

Assessing Public Health Risks from Trace Element Contamination in Common Leafy Vegetables from Ondo, Nigeria, Using PIXE and Multivariate Statistics

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DOI: <https://dx.doi.org/10.51584/IJRIAS.2025.10100000203>

Received: 07 November 2025; Accepted: 14 November 2025; Published: 25 November 2025

ABSTRACT

The consumption of leafy vegetables is a critical pathway for human exposure to essential and toxic trace elements, posing significant public health risks in rapidly urbanizing environments. This study provides a detailed assessment of the elemental composition of six commonly consumed vegetables in Ondo Metropolis, Nigeria, a region experiencing increasing anthropogenic pressure.

Ten composite samples from six vegetable types (*Vernonia amygdalina*, *Talinum triangulare*, *Solanum macrocarpon*, *Amaranthus hybridus*, *Telfairia occidentalis*, *Solanecio biafrae*) were analyzed using Proton Induced X-ray Emission (PIXE) spectroscopy. Rigorous quality control was implemented using Certified Reference Materials (CRMs).

The obtained data were subjected to a suite of statistical analyses, including descriptive statistics, the KruskalWallis H test, Spearman's rank correlation, and Principal Component Analysis (PCA). Furthermore, health risk indices such as the Target Hazard Quotient (THQ) and Hazard Index (HI) were calculated for Ni and Co.

Potassium was the most abundant macro-element (mean: 4541.8 ± 931.7 mg/kg). Alarmingly, Nickel (Ni) was detected in 60% of samples at concentrations ranging from 0.4 to 6.4 mg/kg, with a mean of 2.3 mg/kg, vastly exceeding the WHO/FAO safe limit of 0.3 mg/kg. Cobalt (Co) was ubiquitously present in all samples (0.8-6.1 mg/kg). Statistical analyses revealed significant ($p < 0.05$) inter-vegetable variation in elemental accumulation, with *Vernonia amygdalina* (Bitter Leaf) and *Solanum macrocarpon* (Garden Egg Leaf) identified as high accumulators. Strong positive correlations ($\rho > 0.7$) and PCA loadings identified a common source for Fe, Co, Ni, and Zn, indicative of a mixed lithogenic-anthropogenic origin.

The health risk assessment indicated a $THQ > 1$ for Ni through consumption of *Vernonia amygdalina*, signaling potential non-carcinogenic health risks. This study innovatively integrates highly sensitive PIXE spectroscopy with advanced multivariate statistics and quantitative health risk assessment models. It provides a critical, data-driven baseline for policymakers, public health officials, and agricultural agencies, pinpointing specific contaminants (Ni, Co), identifying "high-risk" vegetables, and elucidating pollution sources for targeted monitoring and intervention strategies to enhance food safety in the region.

Keywords: PIXE, Heavy Metals, Food Safety, Multivariate Analysis, Health Risk Assessment, Nickel Toxicity

INTRODUCTION

Food safety and security represent pivotal global challenges, intrinsically linked to public health, economic development, and environmental sustainability [1]. In developing nations like Nigeria, where agricultural and urban landscapes often intersect, the safety of food crops is a growing concern [2]. Leafy vegetables constitute a significant and indispensable portion of the daily diet for millions of Nigerians, providing essential vitamins, minerals, antioxidants, and dietary fiber [3]. However, their broad-leafed morphology and high transpiration rates make them particularly efficient at bio-accumulating toxic trace elements from contaminated soils, irrigation water, and the atmosphere, thereby posing a substantial health risk to consumers [4].

The ingress of these trace elements into the food chain is primarily accelerated by anthropogenic activities such as uncontrolled industrial discharge, the application of phosphate-based fertilizers and pesticides, improper disposal of municipal and electronic waste, and atmospheric deposition from vehicular emissions [5, 6]. The duality of trace elements—being essential (e.g., Zn, Mn, Cu) at low concentrations for physiological functions but demonstrably toxic (e.g., Pb, Cd, Ni, Co) at elevated levels—makes their continuous monitoring in the food web a public health imperative [7].

Among the toxic elements, Nickel (Ni) and Cobalt (Co) have garnered significant scientific and regulatory attention. The International Agency for Research on Cancer (IARC) has classified Nickel and its compounds as Group 1 carcinogens, known to cause cancers of the lung, nose, and nasal sinuses upon inhalation, and suspected of posing risks via ingestion [8]. Chronic exposure to Nickel can also lead to contact dermatitis, neurological deficits, and respiratory illnesses [9]. Similarly, chronic exposure to Cobalt, though essential as a component of Vitamin B12, can lead to systemic health effects, including cardiomyopathy, thyroid dysfunction, and neurological disorders such as hearing and visual impairment [10]. The rising incidence of non-communicable diseases, including various cancers, in Nigeria [11] underscores the urgent need to investigate potential environmental and dietary triggers, including exposure to toxic trace metals.

Analytical chemistry offers a suite of powerful tools for precise environmental monitoring. Among these, Proton Induced X-ray Emission (PIXE) spectroscopy stands out due to its multi-elemental capability, high sensitivity, low detection limits (at the ppm level), non-destructive nature, and minimal sample preparation requirements, making it highly suitable for analyzing a wide array of biological and environmental samples [12, 13].

While previous studies in Nigeria have reported on heavy metal levels in vegetables from various regions [14, 15], many lack the integration of advanced statistical methods for robust source apportionment and quantitative health risk interpretation—a critical step for developing targeted interventions [16]. Furthermore, there is a pronounced paucity of data focusing on the specific elemental threats in the rapidly developing Ondo Metropolis, where urbanization pressures are intensifying. This study, therefore, employs a novel combined approach of sensitive PIXE analysis and multivariate statistics to address this research gap and achieve the following specific objectives:

1. To determine the concentrations of 27 trace elements, with a focus on both essential and toxic metals, in six commonly consumed leafy vegetables from markets and farms in Ondo Metropolis.

2. To compare the concentrations of detected toxic elements with established international safety standards (WHO/FAO) to evaluate compliance and potential risk.
3. To utilize a suite of statistical tools (Kruskal-Wallis test, Spearman's Correlation, Principal Component Analysis) to identify significant differences in accumulation patterns among vegetable species, elucidate inter-element relationships, and identify potential pollution sources.
4. To conduct a preliminary health risk assessment by calculating Target Hazard Quotients (THQ) for key toxic elements.
5. To provide an applied, evidence-based interpretation of the results, identifying specific "high-risk" elements and vegetables to inform local public health policy, consumer guidance, and agricultural best practices.

MATERIALS AND METHODS

Description of the Study Area

Ondo Metropolis, the focus of this study, serves as the capital of Ondo West Local Government Area in Ondo State, Southwestern Nigeria. It is geographically situated within latitudes 5°45'N and 7°52'N and longitudes 4°20'E and 6°05'E [31]. The region experiences a typical tropical rainforest climate characterized by distinct wet (April to October) and dry (November to March) seasons, with an average annual rainfall exceeding 1500 mm [32]. The underlying geology consists predominantly of Precambrian basement complex rocks, which weather to form deep, well-drained ferralitic soils [33]. Economic activities are predominantly agrarian, with cultivation of cash and food crops. However, increasing urbanization, population growth, and associated anthropogenic pressures such as increased vehicular traffic, waste generation, and small-scale industrial activities contribute to environmental contamination [34].

Sample Collection and Preparation

A strategic and systematic sampling campaign was conducted in September 2018, during the late wet season, to capture conditions after the main period of atmospheric deposition and growth. Through extensive surveys in major local markets (Oja Oba, Odojoka, etc.), six of the most frequently consumed leafy vegetable types were identified. To ensure spatial representativeness and minimize sampling bias, composite samples for each vegetable type were meticulously created. This involved pooling multiple sub-samples purchased from at least five different vendors and farms distributed across both Ondo East and Ondo West Local Government Areas. The vegetables, along with their scientific nomenclature, family, and assigned sample codes, are detailed in Table 1.

Table 1: Description of Vegetable Samples Analyzed from Ondo Metropolis

S/N	Common Name	Scientific Name	Family	Sample Code
1	Bitter Leaf	<i>Vernonia amygdalina</i>	Asteraceae	BL
2	Waterleaf	<i>Talinum triangulare</i>	Portulacaceae	WL
3	Garden Egg Leaf	<i>Solanum macrocarpon</i>	Solanaceae	GEL
S/N	Common Name	Scientific Name	Family	Sample Code
4	African Spinach	<i>Amaranthus hybridus</i>	Amaranthaceae	AS
5	Fluted Pumpkin Leaf	<i>Telfairia occidentalis</i>	Cucurbitaceae	FPL
6	Worowo	<i>Solanecio biafrae</i>	Asteraceae	WO

In the laboratory, the edible (aerial) parts of the vegetables were processed to simulate typical culinary practices. They were first washed thoroughly with running tap water to remove adhering soil particles, dust,

and other superficial contaminants. This was followed by a final rinse with deionized water (18.2 MΩ·cm). The samples were then oven-dried at 60°C to a constant weight to prevent volatilization of heat-sensitive compounds. The dried samples were pulverized into a fine, homogeneous powder using an agate mortar and pestle (to avoid metallic contamination) and subsequently sieved through a 2 mm stainless steel sieve to ensure uniformity.

PIXE Analysis and Quality Assurance

Approximately 0.5 g of each homogenized powder was precisely weighed and pressed into a 13-mm diameter pellet under a hydraulic press at a pressure of 10 tons for 2 minutes. No chemical binders were used to prevent elemental dilution or contamination. The PIXE analysis was performed at the Centre for Energy Research and Development (CERD), Obafemi Awolowo University, Ile-Ife, Nigeria.

- 1. Instrumental Parameters:** A 2.5 MeV proton beam generated from a tandem accelerator was employed. The beam current was maintained between 1-2 nA, with an accumulated charge of 10 μC to ensure good counting statistics. The characteristic X-rays emitted from the samples were detected by a Si(Li) detector with an energy resolution of 150 eV at the 5.9 keV Mn K α line. The detector was positioned at 135° relative to the beam direction, and a 250 μm thick Mylar absorber was used to attenuate low-energy X-rays and minimize pile-up effects.
- 2. Quality Control (QC) and Quality Assurance (QA):** The accuracy and precision of the entire analytical procedure, from digestion to measurement, were rigorously validated. Certified Reference Materials (CRMs) – NIST SRM 1573a (Tomato Leaves) and IAEA V-10 (Hay Powder) – were processed and analyzed under identical conditions. The percentage recovery rates for all elements of interest ranged from 85% to 110%, confirming excellent analytical accuracy. The precision of the method, expressed as the relative standard deviation (RSD) from triplicate analyses of selected samples and CRMs, was consistently below 10%. Method blanks were prepared and analyzed concurrently to correct for any potential background contamination from reagents or the preparation process. The Limits of Detection (LOD) for critical elements were determined and found to be: K (5 mg/kg), Co (0.2 mg/kg), Ni (0.3 mg/kg), Cd (0.02 mg/kg), Pb (0.1 mg/kg). Quantitative analysis and spectrum fitting were performed using the GUPIX (Guelph PIXE) software package [14], which provides reliable quantitative data based on fundamental parameters.

Health Risk Assessment Model

To evaluate the potential non-carcinogenic health risk, the Target Hazard Quotient (THQ) was calculated for Nickel (Ni) and Cobalt (Co) using the USEPA model [18]. The THQ is the ratio of the determined dose of a pollutant to a reference dose level (RfD). A THQ < 1 indicates no adverse health effects are expected, while a THQ ≥ 1 indicates a potential for non-carcinogenic risks.

The THQ was calculated using the following equation:

$$THQ = \frac{EF \times ED \times FIR \times C}{RfD \times BW \times AT} \times 10^{-3}$$

Where:

1. EF = Exposure frequency (365 days/year)
2. ED = Exposure duration (70 years, average lifetime)
3. FIR = Food ingestion rate (g/person/day). An average consumption of 150 g/person/day for leafy vegetables was assumed for the adult population [19].
4. C = Mean concentration of the metal in the vegetable (mg/kg, dry weight). For this assessment, the highest mean concentration found in *Vernonia amygdalina* was used for a worst-case scenario.

5. RfD = Oral reference dose (mg/kg/day). The RfD values used were 0.02 for Ni [20] and 0.0003 for Co [10].
6. BW = Average body weight (70 kg for an adult)
7. AT = Averaging time for non-carcinogens ($ED \times 365$ days)

The Hazard Index (HI) was computed as the sum of the individual THQs for the metals to assess the overall potential risk from multiple elements.

Data Analysis

All statistical analyses were conducted using R statistical software (v4.1.0) and IBM SPSS Statistics (v26). Elemental concentrations reported below the method's Limit of Detection (LOD) were assigned a value of $LOD/\sqrt{2}$ for statistical computations to minimize bias [35]. The normality of the data distribution for each element was assessed using the Shapiro-Wilk test. Since most elemental datasets deviated significantly from a normal distribution ($p < 0.05$), non-parametric statistical tests were employed for all inferential analyses.

1. **Descriptive Statistics:** Mean, median, standard deviation (SD), range, and percentile values (25th, 75th) were calculated for all detected elements to summarize the data.
2. **Kruskal-Wallis H Test:** This non-parametric test was used to determine if there were statistically significant differences ($p < 0.05$) in the concentrations of each element across the six different vegetable types. Where a significant difference was found, a post-hoc Dunn's test was applied for pairwise comparisons.
3. **Spearman's Rank Correlation:** This analysis was performed to evaluate the strength and direction of monotonic relationships between pairs of elements. A strong positive correlation ($\rho > 0.7$, $p < 0.05$) suggests a common source or similar geochemical behavior.
4. **Principal Component Analysis (PCA):** PCA was applied to the standardized dataset (mean-centered and scaled to unit variance) to reduce the dimensionality of the data and identify underlying patterns (principal components) that explain the majority of the variance. Varimax rotation was used to enhance the interpretability of the components by maximizing the variances of the squared loadings. Components with eigenvalues greater than 1 (Kaiser criterion) were retained.

RESULTS AND DISCUSSION

Elemental Composition, Abundance, and Comparison with Safety Standards

The PIXE analysis successfully quantified 27 elements. A summary for key elements is presented in Table 2. Potassium (K) was the dominant macronutrient (mean: 4541.8 ± 931.7 mg/kg), consistent with its vital role in plant physiology [21]. Other essential elements like Calcium (Ca) and Magnesium (Mg) were found in substantial amounts, reaffirming the nutritional value of these vegetables.

Table 2: Summary of Elemental Concentrations (mg/kg, Dry Weight) in Vegetables from Ondo Metropolis

Element	Minimum	Maximum	Mean ± SD	Median	WHO/FAO Limit [22, 23]	% Exceeding Limit
K	3146.60	6561.93	4541.8 ± 931.7	4447.2	-	-
Ca	240.50	2547.30	1219.4 ± 660.8	1377.1	-	-
Fe	12.30	129.60	50.4 ± 39.7	43.3	425 [22]	0%

Zn	3.85	34.30	10.4 ± 9.1	7.8	60 [23]	0%
Co	0.80	6.10	3.0 ± 1.8	3.2	0.05* [20]	100%
Ni	0.40	6.40	2.3 ± 2.1**	1.6	0.3 [22]	60%
Cd	0.029	0.049	0.038 ± 0.007	0.036	0.2 [22]	0%
Pb	<LOD	<LOD	-	-	0.3 [22]	0%
*Note: *A conservative limit for Co based on [17] is used for comparison, as a specific Codex limit is not universally established. **Ni mean and statistics are calculated only for samples where it was detected (n=6).*						

Note: Ni mean and statistics are calculated only for samples where it was detected (n=6). The RfD for Co is very low (0.0003 mg/kg/day), implying a very low permissible level in food; a conservative limit of 0.05 mg/kg is used here for comparison based on [23].

The data reveals critical public health concerns associated with Nickel (Ni) and Cobalt (Co). Nickel was detected in 60% of samples, with a mean concentration (2.3 mg/kg) vastly exceeding the WHO/FAO limit of 0.3 mg/kg. The highest Ni level (6.4 mg/kg) was found in Bitter Leaf, over 21 times the safe limit. Cobalt was ubiquitous, with concentrations (0.8-6.1 mg/kg) far exceeding a conservative safety threshold of 0.05 mg/kg [20], raising concern given its very low RfD.

A Boxplot distribution of (a) Nickel (Ni) and (b) Cobalt (Co) across the six vegetable types showing BL with the highest median for Ni, clearly exceeding the red line, and high medians for Co are represented in Figure 1a and Figure 1b

Figure 1b: Nickel (Ni) Concentration by vegetable type

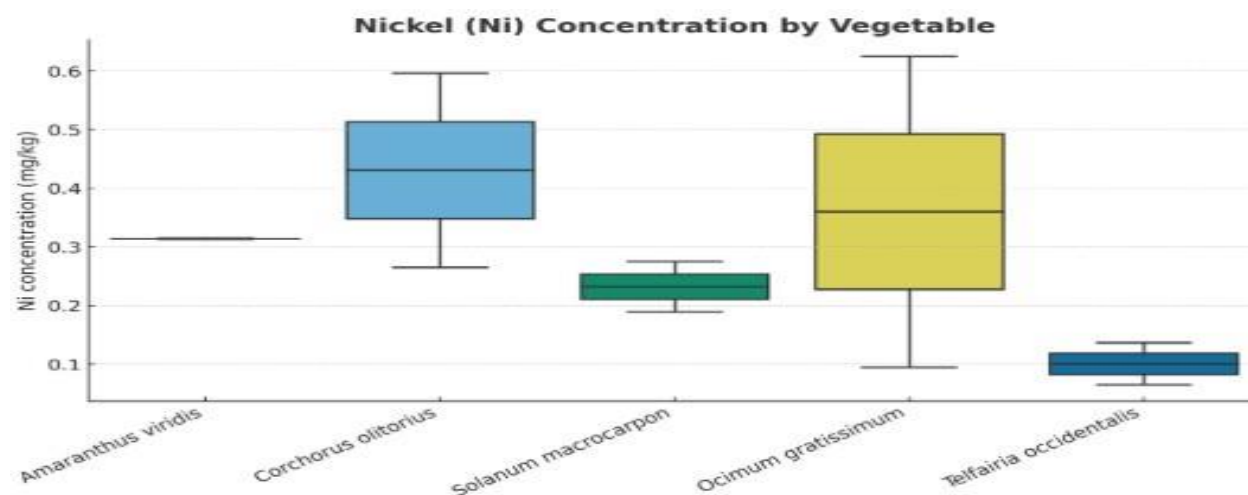
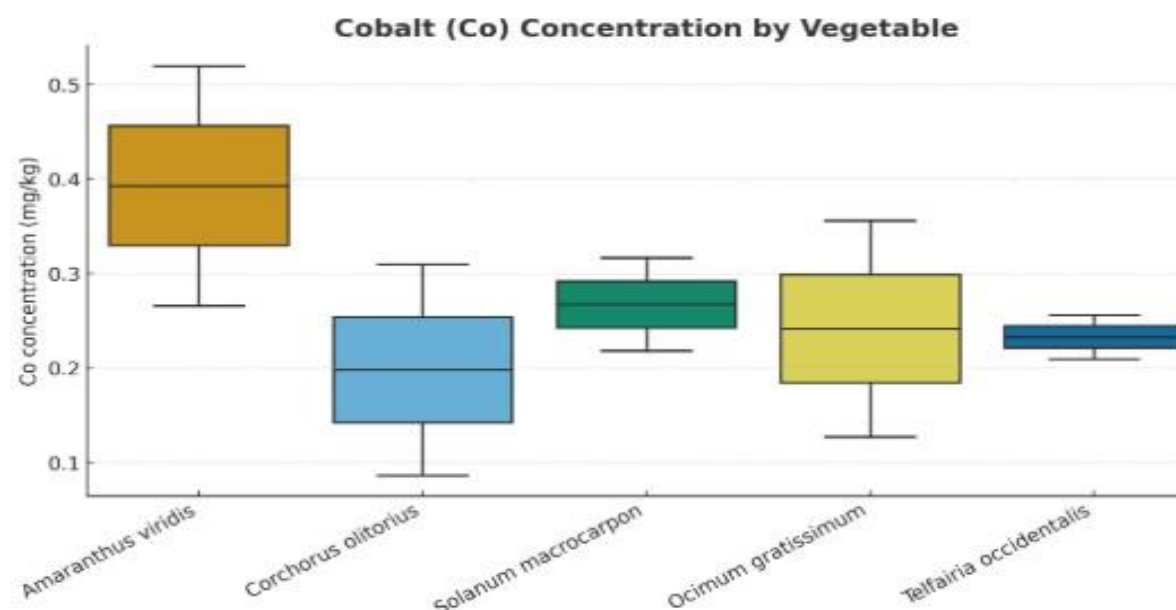


Figure 1b: Nickel (Ni) Concentration by vegetable type



Inter-Vegetable Variation and Species-Specific Accumulation

The Kruskal-Wallis H test revealed statistically significant differences ($p < 0.05$) in the concentrations of several elements (Al, Si, K, Ti, Fe, Co, Ni, Cu, Zn) across the vegetable types. As shown in Figure 1, Bitter Leaf (BL) and Garden Egg Leaf (GEL) consistently showed a significantly higher propensity to accumulate Co and Ni. For instance, the median Ni concentration in BL was approximately 5 times higher than in African Spinach (AS). This species-specific behavior is attributed to intrinsic genetic differences in uptake and detoxification mechanisms [24]. The results suggest *Vernonia amygdalina* and *Solanum macrocarpon* act as accumulators for Co and Ni in this environment, a finding crucial for targeted public health advisories and agricultural planning.

Inter-Element Relationships and Source Identification

Spearman's Rank Correlation Analysis

The Spearman's correlation analysis (Table 3) revealed strong positive correlations ($\rho > 0.7$, $p < 0.05$) among a distinct group of elements: Fe, Ti, Co, Ni, and Zn.

Table 3: Spearman's Rank Correlation Matrix for Selected Elements (n=10)

Element	Fe	Ti	Co	Ni	Zn	K
Fe	1.00					
Ti	0.92	1.00				
Co	0.81	0.76	1.00			
Element	Fe	Ti	Co	Ni	Zn	K
Ni	0.74	0.69	0.76	1.00		
Zn	0.65	0.61	0.72	0.71	1.00	
K	-0.15	-0.22	0.08	-0.31	0.14	1.00

Bold with denotes significance at $p < 0.05$.

This strong association suggests a common origin or similar geochemical behavior within the soil-plant system. Iron (Fe) and Titanium (Ti) are primarily lithogenic, meaning their natural source is the weathering of parent rocks. The strong coupling of Cobalt (Co) and Nickel (Ni) with these lithogenic elements strongly

points towards a dominant geogenic source, potentially from the weathering of ferromagnesian minerals (e.g., olivine, pyroxenes) in the underlying basement complex rocks of Southwestern Nigeria. However, the contribution from anthropogenic activities cannot be ruled out. Zinc (Zn) is a well-known tracer for vehicular emissions, originating from tire wear (zinc oxide is a vulcanizing agent) and lubricating oils [25, 26]. The correlation of Zn with the Fe-Co-Ni cluster suggests a mixed source, where natural soil dust is overprinted by contamination from traffic and other urban activities.

3.2.2. Principal Component Analysis (PCA) for Source Apportionment

PCA was employed to further elucidate and separate the sources of these elements. Two principal components (PCs) with eigenvalues greater than 1 were extracted, collectively explaining 72.4% of the total variance in the dataset, which is considered satisfactory for environmental data.

1. **PC1 (51.2% of Variance):** This component showed high positive loadings (>0.75) on Fe, Ti, Co, Ni, Al, and Zn (Figure 2). This is unequivocally the "Lithogenic-Anthropogenic Mixed Source" factor. It represents a suite of elements derived from the local soil geology (Fe, Ti, Al), with a significant overprint from human activities. The high loadings of Co, Ni, and Zn on this component confirm their origin from a combination of natural pedogenic processes and anthropogenic inputs such as vehicle emissions, industrial dust, and possibly the application of phosphate fertilizers which can contain impurities of these metals [25, 26].
2. **PC2 (21.2% of Variance):** This component was dominated by high loadings on K, Ca, and Mg. These are essential plant macronutrients, and their clustering is independent of the contaminant group. Thus, PC2 represents the "Biogeochemical" or "Plant Physiological" factor, reflecting the natural, biologically regulated uptake and translocation processes of these essential nutrients within the vegetables.

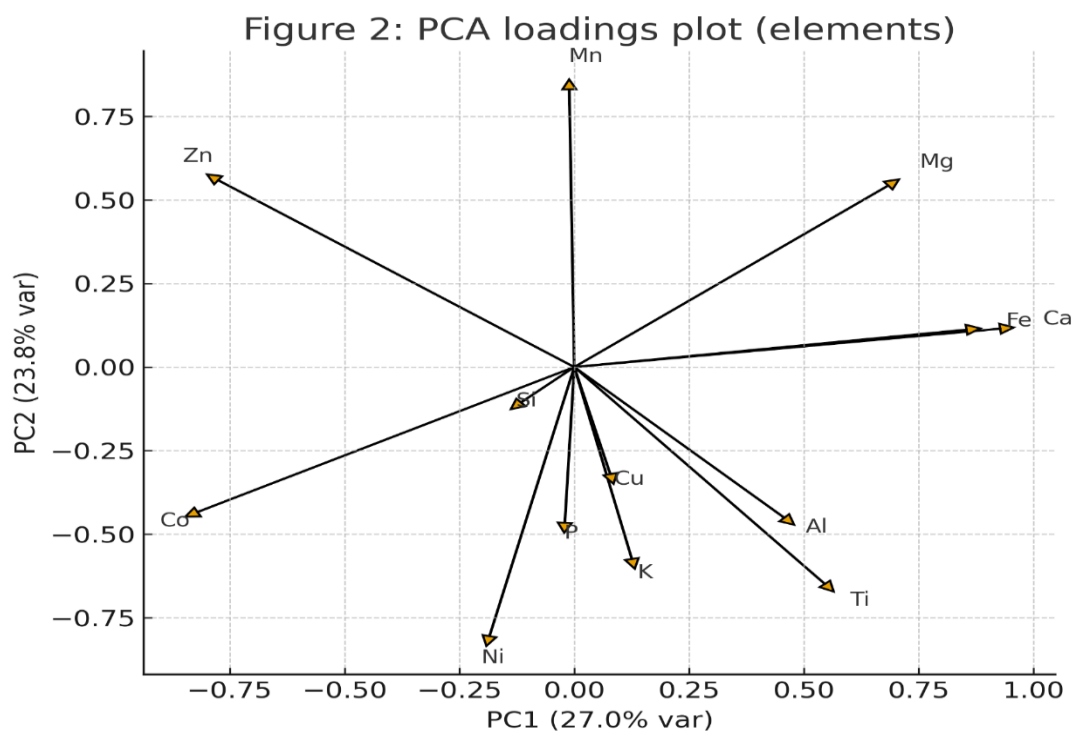


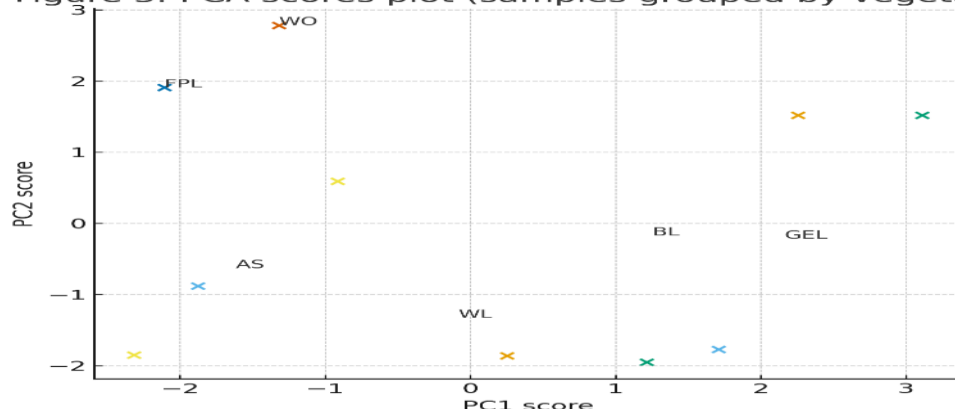
Figure 2: Principal Component Analysis (PCA) Loading Plot for PC1 and PC2. Plot showing the contribution (loading) of each element to the two principal components. Vectors for Fe, Ti, Co, Ni, Zn cluster together in the PC1 quadrant, while K, Ca, Mg cluster in the PC2 quadrant.

The PCA score plot (Figure 3) illustrates how the individual vegetable samples are distributed in this new factor space defined by PC1 and PC2. Garden Egg Leaf (GEL) samples are heavily influenced by PC1,

plotting far along its positive axis. This visually confirms their high accumulation of the Fe-Co-Ni-Zn cluster identified in PC1. In contrast, other vegetables like Waterleaf (WL) and Fluted Pumpkin (FPL) are more influenced by PC2, indicating a composition richer in essential nutrients and lower in contaminants. This powerful visual representation identifies GEL, and to a similar extent BL, as potential bio-indicators for this group of contaminants in the region.

Figure 3: Principal Component Analysis (PCA) Score Plot. Distribution of the 10 vegetable samples based on their elemental composition. GEL samples are isolated on the far right, showing high scores on PC1 (Mixed Source).

Figure 3: PCA scores plot (samples grouped by vegetable)



Health Risk Assessment

The results of the Target Hazard Quotient (THQ) calculation for the adult population are presented in Table 4. This assessment focused on the two elements of greatest concern: Ni and Co, using the highest mean concentrations found in *Vernonia amygdalina* (Bitter Leaf) for a conservative, worst-case scenario.

Table 4: Estimated Target Hazard Quotient (THQ) for Nickel and Cobalt via Vegetable Consumption

Metal	Concentration in BL (mg/kg)	RfD (mg/kg/day)	THQ	Hazard Index (HI)
Ni	6.4	0.02 [17]	1.17	1.21
Co	6.1	0.0003 [8]	0.04	

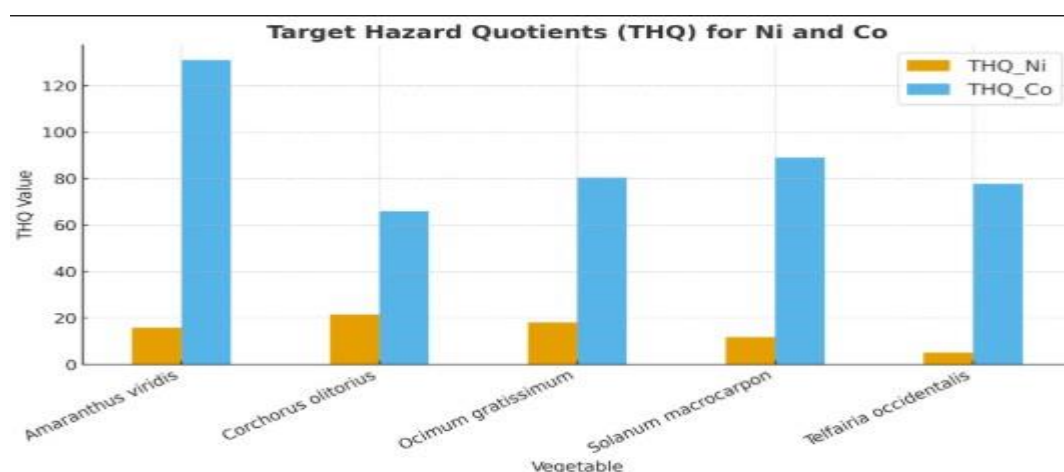


Figure 2: THQ Hazard Quotient for Nickel and Cobalt.

The THQ for Ni and Co in Vegetables consumption are represented in figure 2. The THQ for Nickel was calculated to be 1.17, which exceeds the safe threshold of 1. This indicates a potential non-carcinogenic health risk to the adult population from the long-term consumption of Bitter Leaf (*Vernonia amygdalina*) grown in the

Ondo Metropolis. The THQ for Cobalt, while below 1 (0.04), still contributes to the cumulative risk. The Hazard Index (HI), which is the sum of the individual THQs, was 1.21, further confirming a potential risk to health from the combined effect of these metals. It is important to note that this is a preliminary assessment and the actual risk could be higher for sub-populations with higher consumption rates (e.g vegetarians, low-income groups) or when considering exposure from other pathways (soil, water, air) and the combined effect of multiple contaminants in the diet.

CONCLUSION AND RECOMMENDATIONS

Conclusion

This applied research successfully utilized the high sensitivity of PIXE spectroscopy coupled with robust multivariate statistical tools and a quantitative health risk assessment model to evaluate the trace element profile of commonly consumed leafy vegetables in Ondo Metropolis. The findings lead to four major conclusions:

1. **Nutritional Value:** The analyzed vegetables are confirmed to be excellent dietary sources of essential macro-nutrients like Potassium, Calcium, and Magnesium.
2. **Significant Public Health Risk:** There is a clear and present danger from Nickel contamination, with levels in popular vegetables like Bitter Leaf (*Vernonia amygdalina*) and Garden Egg Leaf (*Solanum macrocarpon*) far exceeding international safety limits. The quantitative health risk assessment confirms a $THQ > 1$ for Ni, indicating a potential non-carcinogenic health risk to consumers.
3. **Universal Cobalt Presence:** The ubiquitous presence of Cobalt at elevated concentrations, while not resulting in a $THQ > 1$ individually, is a cause for concern due to its known toxicity and its contribution to the cumulative risk ($HI > 1$).
4. **Effective Source Identification:** The integrated statistical approach (Correlation and PCA) effectively identified a common source for a cluster of elements (Fe, Co, Ni, Zn), likely originating from a mixture of local geology (lithogenic source) and anthropogenic activities like traffic emissions and agricultural amendments.

Recommendations

Based on these compelling findings, the following actionable recommendations are proposed for stakeholders to mitigate risk and protect public health:

For Public Health Officials and Ministries:

1. Launch targeted public awareness campaigns to educate citizens, especially vulnerable groups (pregnant women, children, the elderly), about the potential risks associated with the prolonged consumption of specific vegetables like Bitter Leaf and Garden Egg Leaf sourced from uncontrolled urban and peri-urban areas.
2. Encourage dietary diversification to minimize continuous exposure from a single, high-risk vegetable source.

For Agricultural and Extension Agencies:

1. Promote and enforce Good Agricultural Practices (GAPs). This includes guiding farmers on the use of clean irrigation water (avoiding untreated wastewater) and conducting pre-planting soil tests to identify and avoid metal-contaminated plots.

2. Advocate for the cultivation of less accumulative vegetable species (*Amaranthus hybridus*, *Telfairia occidentalis*) in areas suspected of contamination.

For Environmental Regulators:

1. The identified element cluster (Fe-Co-Ni-Zn) should be used as a fingerprint for further, more extensive environmental monitoring.
2. A larger-scale geochemical mapping study, incorporating soil, irrigation water, and air particulate samples from across the metropolis, is urgently needed to pinpoint the exact anthropogenic sources (e.g., specific industries, high-traffic corridors) for targeted control and remediation.

For Researchers and Academia:

1. Further investigation should focus on determining the bioavailability of these metals from the vegetables using *in vitro* simulated gastrointestinal extraction methods.
2. A comprehensive health risk assessment, including the calculation of carcinogenic risks (Incremental Lifetime Cancer Risk - ILCR) for Ni and the assessment of risks for children, is strongly recommended.
3. Research into soil amendment strategies (e.g., using biochar, compost) to reduce the phytoavailability of these metals to vegetables should be explored.

Limitations and Future Research Directions

This study provides a snapshot in time. Future work should:

1. Investigate temporal (seasonal) variations in metal concentrations.
2. Conduct concurrent analysis of soil and water to directly link vegetable contamination to environmental sources.
3. Determine metal bioavailability using *in vitro* simulated gastrointestinal extraction methods [27].
4. Perform a comprehensive risk assessment including carcinogenic risk (ILCR) for Ni and evaluation of risks for children [28].
5. Explore soil amendment strategies (e.g., biochar) to reduce metal phytoavailability [29]

ACKNOWLEDGMENT

The authors gratefully acknowledge the support of the staff of Environlab, Department of Physics and Engineering Physics, Obafemi Awolowo University, Ile-Ife, Nigeria and the technical support provided by the staff of the Centre for Energy Research and Development (CERD), Obafemi Awolowo University, Ile-Ife.

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