinogenic health effects due to exposure through accidental ingestion, inhalation and dermal absorption of soil HMs and dietary intake of HM-contaminated vegetables grown in the vicinity of Afam (IV) Power Plant. Based on HM mean carcinogenic risk in soil, Ni and Cd accounted for 60.10% and 37.00% for children and 57.39% and 39.48% for adults while in vegetables, Ni for both children and adults contributed 78.18%.

In the human health risk assessment, nickel accounted for the most toxicity to the public in the study area. The total lifetime carcinogenic risk (TLCR) of a resident due to combined contamination of HMs in soil and vegetable samples ranged from 1.45E-04 to 7.59E-04 with a mean of 4.70E-04. The total carcinogenic risk associated with exposure through ingestion, inhalation and dermal absorption in HM-contaminated soil (CR_{soil}) accounted for 99.49% of the total lifetime carcinogenic risk (TLCR) in the study area. According to carcinogenic risk classification by NYSDOH [38] and Roy et al. [39], the carcinogenic risk of the study area is moderate. It is worth noting that people could be exposed to HMs through other dietary pathways as well, and thus, the real risk scenario would be greater than that estimated in this study [40]. There is a need to take necessary measures to control the health hazards from the Afam (IV) power station. The study is helpful to avoid the possibility of increasing pollution of soil and vegetables in the study area and in ensuring public safety.

Pearson's correlation coefficient matrix is necessary to determine the spatial and temporal inter-relationships among and in between the measured concentrations of heavy metals in the soil and vegetables. Inter-relationship between metals can be used to identify the possible sources and accumulation pathways of these contaminants in the soils and vegetables in an environmental setting [41] and on the assumption that two or more components may correlate either due to atmospheric behaviour or common origin. For Correlation analysis among HMs in soil (Table 8 down), the Pb-Zn (r=0.71) and Mn-Zn (r=0.76) have significantly positive correlations at $p < 0.01$, suggesting that the paired metals may probably have common pollution sources [42], The rest four metals (Cr, Cd, Fe, and Cu) have very weak or no correlation, indicating different anthropogenic contamination source. In vegetables (Table 8 up), strongly significant positive correlations were observed among the three HM pairs: Cr-Cd (r=0.81), Cr-Zn (r=0.81), Fe-Cu (r=0.84) at $p < 0.001$. The higher correlation coefficient values between the HMs possibly indicated mutual dependence as well as revealed same origin or nearly common sources and accumulation pathways in soil and vegetables [43]. This means that Zn and Cr were strongly coupled with Pb and Mn in soil, and Cd and Zn in vegetables, respectively. The other metal pairs of Cr-Ni, Cr-Cu, Ni-Mn, Ni-Fe, Ni-Cu, Ni-Zn, Mn-Cu and Mn-Zn have less or no correlation.

Correlation analysis of HM concentrations in soil and vegetable species, indicated a significant relationship between soil-scent leaf and Cr, Fe, Zn; soil-curry leaf and Ni, Mn and Fe; soil-waterleaf and Cd and Fe; and soil-fluted pumpkin and Cd and Zn. This means that these metals tend to accumulate together. There were no significant relationships observed for the contents of Cr in soil and Cr in curry leaf, waterleaf and fluted pumpkin; Cd in soil-scent leaf and soil-curry leaf; and Ni and Cu in soil and Ni and Cu in scent leaf, waterleaf and fluted pumpkin. The possible reason was that the vegetables had different bioconcentration abilities for different Hms.

Table 1: GPS Coordinates of the sample locations

S/No	Sample location	ID	Type of sample	Coordinates	
				Latitude (N)	Longitude (E)
1	100 m from Afam IV Plant	SLI	Soil,	4.84953	7.35694
2	200 m from Afam IV Plant	SL2	Soil	4.85289	7.25372
3	300 m from Afam IV Plant	SL3	Soil	4.85471	7.26196
4	400 m from Afam IV Plant	SL4	Soil	4.85732	7.25924

Table 2: Parameters applied in exposure assessment model through three pathways

Variables	Definition	Values		References
		Child	Adult	
C_{soil} (mg/kg)	HM concentration in soil	Tables 5		This study
C_{veg} (mg/kg)	HM concentration in vegetable	Tables 6		This study
IR_{soil} (mg/day)	Soil ingestion rate for receptor	200	100	[23]
IR_{air} (mg/day)	Air inhalation rate for receptor	8.85	16	[23]
IR_{veg} (mg/day)	Vegetable ingestion rate for receptor	0.77	1.025	[23]
EF (d/year)	Exposure frequency	350		[23]
ED (year)	Exposure duration	6	30	[23]
BW (kg)	Average body weight	16.2	61.8	[24]
AT_{ca} (day)	Averaging time for carcinogenic	LT × 365		[25]
AF (mg/cm^2)	Soil to skin adherence factor	0.2	0.07	[23]
SA (cm^2/event)	Skin surface area available for exposure	2800	5700	23]
LT (year)	Lifetime	72		[23]
ET (hr/day)	Exposure time	24		[23]
PEF (m^3/kg)	Soil to air particulate emission factor	1.36×10^9		[23]

Table 3: Reference dose (mg/kg-day) and cancer slope factor (kg-day/mg) of HMs for ingestion, inhalation and dermal pathways

HM	RfD_{ing}	RfD_{inh}	RfD_{derm}	CSF_{ing}	CSF_{inh}	CSF_{derm}
Pb	3.50E-03	3.52E-03	5.25E-04	8.50E-03	4.20E-02	8.50E-02
Cr(VI)	3.00E-03	2.86E-05	3.00E-03	5.00E-01	4.20E+01	2.00E+01
Cd	1.00E-03	1.00E-05	1.00E-05	6.10E+00	6.30E+00	6.10E+00
Ni	2.00E-02	2.06E-02	5.40E-03	1.70E+00	8.40E+01	4.25E+01
Mn_d[a]	1.40E-01	1.43E-05	1.84E-03	-	-	-
Mn_{nd}[b]	2.40E-02	1.43E-05	1.84E-03	-	-	-
Fe	7.00E-01	2.20E-04	7.00E-02	-	-	-
Cu	4.00E-02	4.02E-02	1.20E-02	-	-	-
Zn	3.00E-01	3.00E-01	6.00E-02	-	-	-

[a] diet-linked value and [b] non-diet value for RfD_{ing} [25, 22]

Table 4: Descriptive statistical analysis of heavy metal concentrations (mg/kg) in soil samples

	Pb	**Cr**	**Cd**	**Ni**	**Mn**	**Fe**	**Cu**	**Zn**
Mean	3.73	9.16	4.12	7.10	6.46	1344.27	10.84	12.81
SD [a]	1.17	1.32	2.07	1.47	1.78	115.06	1.61	2.01
Max	5.70	10.63	7.59	9.50	9.18	1496.76	13.69	16.99
Min	2.03	7.30	1.61	4.87	4.38	1148.43	8.21	11.05
Kurtosis	-0.92	-1.75	-1.19	-0.79	-1.56	-0.85	-0.83	0.13
Skewness	0.10	-0.35	0.40	0.35	0.29	-0.64	-0.04	1.16
CV (%) [b]	31.34	14.39	50.28	20.66	27.57	8.56	14.84	15.70
FAO/WHO [c]	10	100	≤ 0.3	50	2000	5000	20	50
USEPA [d]	-	25	0.6	-	30	30	16	110
EU [e]	60	200	1	50	-	-	100	200

[a] Standard deviation; [b] Coefficient of variation; [c] [44]; [d][25]; [e] [31]

Table 5: Descriptive statistical analysis of concentrations of heavy metals (mg/kg) in vegetable samples

	Pb	Cr	Cd	Ni	Mn	Fe	Cu	Zn
Mean	-	3.89	0.05	1.18	5.77	9.08	1.21	1.78
SD[a]	-	1.01	0.04	0.31	1.36	4.39	0.35	0.73
Max	-	5.12	0.12	1.65	7.95	12.89	1.79	2.91
Min	-	2.60	0.00	0.90	4.65	2.07	0.91	1.04
Kurtosis	-	-1.87	-1.53	-1.28	-0.67	-0.64	-0.49	-0.79
Skewness	-	-0.08	0.39	0.65	1.05	-1.05	1.14	0.84
CV(%)[b]	-	51.88	191.46	51.82	47.09	96.67	57.95	82.26
FAO/WHO[c]	0.1	0.2	0.02	0.1	0.04	0.3	10	1.5

[a] Standard deviation; [b] Coefficient of variation; [c] [44]

Table 6: Descriptive statistical analysis of estimated carcinogenic risks (cancer risk, CR) associated with exposure through ingestion, inhalation and dermal absorption pathways to soil heavy metals

Life stages	Carcinogenic risk	Statistical parameter	Metal			
			Pb	Cr(VI)	Cd	Ni
Children	CR_{ing}	Min.	2.42E-08	7.32E-07	1.38E-05	1.16E-05
		Max.	6.80E-08	1.06E-06	6.49E-05	2.26E-05
		Mean	4.45E-08	9.18E-07	3.52E-05	1.69E-05
	CR_{inh}	Min.	5.33E-11	2.74E-08	6.35E-09	2.56E-07
		Max.	1.50E-10	4.00E-08	3.00E-08	5.00E-07
		Mean	9.82E-11	3.44E-08	1.62E-08	3.74E-07
	CR_{derm}	Min.	1.72E-08	1.39E-06	6.53E-08	2.76E-05
		Max.	4.84E-08	2.02E-06	3.08E-07	5.37E-05
		Mean	3.17E-08	1.74E-06	1.67E-07	4.02E-05
	TCR_{soil}	Min.	4.14E-08	2.15E-06	1.38E-05	3.94E-05
		Max.	1.16E-07	3.13E-06	6.53E-05	7.69E-05
		Mean	7.63E-08	2.70E-06	3.54E-05	5.75E-05
Adult	CR_{ing}	Min.	1.29E-08	3.92E-07	7.37E-06	6.22E-06
		Max.	3.64E-08	5.70E-07	3.48E-05	1.21E-05
		Mean	2.38E-08	4.92E-07	1.89E-05	9.07E-06
	CR_{inh}	Min.	5.14E-10	2.64E-07	6.11E-08	2.47E-06
		Max.	1.44E-09	3.85E-07	2.88E-07	4.81E-06
		Mean	9.46E-10	3.32E-07	1.56E-07	3.60E-06
	CR_{derm}	Min.	6.45E-09	5.21E-07	2.45E-08	1.03E-05
		Max.	1.81E-08	7.58E-07	1.16E-07	2.01E-05
		Mean	1.19E-08	6.54E-07	6.27E-08	1.51E-05
	TCR_{soil}	Min.	1.99E-08	1.18E-06	7.46E-06	1.90E-05
		Max.	5.60E-08	1.71E-06	3.52E-05	3.71E-05
		Mean	3.67E-08	1.48E-06	1.91E-05	2.77E-05

Table 7: Descriptive statistical analysis of estimated carcinogenic risk (CR) associated with exposure through dietary oral intake to metal in vegetable samples

Life stages	Carcinogenic risks	Descriptive statistics	Metals		
			Cr	Cd	Ni
Children	CR_{ing}	Min.	8.68E-09	4.28E-10	7.13E-08
		Max.	1.71E-08	3.45E-08	1.31E-07
		Mean	1.30E-08	1.33E-08	9.42E-08
Adults	CR_{ing}	Min.	2.79E-08	1.37E-09	2.29E-07
		Max.	5.50E-08	1.11E-07	4.22E-07
		Mean	4.18E-08	4.26E-08	3.03E-07

Table 8: Pearson correlation coefficients of HMs in soil (down) and vegetables (up)

Pb	-	-	-	-	-	-	-
0.05	Cr	0.80 [b]	-0.56	-0.56	0.58 [a]	0.20	0.81 [b]
0.46	0.00	Cd	0.52	0.41	0.64 [a]	0.64 [a]	0.53
-0.17	0.01	0.42	Ni	0.08	0.08	0.08	0.05
0.49	0.53	-0.10	-0.39	Mn	0.58 [a]	0.07	-0.54
-0.31	-0.49	-0.49	0.51	0.37	Fe	0.84 [b]	0.69 [a]
-0.06	0.37	-0.12	0.30	-0.14	0.30	Cu	0.56 [a]
0.71 [a]	0.24	-0.09	0.04	0.76 [b]	-0.21	-0.58	Zn
[a] Strong at p<0.05, [b] significant at p<0.01 and [c] strongly significant at p<0.001							

Table 9: Pearson correlation coefficients between HMs in soil and vegetables

HM	Soil-Scent Leaf	Soil-Curry Leaf	Soil-Water Leaf	Soil-Fluted Pumpkin Leaf
Cr	0.89[c]	-0.82	-0.07	-0.99
Cd	-0.79	0.17	1.00[c]	0.84[b]
Ni	-0.38	0.90[c]	0.28	0.14
Mn	0.69[a]	0.93[c]	-0.58	0.58[a]
Fe	0.64[a]	0.67[a]	0.85[c]	-0.25
Cu	-0.72	0.58[a]	0.35	-0.46
Zn	0.63[a]	0.6 [a]	-0.42	0.88[c]
[a] Strong at p<0.05, [b] significant at p<0.01 and [c] strongly significant at p<0.001				

Conclusions

The current study indicates that the ecological risk and toxicity assessment of heavy metals in the surface soil and vegetable samples around Afam (IV) thermal power plant were contaminated. The soils of the study area presented HMs with low ecological risk, except for cadmium. A low risk of HMs in soils around the power plant. The integrated lifetime cancer risks for HM pollution in both soil and vegetables are within a moderate range. Overall, the results of this study provide a basis for controlling both human and ecological risks. Exposure control may be necessary to prevent significant future health problems that can arise from the detrimental impacts that are believed to be caused by the heavy metals.

Tracking the exposure and preventive actions of the heavy metals can be a proactive measure to eliminate additional exposure to the heavy metals both in the environment and from humans. International and national cooperation is necessary to develop effective techniques to prevent heavy metals from becoming a toxic substance.

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Conflict of Interest

The authors declare that there are no conflicts of interest.

CRediT author statement

BMOO: Conceptualisation, Data curation, Investigation, Resources, Software, Supervision, Validation, Visualisation, Writing – review & editing. EMM: Conceptualisation, Data curation, Formal Analysis, Resources, Software, Writing – original draft. BSA: Managed the analyses of the study and the literature searches. All authors read and approved the final manuscript.

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