Romanian Journal of Ecology & Environmental Chemistry, 8(1), 2026
https://doi.org/10.21698/rjeec.2026.110

Article

Evaluating the health risks associated with essential and non-essential metals in staple food crops sold in major markets in Nasarawa, Nigeria

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Received:	*Accepted:*	*Published:*
28.05.2026	*02.07.2026*	*07.07.2026*

Abstract

The presence of hazardous metals in staple food crops poses a significant threat to human health. This study assessed the concentrations of some toxic and essential metals in black eye bean, soya bean, millet, sorghum, sesame seed, and locust bean obtained from major markets in Nasarawa, Nigeria, using Inductively Coupled Plasma-Optical Emission Spectrometry (ICP-OES). The results indicate that the mean metal concentrations in staple food crops exceeded WHO/FAO safety standards. Fe had the highest average concentrations (564 ± 52 to 1984 ± 124 mg/kg), which exceeded the WHO/FAO guideline of 425.5 mg/kg. Although Pb had the lowest mean concentration (3.80 ± 3.00 to 37.0 ± 14.0 mg/kg), it was still above the permissible limit of 0.20 mg/kg. The general concentration trend followed Fe > Zn > Mn > Ba > Se > Cr > Pb. Estimated daily intake values for most metals complied with USEPA reference thresholds, except for Cr in sesame seed for children, which exceeded safe limits. Hazard indices for black eye bean (1.30), millet (1.22), sorghum (1.29), sesame seed (2.60), and locust bean (1.72) were >1 in children. This indicates a possible health risk, except for the soya bean (0.83). Dermal contact posed a negligible risk, as all HI values were less than 1 for adults and children. The cancer risk value for Cr was above the acceptable range (1.0×10^{-6} to 1.0×10^{-4}), indicating potential carcinogenic hazards associated with their consumption. Overall, the results raised concern, particularly for children, hence the urgent need for surveillance and awareness.

Keywords*:* *health risk determination, food crops, toxic metals, market, ICP-OE*

INTRODUCTION

Heavy metal pollution has increasingly been recognized as a serious global challenge in environmental and food safety due to the non-biodegradable and persistent nature of these elements and their tendency to accumulate along food chains. Toxic metals such as lead (Pb), cadmium (Cd), chromium (Cr), arsenic (As), and copper (Cu) are particularly concerning because they have densities exceeding 5 g/cm³ and exert toxicological effects even at low exposure levels [1]. Humans are exposed to these metals through multiple routes, including ingestion of food and water, inhalation of contaminated air, and dermal absorption [2, 3]. The health impacts of such exposure are far-reaching, ranging from neurotoxicity and renal damage to cardiovascular disorders, gastrointestinal complications, and various forms of cancer [4]. The danger lies in their persistence within ecological systems, where heavy metals infiltrate soil and water, accumulate in crops and livestock, and ultimately reach human populations [5, 6]. Agricultural environments are especially vulnerable, as irrigation with contaminated water and farming on polluted soils introduce these elements directly into the food chain [7]. As a result, heavy metal pollution has become one of the most critical public health issues of the modern era, especially in developing nations where enforcement of environmental regulations remains weak.

The origins of heavy metal contamination in agriculture are multifaceted, stemming from both natural processes and anthropogenic activities [8]. Although trace levels of elements such as iron (Fe), zinc (Zn), and manganese (Mn) are indispensable micronutrients that support physiological processes like enzymatic activity, oxygen transport, and immune functioning, the unregulated accumulation of non-essential and toxic metals undermines both food quality and safety [9]. Prominent anthropogenic contributors include industrial effluents, untreated sewage, improper disposal of solid waste, the use of chemical fertilizers and pesticides, and emissions from fossil fuel combustion [10, 11]. In Nigeria, a notable source of risk is the widespread reliance on untreated irrigation water in rural and peri-urban farming zones [12]. This practice, while economically convenient, promotes the accumulation of toxicants in major staple crops, raising serious health concerns. Prolonged consumption of contaminated crops allows metals to bioaccumulate in critical organs such as the liver, kidneys, and bones, potentially resulting in chronic illnesses and premature mortality [13]. Since food constitutes the primary route of exposure for most populations, heavy metal contamination directly links environmental pollution with public health outcomes. Consequently, there is an urgent need for systematic research to monitor contamination levels and provide strategies for mitigating risks [14].

Staple crops, including legumes, cereals, and oilseeds, are particularly susceptible to contamination because of their widespread cultivation and critical nutritional roles. Legumes such as cowpeas, soybeans, and pigeon peas provide affordable protein, fiber, and micronutrients, serving as dietary staples in developing regions where access to animal protein is limited [15]. Cereals including maize, rice, millet, and sorghum supply more than half of the global caloric intake and remain the backbone of food security worldwide [16]. Similarly, seeds such as sesame, melon, cottonseed, and sunflower play dual roles in human diets and industrial applications, providing oils, colorants, and nutraceutical compounds [17]. However, these crops can readily absorb metals from their growing environments, with uptake influenced by crop type, soil conditions, and agronomic practices [18]. This contamination reduces both the nutritional quality of food and increases toxicological risks to consumers. In developing countries like Nigeria, limited monitoring and regulatory oversight amplify the danger, leaving populations vulnerable to unrecognized health threats. Understanding the scale and distribution of heavy metal contamination in such staple crops is therefore indispensable for food security and sustainable agricultural systems [10, 11].

Northern Nigeria, and particularly Nasarawa State, plays a vital role in national food supply, earning it the reputation of being part of the country’s “food basket.” The region is a major producer of cereals, legumes, and seeds with product distributed across local and regional markets. However, little reliable data exists concerning the extent of heavy metal contamination in crops cultivated in this region. Farming practices such as the use of fertilizers, pesticides, untreated irrigation water, and poorly regulated industrial waste disposal raise the likelihood of contamination [10, 12].

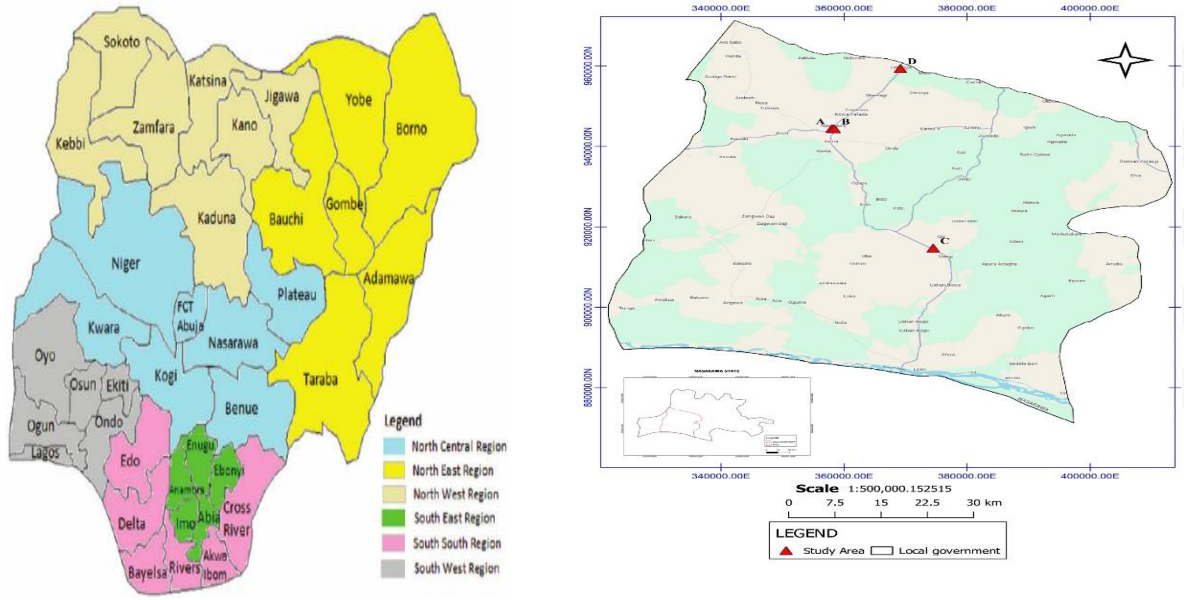
This study therefore addresses a critical gap by quantifying heavy metal concentrations in staple food crops cultivated in the Nasarawa Local Government Area and assessing the potential health risks to consumers. The findings will provide much-needed evidence to guide policymakers, farmers, and consumers in implementing effective interventions. Ultimately, this research not only informs food safety and environmental policy but also addresses broader public health and sustainable development issues. By ensuring safer agricultural practices and reducing exposure risks, this study contributes to both local and global efforts to secure healthier and more resilient food systems.

MATERIALS AND METHODS

Study Area

Nasarawa State is located in Nigeria's North Central geopolitical zone and is administratively segmented into thirteen (13) Local Government Areas. The state is situated between latitudes 7° and

9° North and longitudes 7° and 10° East. It adjoins Benue State to the south (83 km), Kogi State to the west (68 km), the Federal Capital Territory, Abuja, to the northwest (156 km), Kaduna State to the northeast (169 km), Plateau State further northeast (219 km), and Taraba State to the southeast (109 km). Within the state, Nasarawa Local Government Area (LGA) is one of the key administrative units, with its headquarters located in Nasarawa town, positioned at 8°32′N and 7°42′E (Mindat.org, 2020). The LGA occupies a total land area of 5,704 km² and had a population of 189,835 according to the 2006 national census. Economically, Nasarawa serves as a vibrant market hub for several agricultural commodities, including melon, sorghum, millet, soybeans, beans, locust beans, sesame seeds, shea nuts, yams, and cotton, all cultivated in the surrounding region. The town is strategically located at a crossroads, connecting local routes to Keffi, the Benue River ports of Loko, and the towns of Toto and Umaisha. Figure 1a and 1b present maps of Nigeria showing Nasarawa State (a) and the Nasarawa LGA (b) highlighting the three markets where crop samples were collected.



(a) (b)

Fig. 1. The map of the sampling areas

Sample collection, preparation, and analysis

Samples were collected at three different markets. Sampling techniques as reported by Ihedioha et al. [4] was modified and used. At each market, six samples each from different vendors of cereals (millet and sorghum), legumes (black-eyed beans and soya bean), and seeds (sesame seed and locust bean seed) were bought. The sample origins were confirmed via direct communication with sellers at the open markets. A total of 144 samples were collected and composited into 24 sub-samples for analysis. 85% of the sample was from Mararaba–Udege, 10% from Laminga and 5% from Nasarawa. Samples were collected between September to December from Nasarawa main market (A and B), Mararaba - Udege market (C) and Laminga market (D) within the local government. The hard samples were ground in a porcelain mortar and sieved using a 100 µm standard sieve, the pulverized samples were kept in plastic sample bottles for digestion. The wet acid digestion method was used according to the method reported by Akinyele and Shokunbi [19]. About 0.5 g of each homogenized sample was weighed into a Teflon flask. A mixture of 20 cm^3 aqua regia 2:1 of 65 % HNO_3 (Sigma-Aldrich Munich, Germany) and 37% HCl (Sigma-Aldrich Munich, Germany) was added and digested on a heating block in a fume hood at 90^0C for 60 minutes, cooled, and 2 cm^3 of 30 % H_2O_2 (Sigma-Aldrich Munich, Germany) was added and heated until the mixture became colourless indicating that digestion is complete. The digest was then filtered and diluted to 50 cm^3 using deionized water in a standard flask and used for analysis using an ICP-OES instrument type Agilent 720 (Agilent Technologies Inc., New York, USA), at the CTX – ION ANALYTICS laboratory, Lagos, Nigeria.

Quality assurance

An inductively coupled plasma-optical emission spectrometer ICP-OES Agilent 720 equipped with a megapixel CCD detector and configured with an SPS 3 autosampler was used to quantify the metals in the food crops. The metal concentrations from the ICP-OES were calculated using ICP Agilent Expert 11 software. The determination of elements in samples conformed to the US EPA Method 200.7 with modifications [20]. The protocols for the preparation of the standards were as recommended by the Standard Methods for the Examination of Water and Wastewater (ICP Method 3050B, APHA, 2005). The ICP-OES was operated under the following parameter settings: Power (1.0 kW), nebulizer gas pressure 220 Kpa, stabilization time (15 s), plasma flow (15 L/min), auxiliary flow (1.5 L/min), SPS 3 autosampler, pump speed (15 rpm), sample uptake delay (30 s, fast pump), replicate read time (30 s) and rinse time (10 s, fast pump) All tests were repeated three times, using the blank as a control for accuracy, reliability, and repeatability. All glassware was pretreated with 5% HNO_3 solution (Scharlau, Spain), washed with deionized water, and oven-dried. The measurements were made in triplicate, and the means were recorded. The individual metals' limits of detection were Cr-0.001 mg/L, Zn-0.0001 mg/L, Pb-0.002 mg/L, Mn 0.00006 mg/L, Se-0.002 mg/L, Cd-0.0001 mg/L, Fe-0.0002 mg/L and Ba-0.0002 mg/L. The final concentration of each metal in the food crops was calculated using the formula propose by Oyekunle et al. [21]:

$$C\ final\ (mg/kg) = (C_{metal},\ mg/L \times dilution\ factor \times final\ volume,\ mL)/sample\ weight,\ g \quad (1)$$

Recovery analysis was done to ascertain the accuracy of the analytical procedure used by spiking each sample with a standard mixture of the available heavy metal solutions (Pb, Cr, Mn, Cd, Fe, Zn, Se and Ba). Standard and metal solutions were used to fortify the samples with the specified metals, digested, and then analyzed with ICP-OES equipment. The percentage recovery (%) was calculated thus:

$$\%\ Recovery = (C - C_i)x100/A \quad (2)$$

where C = spiked sample value, C_i = sample value, A = spike added

High percent recovery was also observed for all metals, ranging from 93% to 116%, (Table 1).

Table 1. Results of recovery study for metals determined (Mean ± SD, n = 3)

Metal	Initial, mg/L	Spike,mg/L	Total expect, mg/L	Total analyzed, mg/L	Recovery, %	Mean recovery, %
Cr	0.01	1.00	1.01	1.17	116	115.3 ± 0.6
	0.02	1.00	1.02	1.17	115	
	0.02	1.00	1.02	1.17	115	
Pb	0.00	1.00	1.00	1.03	103	102 ± 1.0
	0.02	1.00	1.02	1.04	102	
	0.02	1.00	1.02	1.03	101	
Mn	0.27	1.00	1.27	1.25	98.4	98.0 ± 1.5
	0.15	1.00	1.15	1.14	99.1	
	0.19	1.00	1.19	1.15	96.6	
Se	0.03	1.00	1.03	0.96	93.2	93.0 ± 0.6
	0.03	1.00	1.03	0.96	93.2	
	0.06	1.00	1.06	0.98	92.5	
Zn	0.42	1.00	1.42	1.35	95.1	96.2 ± 1.2
	0.38	1.00	1.38	1.33	96.4	
	0.27	1.00	1.27	1.22	96.1	
Fe	0.42	1.00	1.42	1.35	95.1	95.6 ± 1.2
	0.39	1.00	1.39	1.32	95.0	
	0.50	1.00	1.50	1.45	96.7	
Ba	0.09	1.00	1.09	1.15	105.5	106.4 ± 1.2
	0.06	1.00	1.06	1.12	105.7	
	0.02	1.00	1.02	1.10	107.9	

Statistical analysis

Data obtained were subjected to statistical analysis using Pearson correlation, Principal Component Analysis (PCA) and Cluster Analysis (CA) to get detailed information about the distribution of heavy metals, their similarities and dissimilarities in the samples. All statistical health risk calculations, graphs and charts were performed with OriginPro 2022.

Health risk assessment

Based on the metal concentration, a risk evaluation for carcinogenic (cancer risk and total risk index) and non-carcinogenic (target hazard quotient and hazard index) effects and estimated daily intake was performed in line with the techniques reported by different studies [22÷25]. In table 2 are presented the estimating factors for heavy metal exposure, both for adults and children.

Table 2. Estimating factors for heavy metal exposure assessment

Parameters	Unit	Adults	Children
Metal concentration in samples (C_{food})	(mg/kg)		
Food intake rate (IR)	(kg/person/day)	2.2	1.8
Exposure frequency (EF)	(days/year)	350	350
Exposure duration (ED)	(year)	65	12
Average body weight (BW)	(kg)	70	16
Average time (AT)	(days/year × years)	23725	4380
Skin exposure area (SA)	(cm^2)	18000	6600
Dermal absorption fraction (KP)	(cm/h)	0.001÷0.006	0.001÷0.006
Adherence factor (AF)	(mg/cm^2)	0.07	0.07
Unit conversion factor (CF)	(kg/mg)	10^{-6}	10^{-6}

Source: USEPA, 2012 [26], Wu et al., 2009 [27], Abdul-Aziz et al., 2022 [25].

The Hazard Quotient (HQ) is a numerical assessment of the potential for systemic toxicity posed by a single metal and a single exposure method. By integrating the calculated HQs for each metal, the combined non-carcinogenic potential effects of many metals were assessed and expressed as a Hazard Index (HI).

When HQ and HI exceeds 1 value, there is cause for concern of potential human health risks from exposure to non-carcinogenic elements.

Estimated daily intake (EDI) was calculated using data from table 1 with the equation (3),[22,28]:

$$EDI = (C \times IR)/BW \quad (3)$$

Target Hazard Quotient (THQ)

THQ values were calculated using equations 4 and 5, [22÷24]:

$$THQ = (Ef \times ED \times IR \times C) \times 10^{-3}/(RFD \times BW \times AT) \quad (4)$$

$$THQ_{derm} = (C \times SA \times AF \times ABS \times EF \times ED \times CF) / (RFD \times BW \times AT) \quad (5)$$

Hazard Index (HI)

HI is the total sum of the THQ estimated for specific metals [24, 29]:

$$HI = \sum_{i=1}^{n} THQ \quad (6)$$

Cancer Risk (CR)

The Cancer risk (CR) and total cancer risk (TCR) owing to collective exposure of multiple metals during daily intake of food crops was projected as in equations (7) and (8).

$$CR = EDI \times CSF \quad (7)$$

Multiple-Element Cancer Risk

$$MCR = \sum_{i=1}^{n} CR \quad (8)$$

The CSF (mg/kg/day) of Cd, Cr and Pb are 0.38, 0.5 and 0.0085 respectively, as reported by Emurotu et al. [30]. A cancer risk value of 1.0E-06 and 1.0E-04 and multiple-element CR (TCR) < 1.0 × 10^{-4} [31] are tolerable and pose no lifetime cancer developmental risk.

RESULTS AND DISCUSSION

Concentration of heavy metals in food crops

The statistical distribution of selected metals—chromium (Cr), lead (Pb), manganese (Mn), selenium (Se), cadmium (Cd), zinc (Zn), iron (Fe), and barium (Ba) across legumes, cereals, and seeds is illustrated in Fig. 2 (a -g) and Table 3.

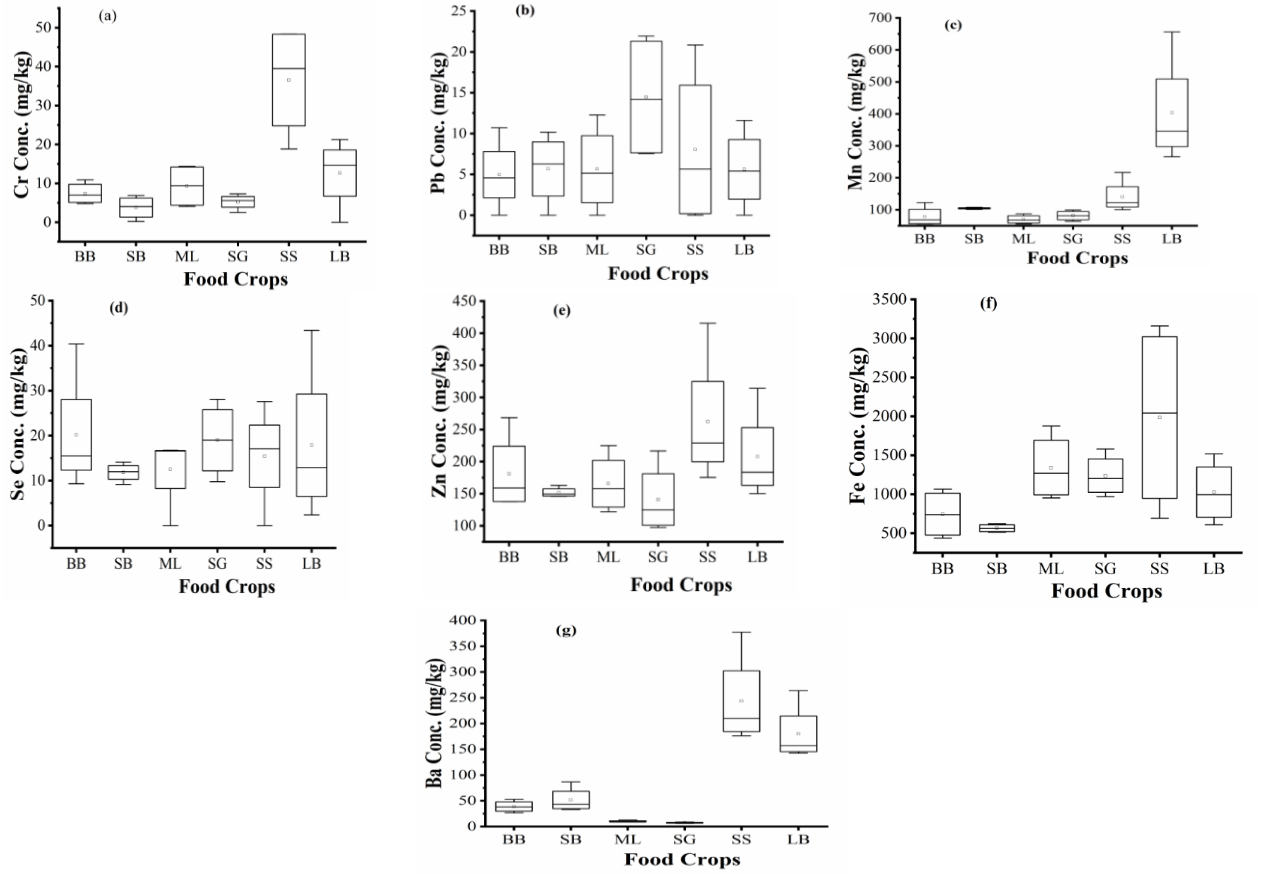


Fig. 2. Metal concentration of food crops

NOTE: BB – Black eye beans, SB – Soyabean, ML – millet, SG -Sorghum, SS – Sesame and LB – Locust bean.

In this boxplot, the small square indicates the mean, and the upper, middle, and lower horizontal lines correspond to the 75th, 50th, and 25th percentiles, respectively. Results demonstrate substantial variation in concentrations across food groups. For legumes, metal levels ranged from 7.40 ± 2.90 mg/kg for Cr to 744 ± 314 mg/kg for Fe. In cereals, concentrations ranged from 5.20 ± 2.00 mg/kg (Cr) to 1341 ± 433 mg/kg (Fe), whereas seeds ranged from 5.60 ± 4.60 mg/kg (Pb) to 1984 ± 124 mg/kg (Fe). Among all analyzed elements, Fe consistently exhibited the highest concentrations across categories.

Iron (Fe) is essential for biological function, supporting oxygen transport, cytochrome activity, and enzymatic processes. However, excessive intake may induce oxidative stress, leading to liver and heart damage, impaired neurological development, and elevated cancer risk [23, 29]. The present study recorded Fe levels exceeding the ($P < 0.05$) [32] permissible threshold of 425.5 mg/kg across all food categories, indicating potential long-term oxidative risk for daily consumers. Concentrations reported here are considerably higher than previous values, reported by other researchers such as 244 ± 4.02 mg/kg [33], 26.9 ± 13.0 mg/kg [34], 99.7 ± 0.35 mg/kg [35], and 84.0 ± 19.0 to 45.0 ± 6.00 mg/kg [17].

Table 3. Concentration (mg/kg) of heavy metals in the sampled food crops

Food crop	Location	Cr	Pb	Mn	Se	Cd	Zn	Fe	Ba
Black eye beans	A	5.40	4.20	55.4	15.7	ND	138	439	33.1
	B	10.9	ND	80.5	15.3	ND	180	961	52.8
	C	8.60	4.90	57.0	9.30	ND	138	513	26.5
	D	4.80	10.7	122	40.4	ND	268	1065	42.9
	Mean ± SD	**7.40 ± 2.90**	**6.60 ± 3.60**	**7.80 ± 31.0**	**20.0 ± 14.0**	**ND**	**181 ± 62.0**	**744 ± 314**	**39.0 ± 12.0**
Soya bean	A	5.60	ND	104	11.5	ND	163	622	33.1
	B	0.20	10.2	101	14.1	ND	147	514	36.4
	C	6.90	7.80	105	9.10	ND	152	527	86.6
	D	2.40	4.70	108	12.5	ND	146	595	50.2
	Mean ± SD	**3.80 ± 3.00**	**7.60 ± 2.70**	**105 ± 2.90**	**11.8 ± 2.10**	**ND**	**152 ± 7.80**	**564 ± 52.0**	**52.0 ± 25.0**
Millet	A	14.0	12.3	87.2	16.6	ND	225	1876	12.6
	B	4.10	ND	55.4	16.8	ND	122	1029	8.60
	C	14.4	3.10	75.5	ND	ND	179	1509	10.1
	D	4.70	7.20	61.1	16.5	ND	136	953.0	9.00
	Mean ± SD	**9.30 ± 5.70**	**7.50 ± 4.60**	**69.8 ± 14.3**	**16.6 ± 1.80**	**ND**	**166 ± 46.0**	**1341 ± 433**	**10.1 ± 1.80**
Sorghum	A	7.30	7.70	73.2	23.5	ND	104	1580	6.70
	B	6.00	7.60	64.2	9.70	ND	97.2	970	6.00
	C	2.50	21.9	89.6	14.6	ND	145	1326	8.60
	D	5.20	20.7	99.4	28.1	ND	217	1078	7.50
	Mean ± SD	**5.20 ± 2.00**	**14.5 ±7.90**	**82.0± 16.0**	**19.0 ± 8.30**	**ND**	**141 ± 55.0**	**1238 ± 271**	**7.20 ± 1.10**
Sesame	A	30.7	11.0	127	16.9	ND	234	120	227
	B	18.8	20.8	100	ND	ND	224	692	193
	C	48.3	0.30	117	17.1	ND	175	3161	176
	D	48.3	ND	217	27.6	ND	415	2883	377
	Mean ± SD	**37.0 ± 14.0**	**11.0 ± 10.0**	**140 ± 52.0**	**20.5 ± 6.10**		**262 ± 105**	**1984 ± 1221**	**243 ± 92.0**
Locust bean	A	21.3	ND	266	2.30	ND	150	1517	148
	B	13.4	6.90	330	15.1	ND	174	609	143
	C	ND	3.90	656	43.4	ND	314	801	264
	D	15.9	11.6	362	10.6	ND	192	1185	165
	Mean ± SD	**16.8 ± 4.00**	**5.60 ± 4.90**	**404 ± 173**	**18.0 ± 57.0**	**ND**	**208 ± 73.0**	**1028 ± 405**	**180 ± 57.0**

Note. A and B Nasarawa main market, C = Mararaba - udege market and D = Laminga market, ND = Not detected

These discrepancies may be linked to soil mineral composition, fertilizer input, and irrigation practices specific to Nasarawa, Nigeria [36, 37]. In a probabilistic context, populations with high staple consumption face an increased likelihood of long-term oxidative burden, though physiological regulation may buffer effects in healthy individuals, vulnerable groups, those with genetic predispositions or high intake, remain at greater risk.

Lead (Pb) exhibited the lowest concentrations yet still raised concerns, ranging from 3.80 ± 3.00 mg/kg in soybean to 37.0 ± 14.0 mg/kg in sesame seed, all surpassing the international regulatory limit of 0.2 mg/kg ($P > 0.2$). Pb lacks biological function and is highly neurotoxic, nephrotoxic, and cardiotoxic, disproportionately affecting children via cognitive and developmental impairments [2, 38]. These levels substantially exceed earlier findings of 0.0048÷0.11 mg/kg in seeds [24], 0.025 mg/kg in cereals [39], and 18.0÷20.0 mg/kg in sorghum and millet [29]. Elevated Pb levels in this study may likely result from anthropogenic sources such as mining, industrial activities, leaded fuel combustion, agrochemicals, and sewage sludge applications [36, 40].

Zinc (Zn), though crucial for gene regulation, immune response, and enzymatic activity, may cause copper deficiency, gastrointestinal distress, and neurological dysfunction when consumed in excess [41, 42]. In this study, Zn ranged from 141 ± 55.0 mg/kg in sorghum to 262 ± 105 mg/kg in sesame seed, the highest in seeds and cereals, both surpassing the 90% WHO/FAO permissible limit of 99.4 mg/kg [32]. These values are significantly higher than prior reports: 32 mg/kg in millet, 24 mg/kg in sorghum [29, 36], 22 mg/kg, 32.6 ± 2.28 mg/kg in seeds [34], 51.26 mg/kg in cereals [39], and 39.5 ± 0.30 mg/kg [35]. Although legumes in this research contained relatively lower Zn levels (34 ± 11 to 37 ± 17 mg/kg [17], yet still higher than many comparatives, implying moderate probabilistic risk from chronic overexposure in seed- and cereal-dominant diets.

Manganese (Mn) is a trace element vital for metabolism, bone integrity, clotting, and inflammation control. Yet excessive intake is associated with manganism, a degenerative neurological syndrome marked by tremors and cognitive decline [43]. Mn levels varied between 69.8 ± 14.3 mg/kg in millet and 404 ± 173 mg/kg in locust bean seed. These results exceed values reported by Bolaños et al. [33] (30.31 ± 0.55 mg/kg), Jin et al. [44] (37.9 mg/kg), and Rubio et al. [34] (26.1 ± 14.4 mg/kg), though they remain within the WHO/FAO safety limit of 500 mg/kg [32]. Excessive consumption of locust bean seeds over time may pose a moderate risk.

Chromium (Cr) is a biogenic microelement in the form of Cr (III) or Cr (VI). While Cr(III) supports metabolism, Cr(VI) is carcinogenic, excess exposure associated with cardiovascular, glycemic, digestive, and gastrointestinal cancer risks [45, 46]. In this study, Cr ranged from 3.8 ± 3.0 mg/kg in soybean to 37 ± 14 mg/kg in sesame seed, values that surpass the WHO/FAO guideline of 2.3 mg/kg [32, 46, 47]. These results also exceeded previously documented averages, of 6.24 mg/kg and 0.038 mg/kg [48]. These concentrations heighten the probabilistic carcinogenic potential with sustained exposure.

Selenium (Se) is crucial for thyroid function, antioxidant defense, and reproductive function, but overexposure may cause selenosis, which manifest as gastrointestinal distress, neurological disorders, and hair and nail abnormalities [49÷51]. Se concentrations ranged from 11.8 ± 21 mg/kg in soybean to 20.5 ± 6.1 mg/kg in sesame seed, values well above the recommended upper intake level of ~0.4 mg/day (400 µg). These findings point to significant health risks for populations reliant on such crops.

Barium (Ba), unlike essential trace elements, offers no physiological benefit. Soluble forms, such as barium chloride, are toxic and can cause cardiac arrhythmias, paralysis, and metabolic imbalances [52]. In this study, Ba concentrations varied from 7.2 ± 1.1 mg/kg in sorghum to 243 ± 92 mg/kg in sesame seed, values far above the safe limit of 0.06 mg/kg [53]. Although information on Ba uptake by plants is scarce [54], the elevated values observed emphasize the necessity for monitoring.

The overall pattern (Fe > Zn > Mn > Ba > Se > Cr > Pb, Cd undetectable) highlights the predominance of essential metals with notable toxic intrusions. High variability and frequent exceedances probabilistically amplify cumulative risks through additive/synergistic effects in staple-reliant populations, likely yielding non-carcinogenic HI >1 and elevated carcinogenic endpoints in probabilistic models. Discrepancies with prior studies stem from Nasarawa-specific factors [55], reinforcing the urgency for irrigation monitoring, input regulation, and public health interventions to mitigate dietary exposure burdens.

Distribution of metals in the food crops

The possible sources of these metals were further explored using Pearson correlations, PCA, and hierarchical clustering. The result highlights specific pairwise correlations, as shown in Fig. 3. These suggest shared contamination pathways, indicating that the metals probably enter the crops via common mechanisms.

Fe and Cr have strong positive associations (r ≥ 0.6): Fe–Cr (r = 0.81). There is a high likelihood (over 80% shared variance, since $r^2 = 0.656$) meaning 65.6% of the variability in one can be predicted from the other. In environmental contexts, both are often linked to industrial activities like steel production or mining, where they co-occur in effluents. The joint distribution of Fe and Cr concentrations is likely tightly coupled, reducing the entropy when one is known.

Ba–Zn (r = 0.76): Strong correlation ($r^2 = 0.578$, ~58% shared variance). Ba and Zn may derive from agricultural inputs (Zn in fertilizers, Ba in pesticides) or traffic emissions (tire wear). Observing high Ba increases the conditional probability of high Zn, suggesting a dependent relationship rather than independent random variables. Cr–Ba (r = 0.69): Moderate-to-strong ($r^2 = 0.476$). Cr and Ba might overlap in sources like leather tanning or barite mining. This implies a probabilistic linkage in which the presence of one metal increases the expected value of the other. Mn–Ba (r = 0.63): Similar strength ($r^2 = 0.397$). Mn and Ba could have geogenic (natural soil minerals) or anthropogenic origins. Probabilistically, this reduces the uncertainty in predicting Mn levels given Ba data.

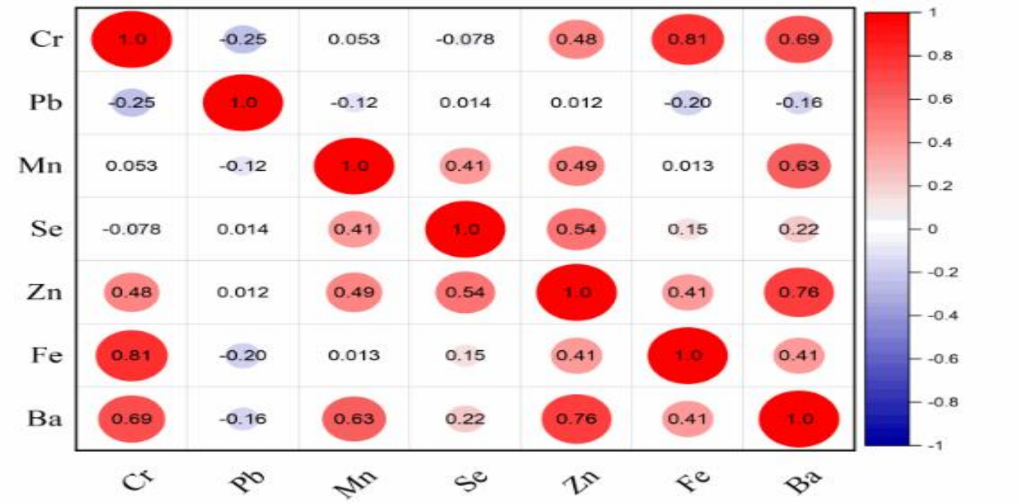


Fig. 3 Correlation between the heavy metals in food crops

Zn–Se (r = 0.54) : Moderate ($r^2 = 0.292$). Zn and Se might co-occur in volcanic soils or from selenium-enriched fertilizers. This suggests a weaker but non-negligible dependency, where the correlation could arise from a mixture of distributions of some samples from contaminated sites and others from baseline levels. Zn–Mn (r = 0.49): Weak-to-moderate ($r^2 = 0.240$). Often seen in studies of soil contamination, as both are essential micronutrients, but they can accumulate from overuse of amendments. Cr–Zn (r = 0.48): Similar ($r^2 = 0.230$). This implies overlapping industrial or agricultural pathways [34, 44, 47].

Principal component analysis

The PCA biplot, as presented in Table 4 and Fig. 4, is a key visualization tool that combines two essential elements of principal component analysis (PCA): food crop samples and the heavy metal variables. It projects the high-dimensional data concentrations of these metals, Fe, Zn, Mn, Ba, Se, Cr, Pb across legumes, cereals, and seeds defined by the first two principal components (PC1 and PC2), which together explain 67.85% of the total variance, PC1 at 45.07% and PC2 at 22.78%. This makes the biplot highly informative, as it captures the dominant patterns in metal distribution and sample grouping. The arrows represent the heavy metal variables, their direction, and the strength of contribution to PC1 and PC2.The dots represent individual food crop samples, and their positions on the biplot reflect how each sample scores on PC1 and PC2. Samples that cluster closely together share similar metal concentration profiles while samples far apart differ markedly in their metal compositions. The Strong alignment of Cr, Pb, and Mn arrows from PC1 dominance and the Fe–Cr, Cr–Ba correlations suggests these metals drive much of the variability, often linked to human activities, mining effluents, agrochemicals, irrigation [29, 50]. These elements more contaminate samples positioned in the direction of these arrows. Pb's arrow may align notably with PC2 as well, emphasizing its distinct influence.

Metals like Fe and Ba have lower variance contributions, 1.95% have shorter arrows, indicating less role in the main separation but still geogenic prominence. The biplot shows groupings of seeds and cereals clustering away from legumes due to higher levels of Zn, Ba, or Se, or mining-impacted samples pulled toward Cr and Pb arrows. This visual separation helps identify pollution gradients across food groups or market origins. The high variance captured nearly 68%, indicating that the biplot reliably summarizes the dataset's structure, and supports the conclusion of mixed geogenic-anthropogenic contamination in the food crops.

Table 4. Showing the eigenvalues, percentage of the variance and cumulative values

Element	Component 1	Component 2
Cr	0.42753	-0.48197
Pb	-0.13541	0.25424
Mn	0.32374	0.46916
Se	0.24539	0.50306
Zn	0.48083	0.22047
Fe	0.37974	-0.42391
Ba	0.50839	0.03958
Eigen value	3.15462	1.59464
Variance, %	45.07	22.78
Cumulative, %	45.07	67.85

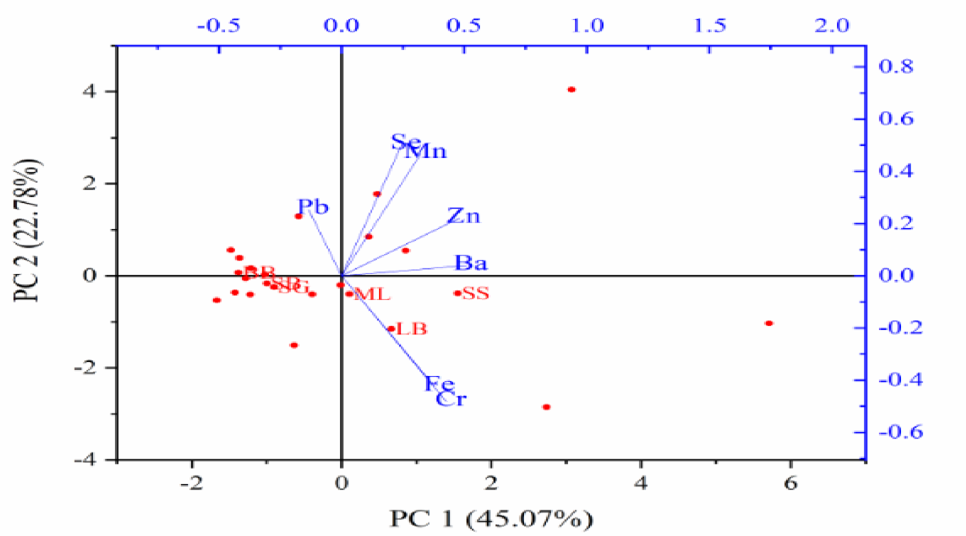


Fig. 4 Biplot of metal distribution in the food crops characterized by PCA

Cluster analysis

The dendrogram, as shown in Fig. 5, grouped the metals into three distinct clusters, confirming patterns observed in the correlations and PCA. In Cluster 1, these metals (Cr, Pb, and Se) merge at relatively low heights, indicating strong similarity in their distributions across samples. This tight grouping suggests shared contamination pathways, predominantly anthropogenic such as industrial emissions, mining activities, phosphate fertilizers, or wastewater irrigation. Their association aligns with PC1 dominance (Cr, Pb, Mn) and strong correlations of Cr-related pairs, pointing to human-induced enrichment rather than purely natural soil weathering [10, 54].

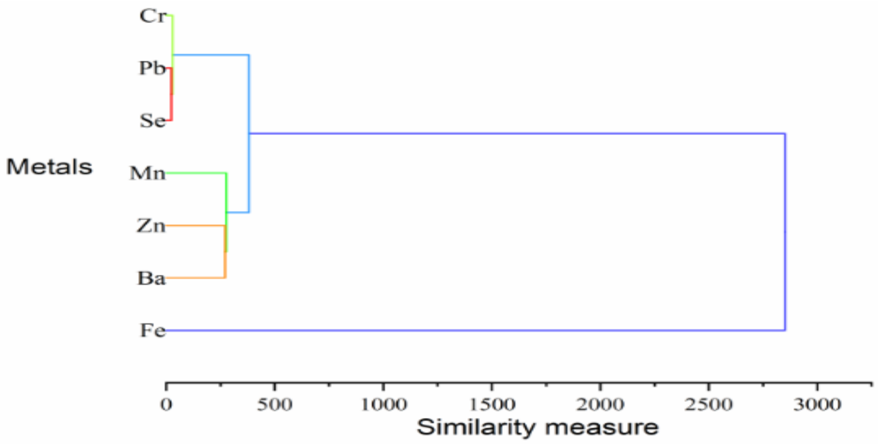


Fig. 5 Dendrogram shows the result of the cluster analysis.

Cluster 2: These metals (Mn, Zn, and Ba) form an intermediate cluster, merging somewhat later than Cluster 1 but before Fe. The grouping implies overlapping geogenic and anthropogenic influences. Mn and Zn are common in parent rock weathering (geogenic) but are frequently elevated by agricultural inputs such as fertilizers (phosphate/organic amendments rich in Zn/Mn) and contaminated irrigation. Ba's inclusion suggests ties to barite mining dust or similar mineral inputs in the region, as Ba often correlates with Zn in polluted soils or crops. Moderate correlations (Ba–Zn r = 0.76, Mn–Ba r = 0.63, Zn–Mn r = 0.49) support this mixed origin, with less extreme anthropogenic dominance than in Cluster 1. Cluster 3: Fe stands apart as a single-member cluster, that merges at the highest level, with the greatest dissimilarity from others. This isolation highlights Fe's distinct behavior, primarily geogenic, as iron is abundant in Nigerian lateritic or iron-rich soils and parent materials. While elevated levels may partly result from anthropogenic sources, its profile differs markedly from the others, consistent with low variance contribution in PCA (1.95%) and lack of strong correlations with most metals (except Fe–Cr r = 0.81, which may reflect partial overlap but not enough for tight clustering).

Overall, the dendrogram visually confirms mixed geogenic-anthropogenic influences in Nasarawa's staple crops, with anthropogenic pressures driving the most variable and concerning metals. This supports calls for regulatory oversight, source control, and ongoing monitoring to reduce dietary risks in the region.

Health risk assessment

Estimated Daily Intake (EDI)

EDI values, as shown in Table 5, represent the average daily metal intake per body weight from consuming these crops. Crop-specific patterns emerged: black-eye beans, soya beans, millet, and sorghum contributed higher EDIs for essential metals like Fe, Zn, and Mn, while sesame seeds were notably enriched in Fe, Zn, and Ba, and locust beans in Fe, Mn, and Zn. All EDI values for Cr, Pb, Mn, Se, Zn, Fe, and Ba fell within the USEPA (2015) oral reference doses (RfDs) of approximately 0.003 mg/kg/day Cr, 0.004 mg/kg/day Pb, 0.14 mg/kg/day Mn, 0.005 mg/kg/day Se, 0.3 mg/kg/day Zn, 0.7 mg/kg/day Fe, and 0.6 mg/kg/day Ba. The sole exception was Cr in sesame seeds for children, with an EDI of 4.11E-03 mg/kg/day slightly exceeding the RfD threshold, signaling a potential concern for pediatric consumers. Children consistently showed higher EDIs than adults across metals, consistent with greater food intake per body weight and heightened vulnerability in developmental stages [25, 28] Ranking of EDIs reflected the dominance of essential metals: for adults, Fe > Zn > Mn > Ba > Se > Pb > Cr, for children, Fe > Zn > Mn > Ba > Se > Cr > Pb. This order aligns with legumes, cereals, and seeds as primary dietary sources of Fe, Zn, and Mn, though chronic excess of even essential elements can pose oxidative or neurological risks if sustained [29, 35].

Table 5. Estimated daily intake for adults and children, mg/kg/day

Food crop	Population	Cr	Pb	Mn	Se	Cd	Zn	Fe	Ba	Total EDIM
Black eye beans	Adult	2.33E-04	2.07E-04	2.48E-03	6.35E-04	ND	5.69E-03	2.34E-02	1.22E-03	3.39E-02
	Child	8.33E-04	9.08E-04	1.08E-02	2.78E-03	ND	2.49E-02	1.02E-01	5.34E-03	1.48E-01
Soya bean	Adult	1.19E-04	2.39E-04	3.28E-03	3.71E-04	ND	4.78E-03	1.77E-02	1.62E-03	2.82E-02
	Child	4.28E-04	1.05E-03	1.44E-02	1.62E-03	ND	2.09E-02	7.76E-02	7.10E-03	1.23E-01
Millet	Adult	2.92E-04	2.36E-04	2.19E-03	5.22E-04	ND	5.20E-03	4.22E-02	3.17E-04	5.09E-02
	Child	1.05E-03	1.03E-03	9.60E-03	2.28E-03	ND	2.28E-02	1.84E-01	1.39E-03	2.23E-01
Sorghum	Adult	1.63E-04	4.56E-04	2.56E-03	5.97E-04	ND	4.43E-03	3.89E-02	2.26E-04	4.74E-02
	Child	5.85E-04	1.99E-03	1.12E-02	2.61E-03	ND	1.94E-02	1.70E-01	9.90E-04	2.07E-01
Sesame	Adult	1.15E-03	3.36E-04	4.41E-03	6.44E-04	ND	8.24E-03	6.24E-02	7.65E-03	8.48E-02
	Child	4.11E-03	1.47E-03	1.93E-02	2.82E-03	ND	3.61E-02	2.73E-01	3.35E-02	3.70E-01
Locust bean	Adult	5.28E-04	1.76E-04	1.27E-02	5.59E-04	ND	6.53E-03	3.23E-02	5.66E-03	5.84E-02
	Child	1.89E-03	7.70E-04	5.55E-02	2.45E-03	ND	2.86E-02	1.41E-01	2.48E-02	2.55E-01

Target hazard quotient (THQ) and hazard index (HI)

Target Hazard Quotient (THQ) and Hazard Index (HI) values, presented in Tables 6 (ingestion pathway) and 5 (dermal, though less emphasized for food), provide a clearer picture of non-carcinogenic risks. THQ, calculated as EDI divided by the respective RfD, assesses individual metal risks, with THQ < 1 indicating negligible concern and THQ > 1 suggesting potential adverse effects [10, 56÷58]. Some individual THQs remained below 1 across metals and crops for both adults and children, suggesting no immediate risks from single-metal ingestion. Exceptions and elevations included Cr (1.31 mg/kg in children's sesame), Pb (0.391 mg/kg in children's sorghum), Se (0.442 mg/kg in children's sesame), and Mn (0.311 mg/kg in children's locust beans). Zn, Fe, and Ba THQs stayed well below RfDs (0.3, 0.7, and 0.6 mg/kg/day), though Zn values were higher than some prior reports for soybean, millet, and sorghum [25].

Table 6. Non-carcinogenic health risk assessment for the heavy metals in the food for adult and children through ingestion

HQing	Population	Cr	Pb	Mn	Se	Cd	Zn	Fe	Ba	HI
Black-eye beans	Adult	7.43E-02	4.97E-02	1.70E-02	1.22E-02	ND	1.82E-02	3.20E-02	1.95E-03	3.15E-01
	Child	2.66E-01	1.78E-01	6.07E-02	4.36E-01	ND	6.51E-02	1.15E-01	6.98E-03	1.13E+00
Soya beans	Adult	3.82E-02	5.73E-02	2.25E-02	7.11E-02	ND	1.53E-02	2.43E-02	2.59E-03	2.31E-01
	Child	1.37E-01	2.05E-01	8.05E-02	2.55E-01	ND	5.47E-02	8.70E-02	9.28E-03	8.28E-01
Millet	Adult	9.34E-02	5.65E-02	1.50E-02	1.00E-01	ND	1.66E-02	5.78E-02	5.07E-04	3.40E-01
	Child	3.34E-01	2.02E-01	5.38E-02	3.58E-01	ND	5.95E-02	2.07E-01	1.82E-03	1.22E+00
Sorghum	Adult	5.22E-02	1.09E-01	1.76E-02	1.15E-01	ND	1.41E-02	5.33E-02	3.62E-04	3.61E-01
	Child	1.87E-01	3.91E-01	6.29E-02	4.10E-01	ND	5.06E-02	1.91E-01	1.29E-03	1.29E+00
Sesame	Adult	3.67E-01	8.06E-02	3.02E-02	1.24E-01	ND	2.63E-02	8.54E-02	1.22E-02	7.25E-01
	Child	1.31E+00	2.89E-01	1.08E-01	4.42E-01	ND	9.43E-02	3.06E-01	4.37E-02	2.60E+00
Locust beans	Adult	1.69E-01	4.22E-02	8.69E-02	1.07E-01	ND	2.09E-02	4.43E-02	9.04E-03	4.79E-01
	Child	6.04E-01	1.51E-01	3.11E-01	3.84E-01	ND	7.48E-02	1.58E-01	3.24E-02	1.72E+00

The cumulative (HI) captures combined exposure risks. For adults, all HI values remained below 1 (0.231÷0.725 across crops), indicating minimal overall non-carcinogenic risk from these staples. In contrast, children's HI values for (Cr, Pb, Mn, Se, Zn, Fe, and Ba)frequently approached or exceeded 1, with notable elevations in black-eye beans (1.13 mg/kg), millet (1.22 mg/kg), sorghum (1.29 mg/kg), sesame (2.60 mg/kg), and locust beans (1.72 mg/kg). These HI >1, particularly for sesame and locust beans, suggest potential additive effects from multiple metals, raising concerns for chronic dietary exposure in child populations reliant on these foods. These findings exceed HI levels reported in comparable studies from Ghana [25], Jos, Nigeria [29], Ebonyi, Nigeria [50], Poland [3], and Korea [24], highlighting region-specific elevations possibly linked to Nasarawa's soil chemistry, mining proximity, or agricultural practices.

Overall, while individual metal exposures pose limited immediate threats and some THQs remain safe, the elevated HI for children driven by higher EDIs and cumulative contributions from metals like Cr in sesame, Se, Pb, and Mn in locust beans underscores disproportionate vulnerability. This pattern aligns with broader evidence that children in agricultural or mining-influenced areas face heightened dietary risks from contaminated staple crops [10, 58]. The results affirm the need for regular monitoring of market-sold crops, source control and targeted public health measures, especially for pediatric groups, to mitigate potential long-term non-carcinogenic effects despite generally acceptable individual exposures

The contribution of individual heavy metals to the cumulative Hazard Index (HI) for non-carcinogenic risks, as shown in Fig. 6, reveals distinct patterns across the food crops (black-eye beans, soya beans, millet, sorghum, sesame seeds, and locust beans) from major markets in Nasarawa, Nigeria. These percentages highlight which metals drive the potential combined exposure burden, particularly for children, where HI values more frequently exceeded 1.

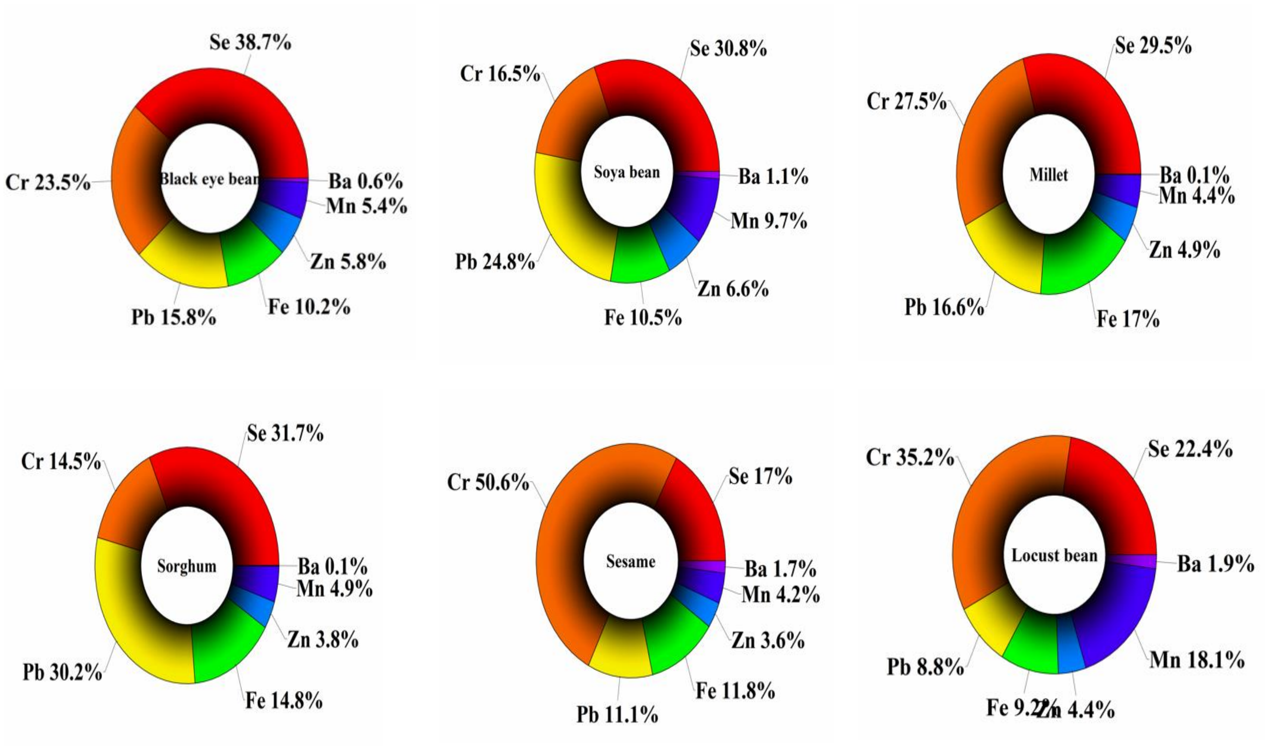


Fig. 6. Comparison of health risks caused by the different metals according to HI among adults and children

For black-eye beans, Se contributed the largest share at 38.7%, followed by Cr at 23.6%, Pb at 15.8%, Fe at 10.2%, Zn at 5.8%, Mn at 5.3%, and Ba at a negligible 0.6%. This pattern persisted with minimal differences between adults and children, in which Se remained dominant (38.7%), Cr at ~23.5%, and others similar, reflecting consistent relative exposures despite higher absolute EDIs in children.

In soya beans, Se again led at 30.8%, followed by Pb (24.8%), Cr (16.5%), Fe (10.5%), Mn (9.7%), Zn (6.6%), and Ba (1.1%). Millet showed Se at 29.4%, Cr at 27.5%, Fe at 17.0%, Pb at 16.6%, Zn at 4.9%, Mn at 4.4%, and Ba at 0.1%. Sorghum featured Se (31.7%) and Pb (30.2%) nearly equally prominent, with Fe (14.8%), Cr (14.5%), Mn (4.9%), Zn (3.9%), and Ba (0.1%).

Sesame seeds stood out with Cr dominating at 50.6%, followed by Se (17.0%), Fe (11.8%), Pb (11.1%), Mn (4.2%), Zn (3.6%), and Ba (1.7%). Similarly, locust beans had Cr as the top contributor at 35.2%, then Se (22.4%), Mn (18.1%), Fe (9.2%), Pb (8.8%), Zn (4.4%), and Ba (1.9%).

Across crops, Se frequently emerged as a major driver in legumes and cereals (29÷39% in black-eye beans, soya beans, millet, sorghum), likely due to its elevated concentrations relative to RfD and moderate bioavailability, contributing to HI elevations despite essentiality at low levels (risking selenosis in excess). Cr assumed primacy in seeds (50.6% in sesame, 35.2% in locust beans), aligning with its higher EDI exceedance in sesame for children and strong anthropogenic signals from prior PCA/clustering (Cr in PC1 with Pb and Mn). Pb contributed substantially in several crops (~25÷30% in soya beans/sorghum), reflecting neurotoxic potential, while essential metals like Fe, Zn, and Mn played secondary roles (<15÷20%), consistent with their higher RfDs buffering individual THQs.

Notably, minimal differences in metal contribution percentages between adults and children indicate that while children's absolute HI values were higher (due to greater intake per body weight), the proportional drivers remained similar, suggesting shared dietary profiles but amplified pediatric vulnerability. The relatively high HI contributions from Cr in sesame (50.6%) and locust beans (35.2%) underscore these crops as key concerns for cumulative non-carcinogenic risks, potentially linked to localized enrichment from mining, fertilizers, or irrigation in Nasarawa [36, 50, 59]. For the dermal pathway (Table 7), THQ and HI values were orders of magnitude lower than those for ingestion, with all individual THQ dermal values well below 1 and HI dermal consistently <1 (7.85E-04 to 3.92E-03 across crops and populations). Values aligned with dermal RfD ranges (Cr ~3.0E-03 to 6.0E-05 mg/kg/day, Pb ~5.3E-03 to 5.25E-04, Mn ~4.0E-03 to 1.85E-03, Se ~5.0E-03, Zn ~6.0E-

02, Fe ~7.0E-02, Ba ~6.0E-02 in various USEPA, confirming negligible non-carcinogenic risks from skin contact with these market-sold crops during handling or preparation. This mirrors findings in similar assessments where dermal exposure from foods is minimal compared to ingestion [25].

Table 7. Non- carcinogenic health risk of heavy metals in food crops for both adults and children via the dermal pathway

Food crops	**Population**	**Cr**	**Pb**	**Mn**	**Se**	**Cd**	**Zn**	**Fe**	**Ba**	**HI**
Black eye beans	Adult	4.26E-05	8.60E-05	3.40E-04	6.97E-05	ND	5.21E-05	1.84E-04	1.12E-05	7.85E-04
	Child	6.83E-05	3.45E-05	5.45E-04	1.12E-04	ND	8.35E-05	2.94E-04	1.79E-05	1.16E-03
Soya bean	Adult	2.19E-05	9.90E-05	4.51E-04	4.07E-05	ND	4.37E-05	1.39E-04	1.48E-05	8.10E-04
	Child	3.51E-05	3.97E-05	7.23E-04	6.53E-05	ND	7.01E-05	2.23E-04	2.38E-05	1.18E-03
Millet	Adult	5.35E-05	9.77E-05	3.01E-04	5.73E-05	ND	4.76E-05	3.31E-04	2.91E-06	8.91E-04
	Child	8.58E-05	3.92E-05	4.83E-04	9.19E-05	ND	7.64E-05	5.31E-04	4.66E-06	1.31E-03
Sorghum	Adult	2.99E-05	1.89E-04	3.52E-04	6.56E-05	ND	4.05E-05	3.05E-04	2.07E-06	9.84E-04
	Child	4.80E-05	7.58E-05	5.65E-04	1.05E-04	ND	6.50E-05	4.90E-04	3.32E-06	1.35E-03
Sesame	Adult	2.10E-04	1.39E-04	6.05E-04	7.08E-05	ND	7.54E-05	4.89E-04	7.00E-05	1.66E-03
	Child	3.37E-04	5.59E-05	9.71E-04	1.14E-04	ND	1.21E-04	7.85E-04	1.12E-04	2.50E-03
Locust bean	Adult	9.67E-05	7.29E-05	1.74E-03	6.14E-05	ND	5.98E-05	2.53E-04	5.18E-05	2.34E-03
	Child	1.55E-04	3.10E-04	2.79E-03	9.86E-05	ND	7.20E-05	4.07E-04	8.31E-05	3.92E-03

Overall, while dermal risks are insignificant, ingestion-driven HI elevations especially in children, from sesame and locust beans, stem from cumulative contributions of Se and Cr with Pb notable in some crops. These patterns emphasize the need for crop-specific interventions, monitoring Se and Cr in seeds, regulating potential sources such as agrochemicals or mining impacts and continuing probabilistic modeling to refine risks in staple-dependent populations.

Cancer risk (CR) and total cancer risk (TCR)

The cancer risk (CR) and total cancer risk (TCR) results from Table 8 indicate significant carcinogenic concerns from chronic ingestion of the staple food crops, primarily driven by Cr, with minor contributions from Pb and negligible from Cd. For Cr, adult risks ranged from 5.97E-05 (soya beans/sorghum) to 5.74E-04 (sesame seeds), while children's risks were higher: 2.14E-04 (soya beans) to 2.05E-03 (sesame seeds). Most Cr CR values exceeded the acceptable range of 1.0×10^{-6} to 1.0×10^{-4} [31, 58], signaling elevated cancer probability, particularly for sesame seeds (adult: 5.74×10^{-4}, child: 2.05×10^{-3}) and locust beans (child: 9.45E-04). Pb CR remained low (adults: 1.50E-06 to 3.87E-06, children: 6.55E-06 to 1.69E-05), within safe limits. Cd was non-detectable, contributing zero risk.

Table 8. Cancer risk assessment for adults and children

HQing	**Population**	**Cr**	**Pb**	**Cd**	**TCR**
Black-eye beans	Adult	1.16E-04	1.76E-06	ND	1.18E-04
	Child	4.16E-04	7.71E-06	ND	4.24E-04
Soya beans	Adult	5.97E-05	2.03E-06	ND	6.17E-05
	Child	2.14E-04	8.88E-06	ND	2.23E-04
Millet	Adult	1.46E-04	2.00E-06	ND	1.48E-04
	Child	5.23E-04	8.77E-06	ND	5.32E-04
Sorghum	Adult	8.17E-05	3.87E-06	ND	8.56E-05
	Child	2.93E-04	1.69E-05	ND	3.09E-04
Sesame	Adult	5.74E-04	2.86E-06	ND	5.76E-04
	Child	2.05E-03	1.25E-05	ND	2.07E-03
Locust beans	Adult	2.64E-04	1.50E-06	ND	2.65E-04
	Child	9.45E-04	6.55E-06	ND	9.52E-04

Total Cancer Risk (TCR) for adults exceeded 1.0×10^{-4} in black-eye beans (1.18E-04), millet (1.48E-04), sesame seeds (5.76E-04), and locust beans (2.65E-04), indicating unacceptable lifetime cancer risk in most crops (except soya beans 6.17E-05 and sorghum 8.56E-05). For children, TCR was consistently higher and exceeded 1.0 × 10^{-4} across all crops (sesame: 2.07E-03, locust beans: 9.52E-04), amplifying concerns given greater relative intake and developmental vulnerability.

These elevated TCRs, driven mainly by Cr with Pb secondary in some crops, align with patterns in other Nigerian studies (e.g., Ikem et al., 2023 in Jos [29], Nnaji et al., 2020 in Umuahia [59]) and international contexts (e.g., Wei, 2020 in Beijing [14]), where Cr and Pb in staples pose cumulative risks. Ingestion dominates over dermal exposure, consistent with food-chain pathways.

CONCLUSIONS

The concentrations of Cr, Pb, Cd, Mn, Se, Fe, Zn, and Ba in six food crops sold in major markets in Nasarawa were studied. The results revealed that metal concentrations exceeded the WHO/FAO permissible limits in all food crops. The health risks associated with ingesting these metals were higher for children. Hazard index values greater than 1 were observed for children consuming most food crops, indicating potential health risks, except for soya bean, where HI values were below 1. Dermal exposure posed little or no health risk, HI values less than 1 for both adults and children.

Cancer risk data showed that Cr exceeded acceptable limits, suggesting a significant cancer risk for both adults and children when consuming sesame seeds, with additional concern for children consuming soybeans. Cancer risks for Cd and Pb remained within safe limits. The total cancer risk (TCR) for adults and children exceeded permitted thresholds, posing concerns except for soya bean and sorghum in adults, which were within safe limits. These food crops may be contaminated through agricultural practices and atmospheric deposition of heavy metals from anthropogenic sources such as vehicular and industrial emissions. Despite their nutritional value, prolonged consumption of these market-sold staples may increase toxic metal burdens in local populations. To safeguard public health in Nasarawa State, Nigeria and the world, regular monitoring of metal levels in rural and urban markets, stricter regulation of agricultural inputs and mining activities, promotion of cleaner farming practices, and enhanced collaboration among producers, vendors, consumers, and regulatory agencies are urgently recommended. Targeted interventions focusing on high-risk crops (sesame seeds, locust beans) and vulnerable groups (children) are essential to reduce dietary exposure and ensure long-term food safety.

Funding

No funding was obtained for this study.

Authors contributions

This work was carried out in collaboration among all authors. Jude Emurotu designed the study, supervised, validated, reviewed and edited. Lydia Mariette Okorafor performed the sampling, conducted the laboratory work, performed the statistical analysis and wrote the first draft of the manuscript. Ephriam Musa Dallatu managed the literature searches and proof read the final manuscript. All authors read and approved the final manuscript.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Citation: Okorafor, L.M., Dallatu, E.M., Emurotu, J.E., Evaluating the health risks associated with essential and non-essential metals in staple food crops sold in major markets in Nasarawa, Nigeria, *Rom. J. Ecol. Environ. Chem*., **2026**, 8, no.1, pp. 133÷150, https://doi.org/10.21698/rjeec.2026.110.