

Potentially toxic elements in per urban agricultural soils and vegetables with soil to plant transfer pollution assessment and human health risks in Wudil Kano State Nigeria

Emmanuel Bernard

bernard@polac.edu.ng

Nigeria Police Academy – Wudil

Augustina Oyibo - Ugwoke

Nigeria Police Academy – Wudil

Amina Bello Mahmoud

Nigeria Police Academy – Wudil

Ayandegi Mushim Olayiwola

Federal College of Education (Technical)

Adepeju Ogunleye

Federal College of Education (Technical)

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Abstract

This study investigated agricultural soil contamination and associated human health risks from consuming vegetables in Wudil, Nigeria. Soil and vegetable samples (spinach, lettuce, cabbage, pepper) were collected during the 2025 dry season and analysed using Microwave Plasma–Atomic Emission Spectroscopy (MP-AES). Soil analysis, employing Contamination Factors (CF), Geoaccumulation Index (Igeo), and the Pollution Load Index (PLI), indicated generally unpolluted soils (PLI = 0.05). However, Cadmium (Cd) showed moderate enrichment (CF = 2.40; Igeo = 0.68), suggesting slight contamination. Soil-to-plant transfer factors (TF) revealed distinct metal mobility. While Cd, Nickel (Ni), and Lead (Pb) exhibited restricted transfer (TF < 1), Manganese (Mn) and Chromium (Cr) demonstrated higher transfer efficiencies. Notably, lettuce recorded the highest Mn TF (3.01) and spinach the highest Cr TF (1.02), highlighting crop-specific accumulation. Human health risk assessment, based on Chronic Daily Intake (CDI) and Hazard Index (HI), identified Cd as the primary concern. Cadmium presented an HI of 1.51, exceeding the safety threshold (HI > 1), indicating a potential non-carcinogenic health risk from prolonged dietary exposure to mixed vegetables. Ni, Pb, Mn, and Cr had HI values well below 1. Cancer risk for Cd and Cr remained within acceptable ranges ($10^{-6} - 10^{-4}$). Despite low soil contamination, plant uptake significantly influences dietary exposure. While Wudil's vegetables are generally safe, the elevated Cd risk necessitates targeted interventions. Recommendations include routine monitoring of potentially toxic elements (especially Cd, Cr), improved irrigation, responsible agrochemical use, and periodic food safety assessments to support sustainable peri-urban agriculture and safeguard public health.

1.0 Introduction

Rapid urbanisation, industrialisation, and agricultural intensification have substantially increased the release of potentially toxic elements (PTEs) into terrestrial ecosystems, raising global concerns regarding soil quality, food safety, and human health. Agricultural soils serve as both reservoirs and potential sources of PTEs, which may accumulate through atmospheric deposition, wastewater irrigation, agrochemical application, traffic emissions, mining activities, and industrial discharges [1]. Once introduced into the soil, these elements can persist for long periods because they are non-biodegradable, undergo limited natural attenuation, and may be transferred into edible crops, thereby entering the human food chain through dietary exposure [2, 3].

Vegetables are recognised as one of the principal pathways of human exposure to PTEs because of their capacity to absorb and accumulate metals from contaminated soils, irrigation water, and atmospheric deposition. [4–6]. The extent of accumulation depends on several factors, including soil physicochemical properties, metal speciation, bioavailability, crop species, root morphology, and environmental conditions. Leafy vegetables generally exhibit greater accumulation of PTEs than fruit vegetables because of their larger surface area, higher transpiration rates, and greater physiological demand for mineral nutrients. Consequently, regular consumption of contaminated vegetables may contribute to chronic dietary exposure and increase the risk of adverse health outcomes. [4, 7–9]

Among the PTEs commonly detected in agricultural systems, cadmium (Cd), lead (Pb), nickel (Ni), manganese (Mn), and chromium (Cr) are of environmental and toxicological importance. Cadmium and Pb are non-essential elements with high toxicity even at low concentrations and have been associated with renal dysfunction, neurological disorders, cardiovascular disease, and impaired child development following prolonged exposure. Chromium presents a more complex toxicological profile because its toxicity depends on chemical speciation; trivalent chromium [Cr(III)] is an essential trace element, whereas hexavalent chromium [Cr(VI)] is highly toxic and carcinogenic. Nickel is required only in trace quantities by some organisms, but excessive exposure may cause allergic reactions and respiratory effects. In contrast, manganese is an essential micronutrient involved in enzyme activation, photosynthesis, and antioxidant defence, although excessive intake has been linked to neurological disorders. These differences highlight the importance of evaluating both metal concentrations and associated health risks when assessing food safety [10–13]

Nigeria has experienced rapid urban expansion over recent decades, resulting in increasing pressure on peri-urban agricultural systems that supply fresh vegetables to growing populations. Farmers frequently cultivate vegetables close to roads, residential areas, and commercial activities where soils may receive inputs from wastewater irrigation, vehicle emissions, agrochemicals, and other diffuse pollution sources. Although several studies have reported PTE concentrations in agricultural soils and vegetables across different regions of Nigeria, most have focused primarily on concentration levels without integrating soil contamination status, soil-to-plant transfer, pollution indices [1, 14, 15], and quantitative human health risk assessment. Consequently, comprehensive evaluations linking environmental contamination with dietary exposure remain limited, particularly for peri-urban farming systems in northern Nigeria [5, 7]

Wudil Local Government Area, Kano State, is an important vegetable-producing region that supplies fresh produce to surrounding urban centres. Increasing agricultural intensification, expanding urban development, and changing land-use practices have raised concerns regarding the potential accumulation of PTEs in agricultural soils and edible crops. However, information on the occurrence, transfer behaviour, and health implications of PTEs in this production system remains scarce [16–19].

This study therefore aimed to provide an integrated assessment of PTE contamination in peri-urban agricultural soils and vegetables from Wudil, Kano State, Nigeria. Specifically, the study: (i) quantified the concentrations of Cd, Ni, Pb, Mn, and Cr in paired soil and vegetable samples using Microwave Plasma–Atomic Emission Spectroscopy (MP-AES); (ii) evaluated soil contamination using contamination factor (CF), geoaccumulation index (I_{geo}), and pollution load index (PLI); (iii) assessed soil-to-plant transfer using transfer factors (TF); and (iv) evaluated potential non-carcinogenic and carcinogenic health risks for adults and children using estimated daily intake (EDI), target hazard quotient (THQ), hazard index (HI), and cancer risk (CR). The findings provide baseline information for environmental monitoring, food safety management, and sustainable peri-urban agricultural development in northern Nigeria.

2.0 Materials and Methods

2.1 Study Area

The study was conducted in Wudil Local Government Area, Kano State, north-western Nigeria (Fig. 1). Wudil lies (11°45'N and 8°51' E) within the Sudan Savannah agroecological zone and experiences a tropical semi-arid climate characterised by distinct wet (May–October) and dry (November–April) seasons. Mean annual rainfall ranges from approximately 800 to 900 mm, while average temperatures vary between 25 and 35°C. Agriculture is the predominant economic activity, with intensive cultivation of leafy and fruit vegetables supported by irrigation from surface water and shallow groundwater sources. Increasing urbanisation, agricultural intensification, wastewater reuse, and agrochemical application have raised concerns regarding the accumulation of potentially toxic elements (PTEs) in agricultural soils and edible crops [20, 21].

2.2 Sample Collection

Field sampling was conducted during the dry season (September – November 2025) within the Wudil Local Government Area (LGA). Five representative vegetable farms were selected to encompass variations in irrigation practices and potential contamination sources. At each of the five farms, five topsoil subsamples (0–20 cm depth), corresponding to the active root zone, were collected. These subsamples were thoroughly homogenised to form three composite soil samples per farm, resulting in a total of 15 composite soil samples (5 farms × 3 composites/farm).

Concurrently, vegetable samples of *Capsicum annuum* (pepper), *Lactuca sativa* (lettuce), *Spinacia oleracea* (spinach), and *Brassica oleracea* (cabbage) were collected from the same plots as the soil samples. For each crop species, three individual plants were harvested from five distinct locations within each farm and pooled to form a composite sample. This yielded a total of 33 composite vegetable samples, specifically comprising nine samples each for pepper, lettuce, and spinach ($n = 9$), and six samples for cabbage ($n = 6$).

To enable the assessment of soil-to-plant transfer, all soil and vegetable composite samples were spatially paired. Following collection, samples were immediately placed in pre-cleaned polyethene bags, labelled, and transported to the laboratory in insulated containers for prompt processing.

2.3 Sample Preparation

Soil samples were air-dried at room temperature, gently crushed, and passed through a 2-mm polyethene sieve to remove stones and plant debris before chemical analysis. Vegetable samples were thoroughly rinsed with running tap water, followed by deionised water to remove adhering soil particles and atmospheric dust. The edible portions were chopped into small pieces and oven-dried at 70°C to constant weight. Dried samples were ground using a stainless-steel mill and stored in acid-washed polyethene containers until analysis.

2.4 Acid Digestion and Elemental Analysis

Approximately 0.50 g of each dried soil or vegetable sample was accurately weighed into a digestion vessel. Samples were digested using concentrated nitric acid (HNO₃) and hydrogen peroxide (H₂O₂) following standard wet-acid digestion procedures recommended by the USEPA for trace element analysis. Following complete digestion, the solutions were filtered and diluted to 50 mL with deionised water. Concentrations of cadmium (Cd), nickel (Ni), lead (Pb), manganese (Mn), and chromium (Cr) were determined using a Microwave Plasma–Atomic Emission Spectrometer (MP-AES 4210, Agilent Technologies, Australia). Instrument calibration was performed using multi-element standard solutions prepared from certified stock standards. Analytical blanks, duplicate samples, and certified reference materials were included throughout the analytical procedure to ensure data quality. Recoveries ranged between 90 and 110%, and all measured concentrations were corrected for procedural blanks.[23].

2.5 Pollution Assessment

Agricultural soil contamination was assessed using three widely applied pollution indices: the Contamination Factor (CF), Geoaccumulation Index (I_{geo}), and Pollution Load Index (PLI).

The Contamination Factor quantifies the degree of enrichment of potentially toxic elements (PTEs) relative to background levels using Eq. 1.

$$CF = \frac{C_{sample}}{C_{background}}$$

1

where C_{sample} is the measured concentration of each PTE and $C_{background}$ is the corresponding background concentration. CF values were interpreted as follows: $CF < 1$ (low contamination), $1 \leq CF < 3$ (moderate contamination), $3 \leq CF < 6$ (considerable contamination), and $CF \geq 6$ (very high contamination) [24]

The Geoaccumulation Index, proposed by Müller, was calculated using Eq. 2:

$$I_{geo} = \log_2 \left(\frac{C_n}{1.5B_n} \right)$$

2

where C_n is the measured concentration, and B_n is the geochemical background value. The constant 1.5 accounts for natural lithogenic variability. The I_{geo} values were classified into seven contamination classes ranging from Class 0 (I_{geo} ≤ 0, uncontaminated) to Class 6 (I_{geo} > 5, extremely contaminated) [25]

Overall soil quality was calculated using Eq. 3, the Pollution Load Index (PLI),

$$PLI = (CF_1 \times CF_2 \times \dots \times CF_n)^{1/n}$$

3

where n is the number of analysed metals. A PLI value < 1 indicates no overall pollution, $= 1$ indicates baseline contamination, and > 1 reflects progressive pollution [26–29].

2.6 Soil-to-Plant Transfer Factor

The Transfer Factor (TF) was used to assess the mobility and bioavailability of PTEs from soil into edible plant tissues and was calculated using Eq. 4.

$$TF = \frac{C_{vegetable}}{C_{soil}}$$

4

where $C_{vegetable}$ and C_{soil} represent PTE concentrations in vegetable tissues and the corresponding soil. Higher TF values indicate more efficient transfer and greater bioavailability.

2.7 Human Health Risk Assessment

Human health risks associated with vegetable consumption were assessed for adults and children following the United States Environmental Protection Agency (USEPA) methodology.

The Estimated Daily Intake (EDI) was calculated using Eq. 5.

$$EDI = \frac{C \times IR \times EF \times ED \times CF}{BW \times AT}$$

5

where C is the metal concentration in vegetables, IR is ingestion rate, EF is exposure frequency, ED is exposure duration, CF is the conversion factor, BW is body weight, and AT is averaging time.

Non-carcinogenic risk was evaluated using Eq. 6, the Target Hazard Quotient (THQ):

$$THQ = \frac{EDI}{RfD}$$

6

where RfD is the oral reference dose.

The Hazard Index (HI), representing cumulative non-carcinogenic risk, was obtained by summing all THQs, Eq. 7.

$$HI = \sum THQ$$

Values of THQ or HI < 1 indicate negligible non-carcinogenic risk, whereas > 1 suggests potential adverse health effects [30, 31].

Lifetime carcinogenic risk for Cd and Cr was estimated using Eq. 8.

$$CR = EDI \times CSF$$

where *CSF* is the cancer slope factor. According to USEPA guidelines, cancer risks between 10⁻⁶ and 10⁻⁴ are considered acceptable [32, 33].

The exposure and toxicological parameters used for the human health risk assessment are summarised in Table 1.

Table 1
Exposure and Toxicological Parameters Used for Human Health Risk Assessment (EDI, HQ, HI, THQ and CR)

Parameter	Adults	Children	Units	Source
Exposure frequency (EF)	365	365	days/year	USEPA
Exposure duration (ED)	30	6	years	USEPA
Body weight (BW)	70	15	kg	USEPA
Averaging time (AT, non-cancer)	ED × 365	ED × 365	days	USEPA
Averaging time (AT, cancer)	70 × 365	70 × 365	days	USEPA
Vegetable ingestion rate (IR)	0.345	0.232	kg/day	FAO/WHO
Conversion factor (K)	0.085	0.085	–	FAO/WHO
Reference dose (RfD) (Cd)	0.001	0.001	mg/kg/day	USEPA
Reference dose (RfD) (Ni)	0.02	0.02	mg/kg/day	USEPA
Reference dose (RfD) (Pb)	0.0035	0.0035	mg/kg/day	USEPA
Reference dose (RfD) (Mn)	0.14	0.14	mg/kg/day	USEPA
Reference dose (RfD) (Cr(VI))	0.003	0.003	mg/kg/day	USEPA
Cancer slope factor (CSF, Cr(VI))	0.5	0.5	(mg/kg/day) ⁻¹	USEPA

2.8 Statistical Analysis and Boxplot Generation

Concentrations of Cd, Ni, Pb, Mn, and Zn in soil and vegetable samples were summarised using box-and-whisker plots to visualise distributional characteristics and compare metals across matrices. All

concentration data were log-transformed before plotting to accommodate skewness and to ensure appropriate visual scaling across several orders of magnitude. For each metal, boxplots display the median (horizontal line), interquartile range (IQR), whiskers extending to $1.5 \times \text{IQR}$, and outliers plotted as individual points. Mean values are shown as white diamonds to complement median-based distribution summaries. Differences between soil and vegetable groups were assessed using one-way ANOVA followed by Tukey's Honest Significant Difference (HSD) post-hoc test, with significance set at $p < 0.05$; homogeneous groups are indicated by boxes. WHO/FAO [34]. Permissible limits for each metal were added as dashed horizontal reference lines to facilitate interpretation relative to international food-safety thresholds.

3.0 Results and Discussion

3.1 Concentrations of Potentially Toxic Elements in Soils and Vegetables

All five potentially toxic elements (Cd, Ni, Pb, Mn, Cr) were detected in soils and vegetables from Wudil, Kano State, and are summarised in Table 2, showing marked variation across crop species. Soil concentrations were generally low and below international guideline values, indicating minimal anthropogenic contamination. Mn dominated the soil metal profile ($2.37\text{--}3.39$ mg/kg; mean 3.03 ± 0.57 mg/kg), consistent with ferruginous Sudan-Savannah soils enriched through natural weathering processes. Cd was the next most abundant ($0.50\text{--}1.06$ mg/kg; mean 0.84 ± 0.30 mg/kg), followed by Cr, Pb, and Ni, all present at comparatively low levels.

Vegetables exhibited distinct species-specific accumulation patterns. Mn showed the greatest variability, with lettuce accumulating the highest levels (9.11 ± 1.66 mg /g), followed by pepper (4.45 ± 0.10 mg/kg), while spinach and cabbage contained substantially lower concentrations. Cd accumulation was moderate across species ($0.31\text{--}0.53$ mg/kg), whereas Ni remained uniformly low, reflecting limited soil-to-plant transfer. Pb concentrations were consistently higher in soils than in edible tissues, confirming its low phytoavailability [35]. Cr displayed moderate variability, with spinach showing the highest levels (0.50 ± 0.30 mg/kg) and lettuce the lowest (0.11 ± 0.04 mg/kg).

Table 2

Mean $\pm$ standard deviation and concentration range (mg k/g dry weight) of potentially toxic elements in agricultural soils and vegetables from Wudil, Kano State, Nigeria.

Sample	Cd (mg/kg)	Ni (mg/kg)	Pb (mg/kg)	Mn (mg/kg)	Cr (mg/kg)
soil	0.84 $\pm$ 0.30 (0.50–1.06)	0.19 $\pm$ 0.09 (0.11–0.29)	0.33 $\pm$ 0.10 (0.23–0.42)	3.03 $\pm$ 0.57 (2.37–3.39)	0.49 $\pm$ 0.09 (0.40–0.58)
Pepper	0.53 $\pm$ 0.27 (0.32–0.84)	0.13 $\pm$ 0.06 (0.07–0.19)	0.23 $\pm$ 0.06 (0.17–0.28)	4.45 $\pm$ 0.10 (4.36–4.56)	0.18 $\pm$ 0.04 (0.14–0.22)
Lettuce	0.31 $\pm$ 0.05 (0.27–0.37)	0.09 $\pm$ 0.03 (0.07–0.13)	0.08 $\pm$ 0.04 (0.05–0.13)	9.11 $\pm$ 1.66 (7.58–11.03)	0.11 $\pm$ 0.04 (0.08–0.16)
Spinach	0.32 $\pm$ 0.11 (0.21–0.43)	0.04 $\pm$ 0.03 (0.02–0.08)	0.25 $\pm$ 0.24 (0.09–0.53)	1.63 $\pm$ 0.82 (0.76–2.39)	0.50 $\pm$ 0.30 (0.22–0.82)
Cabbage	0.32 $\pm$ 0.16 (0.17–0.49)	0.04 $\pm$ 0.03 (0.02–0.08)	0.15 $\pm$ 0.07 (0.07–0.21)	0.82 $\pm$ 0.24 (0.56–1.02)	0.37 $\pm$ 0.26 (0.09–0.61)

Generally, the data indicate that vegetable species exert a stronger influence on PTE accumulation than the relatively uniform soil concentrations. Differences in leaf morphology, root architecture, nutrient demand, and metal transport pathways likely explain the observed inter-species variation. Despite these differences, the generally low soil metal levels suggest limited risk of excessive PTE accumulation under current agricultural conditions.

From a food-safety perspective, the consistent detection of Cd across all vegetable species is noteworthy. Cd is a non-essential metal with a long biological half-life and well-documented cumulative toxicity, and chronic dietary exposure has been linked to renal impairment, skeletal damage, and elevated cancer risk [35].

To evaluate potential dietary concerns, Cd concentrations were compared with Codex Alimentarius maximum levels (MLs). For leafy vegetables such as spinach and lettuce, the Codex ML is 0.2 mg/kg (fresh weight) (CAC/GL 5-2019). Although the present study reports dry-weight values, the measured concentrations already exceed this threshold before conversion. Spinach (0.32 $\pm$ 0.11 mg/kg dry weight) and lettuce (0.31 $\pm$ 0.05 mg/kg dry weight) both surpass the Codex ML when expressed on a fresh-weight basis. Pepper also showed relatively high Cd levels (0.53 $\pm$ 0.27 mg/kg dry weight), suggesting that fruit vegetables may likewise exceed relevant Codex limits after conversion [36].

Although Cd concentrations in Wudil vegetables were lower than those reported in heavily contaminated systems such as Saudi Arabia [37], the widespread occurrence of Cd in edible tissues and the likelihood of exceeding Codex MLs underscores the need for continued monitoring. This is particularly important in peri-urban agricultural settings where future anthropogenic pressures may increase environmental Cd loading and heighten dietary exposure risks [38].

3.2 Variability in Metal Accumulation Among Vegetable Species

Figure 2–6 visually illustrate the pronounced differences in PTE accumulation observed among the four investigated vegetable species. These variations occurred despite their cultivation under broadly similar environmental conditions, highlighting the dominant influence of plant-specific uptake traits over differences in soil metal availability. Mn exhibited the greatest inter-species variability [35]. *Lactuca sativa* (lettuce) accumulated markedly higher Mn concentrations (8.12–11.03 mg/kg) compared with *Capsicum annuum* (pepper) (4.36–4.56 mg/kg). *Spinacia oleracea* (spinach) and *Brassica oleracea* (cabbage) contained substantially lower levels. This pattern reflects Mn's essential physiological role as a micronutrient and the inherently higher nutrient demand and uptake efficiency characteristic of leafy vegetables such as lettuce. Cd displayed moderate inter-species variation, with pepper exhibiting the highest concentrations and lettuce the lowest. Ni remained consistently low across all species, indicating limited soil mobility and restricted transfer to edible tissues. Pb concentrations were generally higher in soils than in vegetables, confirming Pb's strong affinity for soil particles and its limited translocation to above-ground plant parts. Cr showed moderate species-specific differences, with spinach accumulating the highest levels and lettuce the lowest.

Collectively, these observed patterns demonstrate that vegetable species exert a stronger control over PTE accumulation than the relatively uniform soil concentrations observed across the study area. This underscores the critical importance of considering crop-specific uptake characteristics when evaluating food safety and assessing dietary exposure in peri-urban agricultural systems.

3.2.1 Cadmium (Cd) – Concentrations and Accumulation

Cadmium (Cd) concentrations in soils and vegetables from the Wudil production system are presented in Fig. 2. Soil samples consistently had higher Cd concentrations (mean: 0.84 ± 0.30 mg/kg; range: 0.50–1.06 mg/kg) than corresponding vegetable tissues, indicating that agricultural soils serve as the primary Cd reservoir in the area. While these soil Cd concentrations exceeded those reported for several agricultural regions in India [39], yet remained considerably below values documented for intensively cultivated urban soils in Lagos, Nigeria, [40], thereby suggesting a moderate level of contamination overall in the study area, [41].

All vegetable species accumulated substantially lower Cd concentrations than their corresponding soils, confirming limited but measurable soil-to-plant transfer. *Capsicum annuum* (pepper) exhibited the highest Cd level (0.53 ± 0.27 mg/kg) and the greatest variability, potentially reflecting differences in root physiology, rhizosphere interactions, or microsite soil conditions. Conversely, *Lactuca sativa* (lettuce) recorded the lowest Cd concentration (0.31 ± 0.05 mg/kg), with narrow concentration ranges in lettuce and *Brassica oleracea* (cabbage) suggesting more uniform uptake across sampling locations for these species.

The restricted transfer of Cd from soil to edible tissues implies that a significant proportion of soil-bound Cd remained biochemically unavailable for plant uptake. Cd bioavailability is strongly influenced by soil physicochemical properties, including pH, organic matter content, cation exchange capacity, and metal

speciation, which collectively regulate its mobility. Similar patterns have been reported in southeastern Nigeria, where elevated soil Cd concentrations did not translate into proportionally high vegetable concentrations due to limited phytoavailability [35].

From a food safety perspective, the consistent presence of Cd in all vegetable species is notable. Cadmium is a non-essential metal characterised by a long biological half-life and cumulative toxicity. Chronic dietary exposure is associated with renal dysfunction, skeletal damage, and an increased cancer risk [35, 42]. Although the Cd levels observed in this study were lower than those reported in heavily contaminated agricultural systems Najmi, 2023 #1086}, its consistent detection in edible vegetables underscores the imperative for continued monitoring. This is particularly crucial in peri-urban agricultural systems, such as Wudil, where future anthropogenic pressures could increase environmental Cd loading and, consequently, dietary exposure risks.

3.2.2 Nickel (Ni) – Concentrations and Accumulation

Nickel (Ni) concentrations in soils and vegetables are presented in Fig. 3. Ni levels were uniformly low across all samples. Soils contained slightly higher concentrations (mean: 0.19 ± 0.09 mg/kg; 0.11–0.29 mg/kg) compared to vegetable tissues. Among the edible species, *Capsicum annuum* (pepper) accumulated the highest Ni concentration (0.13 ± 0.06 mg/kg), whereas *Spinacia oleracea* (spinach) and *Brassica oleracea* (cabbage) contained the lowest (0.04 ± 0.03 mg/kg). The narrow concentration ranges observed across all matrices indicate limited spatial variability and a relatively uniform Ni distribution within the study area.

The consistently lower Ni concentrations in vegetables compared with soils suggest restricted soil-to-plant transfer and low bioavailability under the prevailing environmental conditions [35]. Soil pH, organic matter content, redox status, and metal speciation are recognised factors that strongly influence Ni solubility and uptake; these likely contributed to the limited mobility observed. Similar trends have been reported in other agricultural systems, including Kano [41], India [39], and Tanzania [43]. where Ni typically exhibits low mobility and minimal transfer to edible plant tissues.

Although Ni is an essential micronutrient involved in urease activity and nitrogen metabolism, excessive dietary intake can cause allergic reactions, gastrointestinal disturbances, and respiratory problems [35, 37]. The Ni concentrations measured in this study were significantly below levels associated with phytotoxicity or adverse human health effects. This indicates that Ni currently poses a minimal dietary risk in the Wudil agricultural system [12, 35]. Nonetheless, continued monitoring remains advisable, particularly given increasing anthropogenic pressures characteristic of peri-urban agriculture.

3.2.3 Lead (Pb) – Concentrations and Accumulation

Lead concentrations in soils and vegetables are shown in Fig. 4. Soil Pb concentrations (mean 0.33 ± 0.10 mg/kg; 0.23–0.42 mg/kg) were consistently higher than those in vegetable tissues, indicating limited transfer from soil to edible plant parts. This pattern reflects Pb's strong affinity for soil minerals, organic matter, and Fe/Mn oxides, which substantially restrict its mobility and phytoavailability [35]. Pb

concentrations in Wudil soils were slightly higher than those reported for some agricultural areas in northern Nigeria [44], but remained well below levels documented in more contaminated urban and industrial environments in Lagos, South Africa, and India [39, 40]. Overall, the results suggest relatively low Pb contamination and minimal accumulation in edible vegetables.

Among the vegetable species, *Spinacia oleracea* (spinach) contained the highest Pb concentration (0.25 ± 0.24 mg/kg), followed by *Capsicum annuum* (pepper) (0.23 ± 0.06 mg/kg), *Brassica oleracea* (cabbage) (0.15 ± 0.07 mg/kg), and *Lactuca sativa* (lettuce) (0.08 ± 0.04 mg/kg). The greater variability observed in spinach may reflect enhanced interception of atmospheric particulates due to its broad leaf surface, as well as species-specific differences in Pb uptake and internal translocation [37]. Although Pb concentrations were relatively low, its detection in all vegetable species warrants continued monitoring. This is crucial because Pb is a non-essential metal with cumulative toxicity and is associated with neurological impairment, cardiovascular disease, and renal dysfunction following prolonged dietary exposure [42].

3.2.4 Manganese (Mn) – Concentrations and Accumulation

Manganese (Mn) was the most abundant element detected in the vegetable samples (Fig. 5), with concentrations ranging from 0.82 ± 0.24 mg/kg in *Brassica oleracea* (cabbage) to 9.11 ± 1.66 mg/kg in *Lactuca sativa* (lettuce). The markedly higher Mn concentrations in vegetables, particularly lettuce, indicate high Mn bioavailability and efficient plant uptake. As an essential micronutrient involved in photosynthesis, enzyme activation, and antioxidant defence, Mn is naturally absorbed and translocated more readily by plants compared to non-essential metals such as Cd and Pb.

Lactuca sativa (lettuce) accumulated substantially higher Mn concentrations than *Capsicum annuum* (pepper), *Spinacia oleracea* (spinach), and *Brassica oleracea* (cabbage). This reflects species-specific differences in nutrient demand, root uptake efficiency, and physiological traits. Comparable Mn levels have been reported in vegetables grown in Kano and other regions of Nigeria, as well as in India and South Africa [12, 39, 41, 42]. In contrast, considerably higher Mn concentrations have been documented in vegetables from Saudi Arabia, where elevated levels have been attributed to differences in soil geochemistry, irrigation water quality, and broader environmental conditions[37, 45].

Although Mn is an essential dietary element, long-term excessive exposure has been associated with neurological disorders, particularly in vulnerable populations. However, the Mn concentrations measured in this study fall within ranges commonly reported for edible vegetables and are unlikely to pose an immediate health concern. The predominance of Mn in these vegetables therefore reflects natural nutrient acquisition rather than anthropogenic contamination [34]. This underscores the importance of distinguishing between essential micronutrients and non-essential toxic metals when evaluating food safety and environmental quality.

3.2.5 Chromium (Cr) – Concentrations and Accumulation

Chromium concentrations in vegetables ranged from 0.08 to 0.82 mg/kg (Fig. 6), indicating moderate variability across crop species. These differences likely reflect variations in soil physicochemical properties, Cr speciation, and plant physiological traits [35], that jointly regulate metal uptake and internal transport. Unlike essential micronutrients such as Mn, Cr is generally not readily accumulated by plants, and its bioavailability is strongly controlled by soil pH, organic matter content, redox conditions, and chemical speciation. The Cr concentrations measured in this study are comparable to values previously reported for agricultural systems in Kano State [41]. But exceed those documented for some northern Nigerian regions [44]. Conversely, they remain substantially lower than concentrations reported in Saudi Arabia, where elevated Cr levels have been linked to local geochemical conditions and intensive irrigation practices [37].

Among the vegetable species, *Spinacia oleracea* (spinach) accumulated the highest Cr concentration ($0.50 \pm 0.30 \text{ mg kg}^{-1}$), followed by *Brassica oleracea* (cabbage) ($0.37 \pm 0.26 \text{ mg/kg}$), while *Lactuca sativa* (lettuce) contained the lowest ($0.11 \pm 0.04 \text{ mg/kg}$). These patterns suggest species-specific differences in root uptake efficiency and internal transport, with spinach exhibiting a greater capacity for Cr accumulation. Similar concentration ranges have been reported for vegetables grown in southeastern Nigeria [42].

The toxicological significance of Cr depends on its oxidation state: trivalent Cr(III) is considered a beneficial trace element at low concentrations, whereas hexavalent Cr(VI) is highly toxic and carcinogenic. Since only total Cr was measured in this study, speciation could not be determined. Following USEPA recommendations, the health-risk assessment therefore adopted a conservative assumption by treating all Cr as Cr(VI)[46]. Even under this precautionary approach, the relatively low Cr concentrations observed suggest limited environmental contamination and low dietary exposure. Overall, Cr accumulation in Wudil vegetables appears to be driven primarily by plant-specific uptake characteristics and local soil conditions rather than substantial anthropogenic inputs.

3.3 Soil contamination assessment

The degree of potentially toxic element (PTE) contamination in agricultural soils was evaluated using the Contamination Factor (CF), Geoaccumulation Index (I_{geo}), and Pollution Load Index (PLI). The results, summarized in Table 3, indicate that the soils were generally unpolluted, with minimal evidence of significant anthropogenic metal enrichment[24, 47].

Table 3
Soil contamination indices for agricultural soils from Wudil, Kano State, Nigeria

Metal	Mean concentration (mg/kg)	Background (mg/kg)	CF	Igeo	Contamination class (Igeo)
Cd	0.84 ± 0.30	0.35	2.40	0.68	Moderate contamination
Ni	0.19 ± 0.09	35	0.005	-8.12	Uncontaminated
Pb	0.33 ± 0.10	20	0.017	-6.51	Uncontaminated
Mn	3.03 ± 0.57	850	0.004	-8.72	Uncontaminated
Cr	0.49 ± 0.09	70	0.007	-7.75	Uncontaminated
Overall Pollution Load Index (PLI) = 0.05; Interpretation: Unpolluted (PLI < 1)					

Among the analysed metals, Cd exhibited the highest contamination factor (CF = 2.40), indicating moderate contamination according to the classification of Hakanson [24]. This relatively higher CF reflects the naturally low background concentration of Cd and suggests slight enrichment compared with other metals. In contrast, Ni, Pb, Mn, and Cr all exhibited CF values well below unity, indicating low contamination and levels close to natural background concentrations.

The Geoaccumulation Index (Igeo) further confirmed the low contamination status of the soils. Cadmium recorded an Igeo value of 0.68, corresponding to the class "uncontaminated to moderately contaminated", whereas all other metals exhibited strongly negative Igeo values (- 6.51 to - 8.72), indicating uncontaminated soils according to Müller's classification [25, 47].

The overall Pollution Load Index (PLI) was 0.05, substantially below the critical threshold of 1, demonstrating that the agricultural soils have not undergone significant deterioration due to heavy metal contamination. The low PLI indicates that the combined influence of all analysed metals remains minimal, and the soils are generally suitable for agricultural production.

3.7 Soil Contamination, Plant Uptake, and Dietary Exposure Risks from Heavy Metals in Wudil

Despite the generally low soil contamination indicated in Table 4, measurable concentrations of potentially toxic elements were detected in all vegetable species. This highlights that soil quality alone does not fully represent potential human exposure, as plant uptake is influenced by metal bioavailability, plant physiological characteristics, and soil–plant transfer processes [48]. Vegetables can serve as efficient pathways for transferring PTEs into the food chain, even from apparently uncontaminated soils.

Table 4
Risk Characterisation of Heavy Metal Exposure from Mixed Vegetables (CDI/RfD Ratios)

Metal	RfD (mg/kg/day)	CDI (mg/kg/day)	Risk Index (RI = (CDI/RfD)
Cadmium (Cd)	0.001	0.00151	1.51
Nickel (Ni)	0.02	0.00015	0.0075
Lead (Pb)	0.004	0.00063	0.1575
Manganese (Mn)	0.14	0.00840	0.06
Chromium (Cr VI)	0.003	0.000205	0.0683

Among the analysed metals, cadmium (Cd) posed the greatest toxicological concern. Its Risk Index (RI = 1.51) exceeded the standard non-carcinogenic safety threshold (RI > 1), indicating that prolonged dietary exposure may present a potential health risk. This aligns with established risk-assessment guidance, where RI > 1 signals possible non-cancer effects. In contrast, Ni, Pb, Mn, and Cr (VI) all exhibited RI values below 1, suggesting acceptable non-cancer risks under the assumed exposure scenario. Pepper and spinach contributed more substantially to dietary exposure due to their relatively higher accumulation of Cd, Mn, and Cr, whereas lettuce and cabbage generally presented lower toxicological risks. This pattern is consistent with broader literature showing that leafy vegetables often accumulate higher concentrations of cadmium and other metals compared with non-leafy crops [48–50].

The findings reinforce that low soil contamination does not necessarily equate to negligible dietary risk, as plant uptake characteristics and metal bioavailability strongly influence human exposure. This principle is widely recognised in environmental-health assessments, which emphasise that food-chain transfer can be a dominant exposure route even when soil concentrations are low.

3.4 Soil–Plant Transfer Factors and Metal Bioaccumulation.

The soil–plant transfer factor (TF) quantifies the mobility of potentially toxic elements (PTEs) from soil into edible plant tissues, calculated as the ratio of metal concentration in the vegetable to that in the corresponding soil. Mean TF values for each crop-metal pair are presented in Table 4.

Table 4
Soil–plant transfer factors (TFs) of potentially toxic
elements in vegetables cultivated in Wudil, Kano State,
Nigeria.

Vegetable	Cd TF	Ni TF	Pb TF	Mn TF	Cr TF
Pepper	0.63	0.68	0.70	1.47	0.37
Lettuce	0.37	0.47	0.24	3.01	0.22
Spinach	0.38	0.21	0.76	0.54	1.02
Cabbage	0.38	0.21	0.45	0.27	0.75

The TF values reveal clear differences in metal mobility and accumulation among vegetable species. Cd, Ni, and Pb all exhibited TF values below unity, indicating restricted transfer from soil to edible tissues. This behaviour aligns with the strong adsorption of these metals to soil organic matter, clay minerals, and Fe/Mn oxides, which limits their mobility and phytoavailability [51, 52]. Despite their detection in all vegetables, low TF values suggest constrained plant uptake even with measurable soil concentrations.

In contrast, Mn and Cr showed higher transfer efficiencies, reflecting both their environmental behaviour and crop-specific uptake characteristics. Lettuce recorded the highest Mn TF (3.01), demonstrating efficient uptake of this essential micronutrient, while spinach exhibited the highest Cr TF (1.02), indicating a comparatively greater capacity for chromium accumulation. These patterns highlight the importance of plant physiological traits such as root architecture, nutrient demand, transpiration rate, and metal transport mechanisms in governing metal accumulation [51, 53].

Overall, the TF results demonstrate that metal transfer within the Wudil agricultural system is strongly crop-dependent. The elevated TF values for Mn in lettuce and Cr in spinach suggest that these vegetables may contribute disproportionately to dietary exposure. Consequently, crop-specific monitoring should be prioritised in food-safety programmes, particularly in peri-urban agricultural systems where variations in metal bioavailability and plant uptake can significantly influence human health risks.

3.5 Compliance with International Food Safety Standards and Dietary Exposure Considerations

The concentrations of Cd, Ni, Pb, Mn, and Cr in the analysed vegetable samples were rigorously evaluated against established international food safety standards, including those from the Codex Alimentarius Commission (CAC) and other relevant regulatory bodies (FAO/WHO) [8, 34, 36]. While the mean concentrations of Ni, Pb, Mn, and Cr generally remained below their respective maximum permissible limits (MPLs), Section 3.2.1 highlighted that Cd concentrations in several vegetable species (e.g., spinach, lettuce, pepper) may exceed Codex Maximum Levels (MLs) for fresh weight when converted from dry weight. This nuanced finding challenges a blanket statement of full compliance across all elements.

Despite general compliance for most elements, significant inter-species differences in metal accumulation were evident. *Lactuca sativa* (lettuce) consistently accumulated higher Mn concentrations, whereas *Spinacia oleracea* (spinach) exhibited the highest Cr concentration and transfer factor. These patterns underscore the differential capacity of species to accumulate specific elements, influenced by their unique physiological and biochemical characteristics [8, 34].

Although elemental concentrations may fall below immediate regulatory thresholds, the potential for cumulative dietary exposure from prolonged consumption remains a critical concern, particularly in regions where these vegetables form a major dietary component. Therefore, reliance solely on concentration-based standards may not fully address potential health risks. A more comprehensive food safety evaluation necessitates integrating contaminant concentrations with robust dietary exposure assessment methodologies. This approach provides a holistic understanding of risk, supporting evidence-based management strategies for peri-urban agricultural systems, especially given the potential long-term health implications of continuous low-level exposure to potentially toxic elements [54].

3.6 Toxicological Interpretation of Exposure and Risk Indices.

The comparative assessment of Chronic Daily Intake (CDI), Reference Dose (RfD), and Hazard Index (HI = CDI/RfD) for Cadmium (Cd), Nickel (Ni), Lead (Pb), Manganese (Mn), and Chromium (VI) is presented in Fig. 7 and this illustrates the values, with CDI and RfD typically presented on a logarithmic scale to accommodate their wide range, and HI on a linear scale for direct comparison to the critical threshold. The results indicate substantial differences in toxicological risk among the analysed metals.

Non-Carcinogenic Risk: Cadmium exhibited the highest Hazard Index (HI = 1.51), exceeding the critical threshold of HI = 1. This indicates that the estimated dietary exposure slightly surpasses the reference dose, suggesting a potential non-carcinogenic health risk under the current exposure scenario. Although Cd concentrations measured in vegetables were relatively low, its very low reference dose (0.001 mg/kg/day) and cumulative toxicity resulted in the highest toxicological significance among the analysed metals. Long-term dietary exposure to cadmium is associated with renal dysfunction, skeletal damage, and an increased risk of carcinogenic effects [8, 45, 46].

In contrast, the calculated HI values for Ni (0.0075), Pb (0.158), Mn (0.060), and Cr(VI) (0.068) remained well below the safety threshold (HI < 1). This suggests that current dietary exposure to these metals from mixed vegetable consumption is unlikely to result in significant non-carcinogenic health effects.

Notably, the toxicological assessment demonstrates that cadmium is the principal contributor to non-carcinogenic health risk in the study area, whereas the remaining metals remain within acceptable safety limits. These findings further demonstrate that toxicological potency, rather than concentration alone, governs human health risk, highlighting the importance of integrating exposure assessment with toxicological benchmarks when evaluating food safety.

Cancer risk estimates for Cd and Cr remained within the internationally acceptable lifetime risk range (10^{-6} – 10^{-4}), suggesting a low probability of carcinogenic effects through vegetable consumption. Nevertheless, cadmium and chromium contributed most to the overall carcinogenic risk due to their higher toxicological potency and lower acceptable exposure thresholds. Consequently, continued monitoring of these metals, particularly in leafy vegetables cultivated in peri-urban agricultural systems, is recommended.

Estimated Daily Intake (EDI) values for all analysed metals were generally below provisional tolerable daily intake levels. However, Cadmium (Cd) and Lead (Pb) showed comparatively higher EDI values, particularly in vegetables with elevated concentrations. This indicates that chronic consumption of such vegetables could contribute meaningfully to long-term exposure for these metals [28, 34].

The Target Hazard Quotient (THQ) values for most metals were below the threshold of 1, indicating low non-carcinogenic risks under current exposure conditions [55]. However, Cd and Pb exhibited comparatively higher THQ values relative to other metals. This highlights their cumulative toxicity and inherently low safe-exposure thresholds [56].

The cumulative Hazard Index (HI) values for most vegetable types remained below unity ($HI < 1$), suggesting that combined non-carcinogenic risks are generally within acceptable limits. Nevertheless, vegetables with higher Manganese (Mn) and Chromium (Cr) concentrations contributed disproportionately to the overall HI values. Although Mn is an essential micronutrient, excessive intake may pose neurological risks. Elevated Cr levels, depending on speciation, may also increase the potential for adverse health effects [39, 41].

Cancer Risk (CR) estimates for Cadmium (Cd) and Lead (Pb) were within acceptable limits ($< 10^{-4}$). While Chromium (Cr) variability in spinach produced slightly higher CR values, these also remained within permissible limits. Across all vegetables, however, Cd and Cr were the dominant contributors to overall carcinogenic risk.

Overall, while the vegetables produced in Wudil can be regarded as generally safe for consumption, the elevated cadmium risk warrants continued surveillance. Routine monitoring of potentially toxic elements, particularly Cd and Cr, improved irrigation management, responsible agrochemical use, and periodic food safety assessments are recommended to minimise future health risks and support sustainable peri-urban agriculture in northern Nigeria. The risk profile is clearly dominated by Cd, and any food safety or risk management interventions should prioritise reducing Cd levels within the vegetable pathway.

5.0 Conclusion

This study provides a comprehensive assessment of potentially toxic element (PTE) contamination in agricultural soils and vegetables from Wudil, Kano State, Nigeria, and evaluates the associated human health risks. The findings indicate that while agricultural soils are generally unpolluted ($PLI = 0.05$), specific elements like Cadmium show signs of moderate enrichment. Crucially, the study highlights a

critical disconnect: low soil contamination does not automatically translate to negligible human health risk. This is primarily due to the efficient transfer of PTEs from soil to vegetables, which is strongly influenced by crop-specific uptake characteristics. The Hazard Index (HI) assessment revealed that Cadmium poses a potential non-carcinogenic health risk (HI = 1.51) through the consumption of mixed vegetables, primarily due to its low Reference Dose and cumulative toxicity. Although other elements (Ni, Pb, Mn, Cr) were within acceptable individual risk levels, and carcinogenic risks for Cd and Cr were within internationally acceptable ranges, the elevated Cd risk warrants immediate attention.

In conclusion, while the vegetables produced in Wudil are generally safe for consumption, the identified cadmium risk necessitates a proactive, integrated management approach. This includes implementing routine monitoring programs for PTEs, particularly Cd and Cr, alongside sustainable agricultural practices such as improved irrigation management, responsible agrochemical use, and regular food safety assessments. Such measures are vital to minimise future health risks, ensure food security, and support sustainable peri-urban agriculture in northern Nigeria.

Declarations

Author contributions

EB: Conceptualisation; study design; field sampling; laboratory analysis; data curation; statistical analysis; interpretation of results; manuscript drafting and critical revision; project administration. **AU:** Field sampling; laboratory preparation and digestion of samples; data validation; literature review; contribution to manuscript writing. **AM:** Methodology; instrumental analysis (MP-AES); quality assurance/quality control (QA/QC); verification of analytical data; review and editing of the manuscript. **MO:** Supervision; methodological guidance; interpretation of environmental geochemistry results; critical revision of the manuscript for intellectual content. **AO:** Data analysis support; preparation of tables and figures; assistance with health-risk assessment calculations; manuscript proofreading.

All authors reviewed and approved the final version of the manuscript and agree to be accountable for all aspects of the work.

Déclarations

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Ethics approval and consent to participate

Ethics and Consent to Participate

The collection of plants and plant parts used in this study complied fully with local and national guidelines for agricultural and environmental research in Nigeria. All sampled vegetables—*Capsicum annuum* (pepper), *Lactuca sativa* (lettuce), *Spinacia oleracea* (spinach), and *Brassica oleracea* (cabbage)—

were cultivated crops obtained from peri-urban farms in Wudil, Kano State, with the consent of the farmers. No wild, protected, endangered, or threatened plant species were collected. As all plant materials originated from cultivated plots under routine farming practices, no special permits or licences were required. All procedures adhered to ethical standards for environmental sampling and agricultural research.

Consent for publication

Not applicable.

Data availability

The datasets generated during and/or analysed during the current study are available from the corresponding author on reasonable request.

Competing Interests

The authors declare no known competing interests

Clinical trial number: not applicable

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Figures

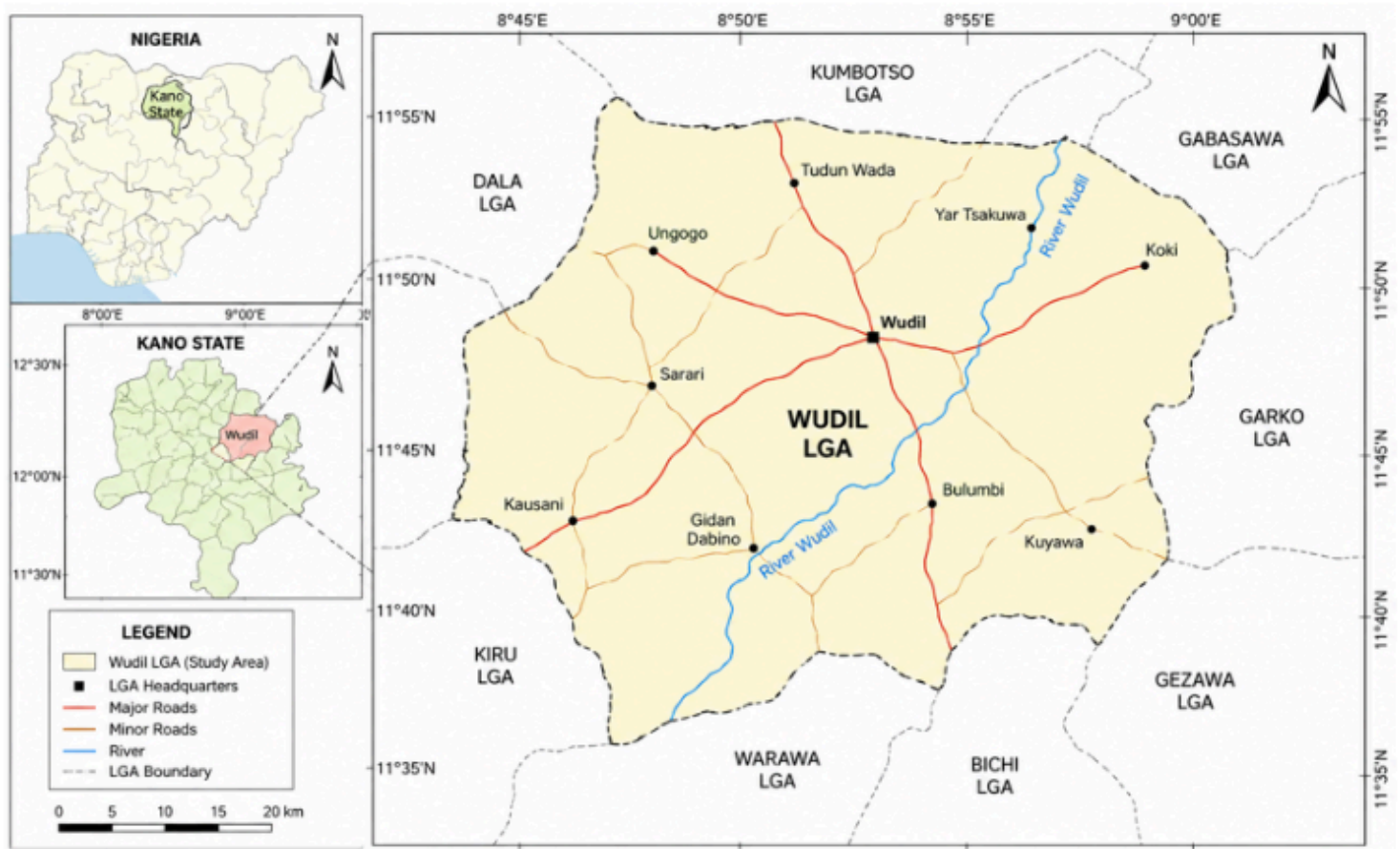


Figure 1

Location map of Wudil Local Government Area showing the study area, major road networks, River Wudil, and surrounding Local Government Areas in Kano State, Nigeria [22]

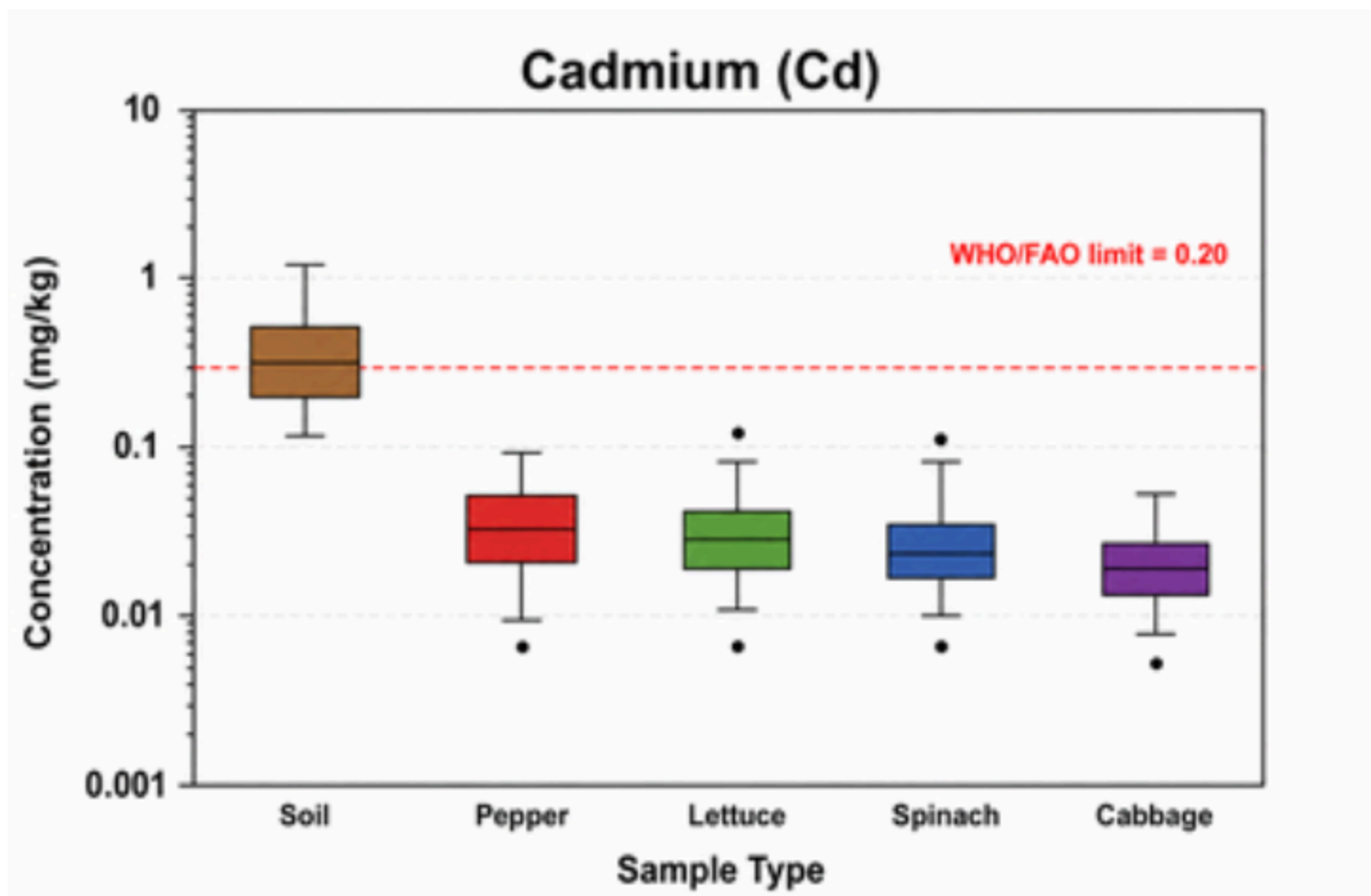


Figure 2

Cadmium concentrations (mg/kg) in soil and selected vegetable samples from Wudil Local Government Area, Kano State, Nigeria

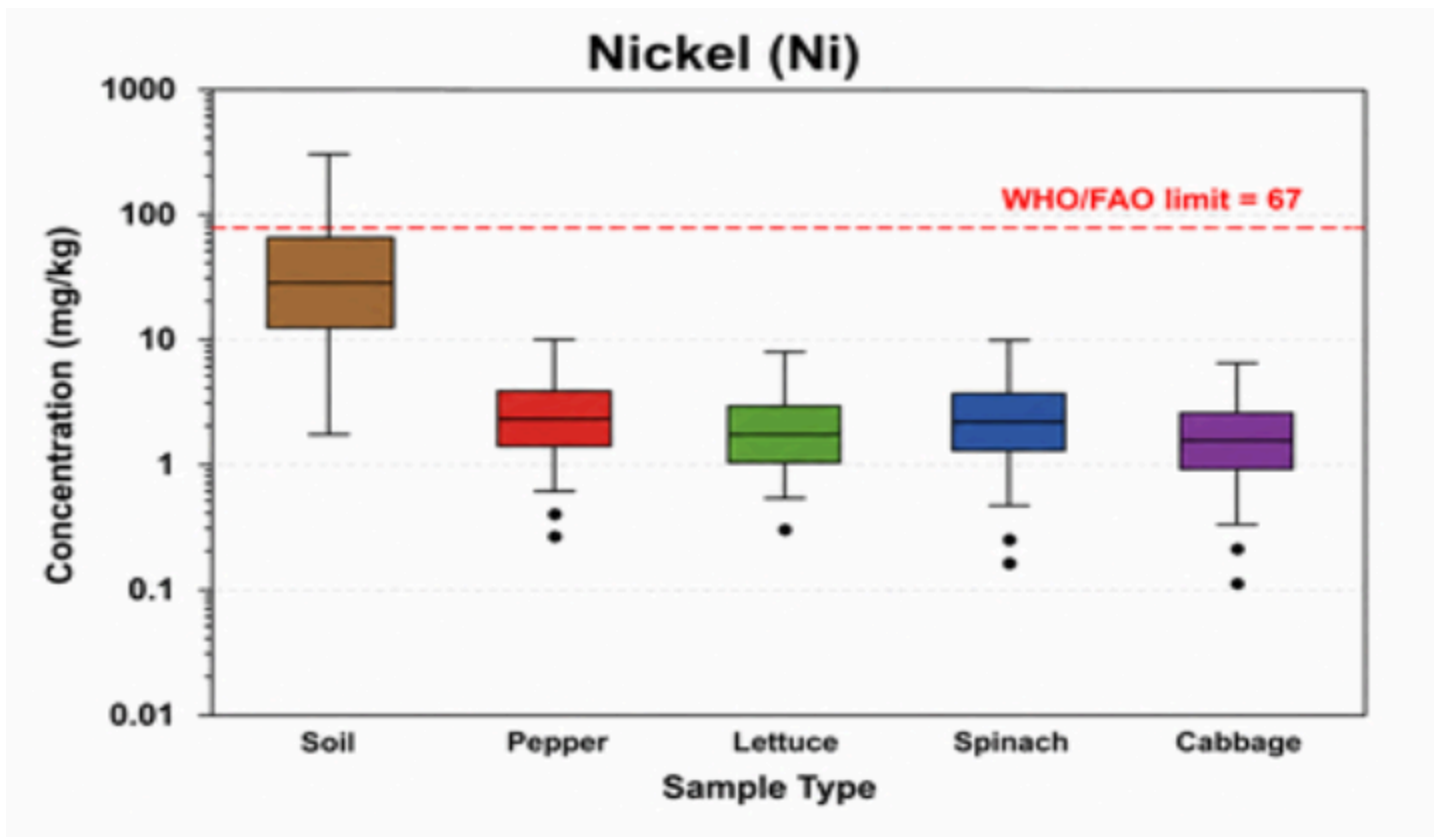


Figure 3

Nickel concentrations (mg/kg) in soil and selected vegetable samples from Wudil Local Government Area, Kano State, Nigeria.

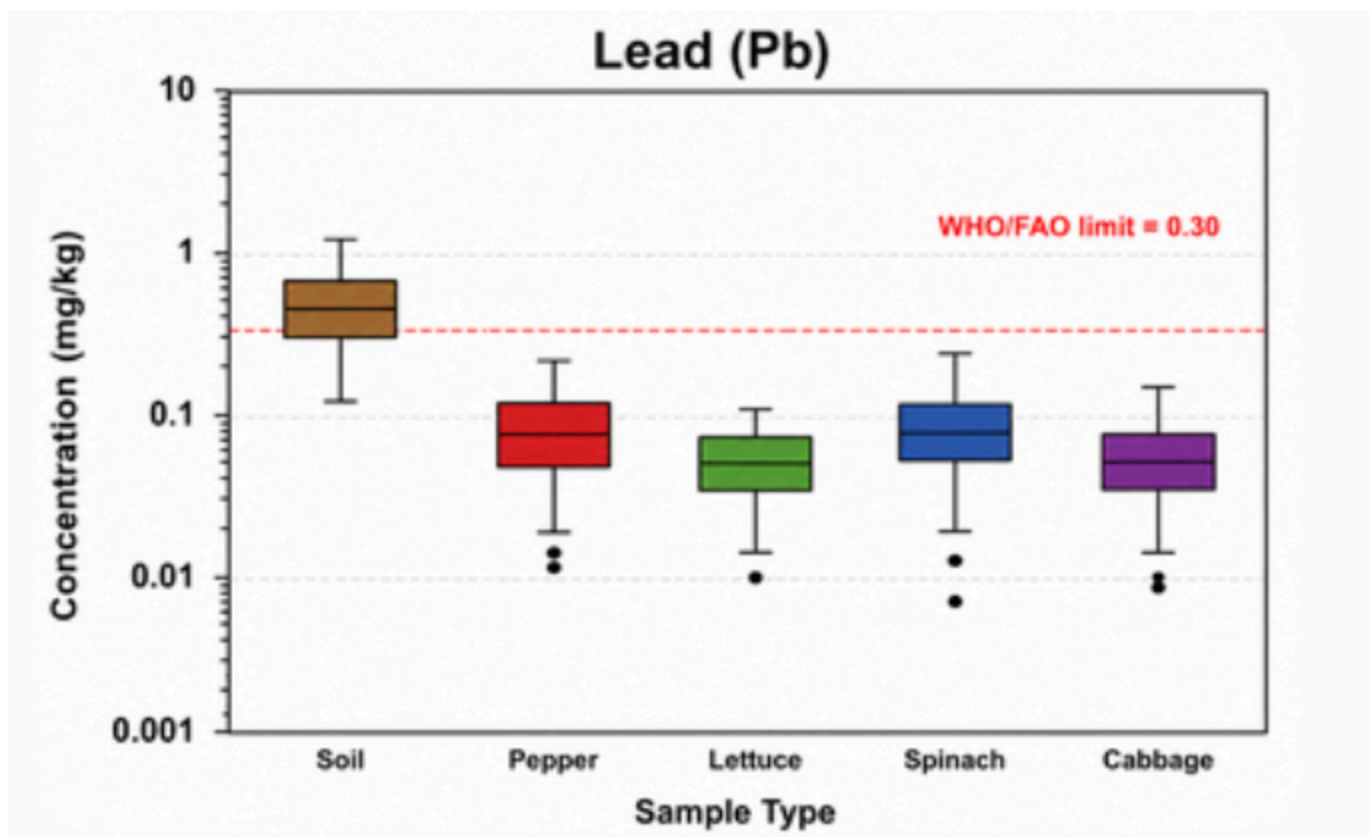


Figure 4

Lead concentrations (mg/kg) in soil and selected vegetable samples from Wudil Local Government Area, Kano State, Nigeria.

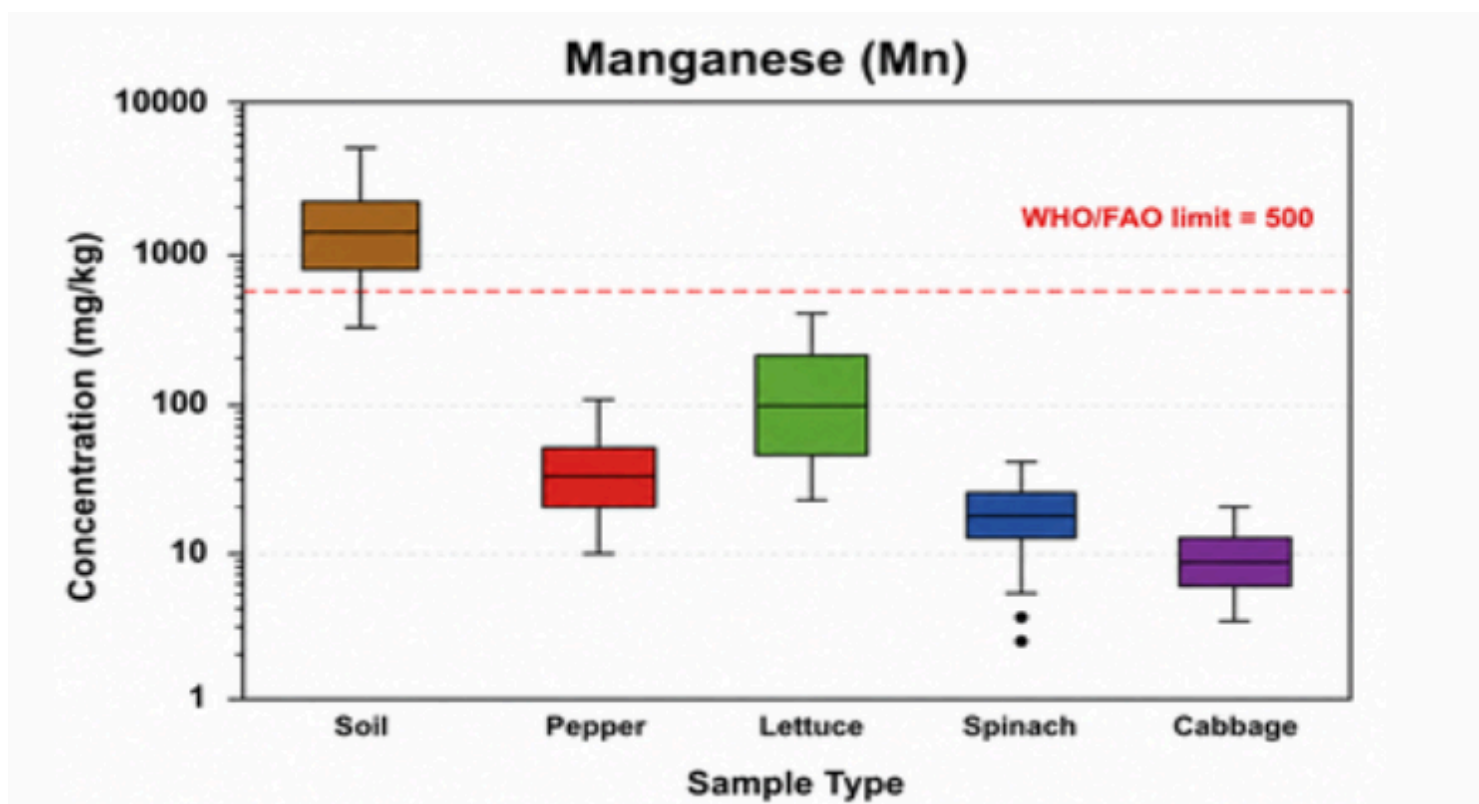


Figure 5

Manganese concentrations (mg/kg) in soil and selected vegetable samples from Wudil Local Government Area, Kano State, Nigeria.

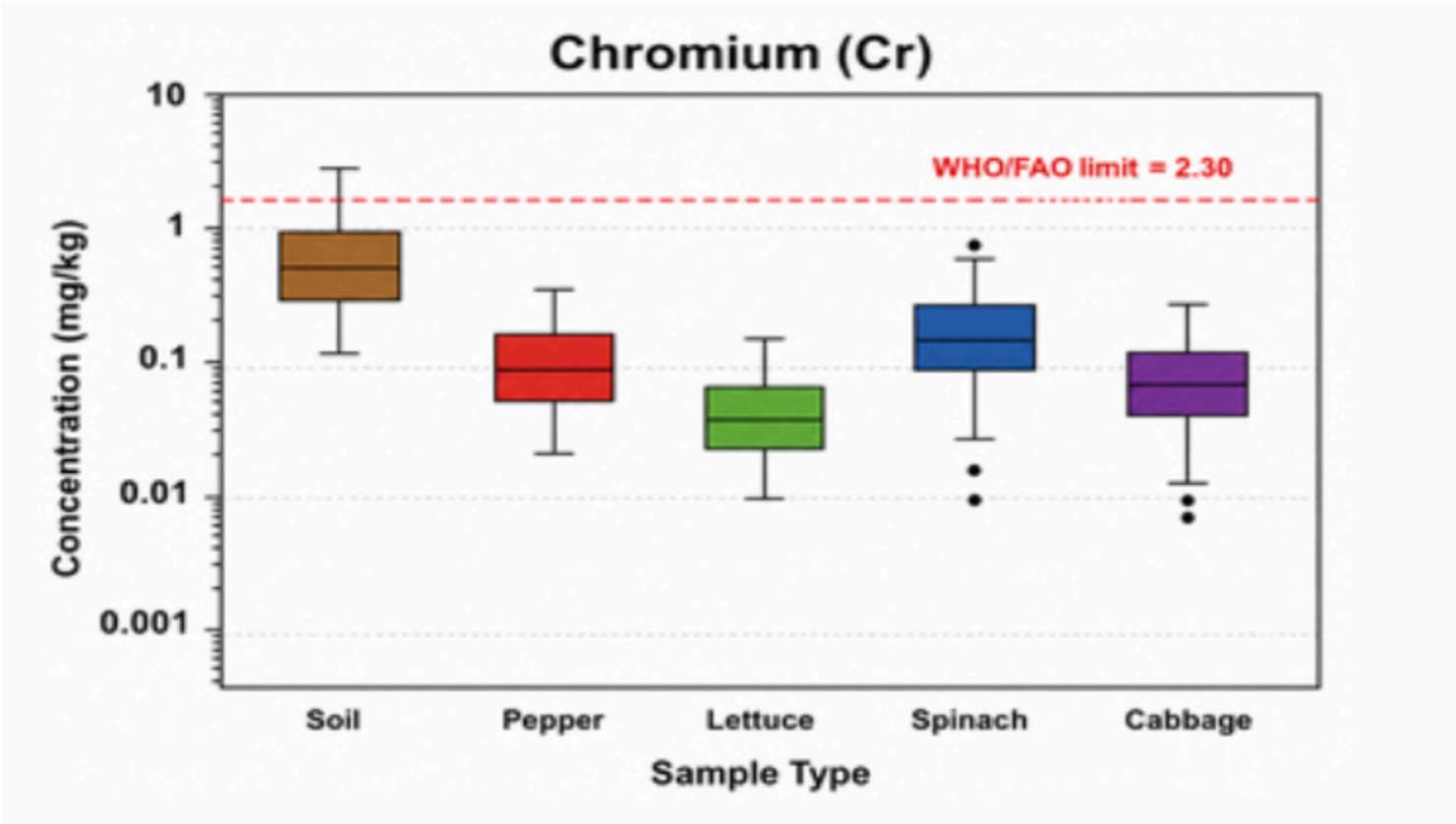


Figure 6

Chromium concentrations (mg/kg) in soil and selected vegetable samples from Wudil Local Government Area, Kano State, Nigeria.

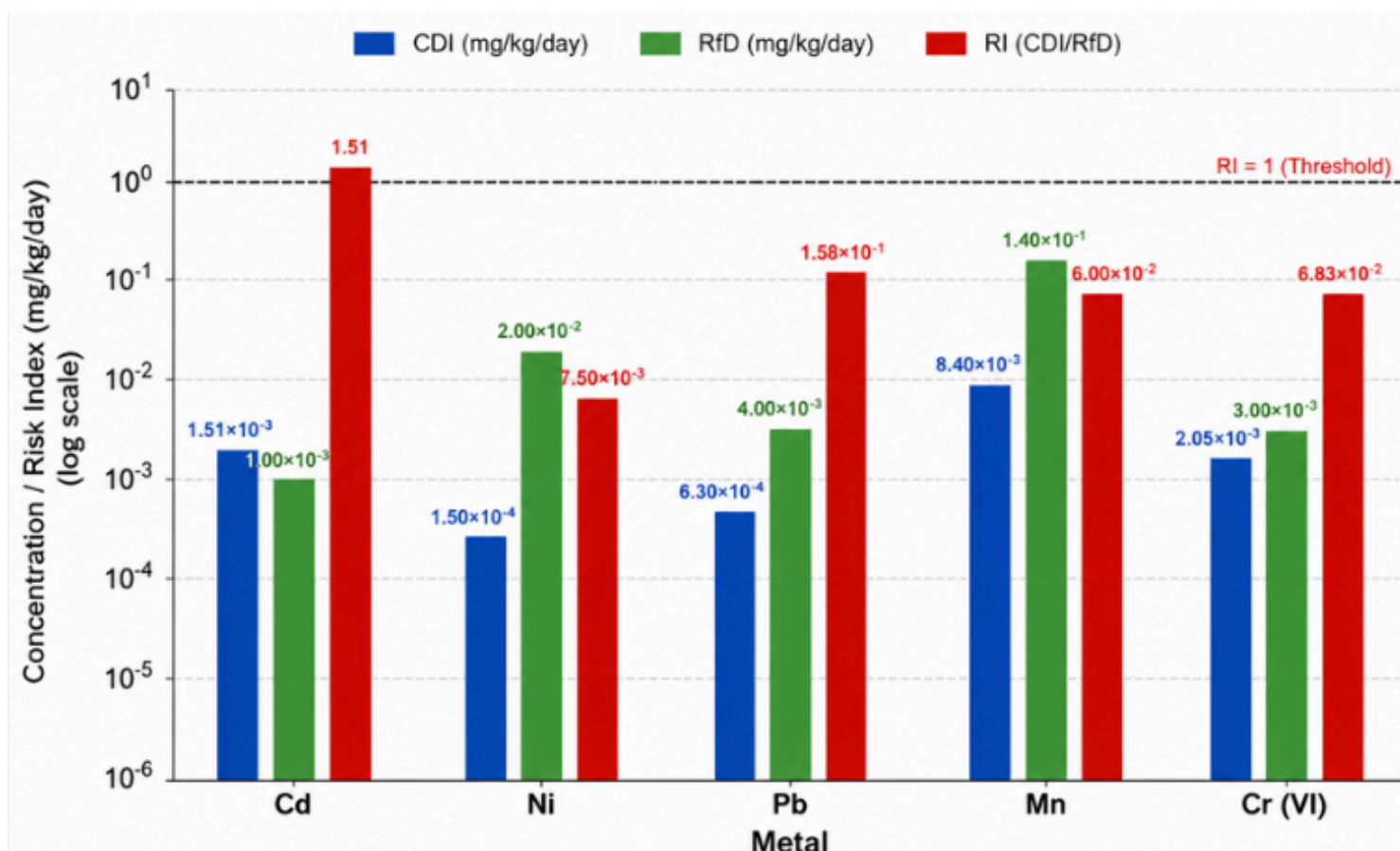


Figure 7

Comparison of Chronic Daily Intake (CDI), Reference Dose (RfD), and Risk Index (RI) for Cd, Ni, Pb, Mn, and Cr (VI) based on vegetable consumption in Wudil, Kano State