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Authors contributions

Adam Salifu: conceptualization, methodology, investigation, data analysis, wrote the original draft.

Arsene Mushagalusa Balasha: conceptualization, methodology, validation, supervision, review and editing.

Jonas Lwalaba Wa Lwalaba: conceptualization, methodology, validation, research permit acquisition, supervision, review.

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Ethics statement

The study protocol was approved by the Faculty of Agronomy and Environmental Sciences Research Committee, University of Lubumbashi (Nº. Ref/FAC/AGRO/596/2025), in accordance with the University of Lubumbashi institutional guidelines for research involving human participants.

Consent to participate

Participation was entirely voluntary, and all respondents provided informed oral consent prior to inclusion in the study.

Consent for publication: Not applicable

Clinical trial number: not applicable

Conflicts of interest: Authors have no conflicts of interest to declare

Data availability

The data that supports the findings of this study are available from the corresponding author upon reasonable request.

Abstract

In the mining city of Lubumbashi (Democratic Republic of the Congo), intensive mining activities have led to heavy metal contamination of food crops, posing serious public health risks. Using an interdisciplinary framework, this study addresses a critical knowledge gap by quantifying heavy metal concentrations in the six most consumed vegetables, assessing potential health risks to consumers, and examining perceptions of food-chain contamination in Lubumbashi. Mean concentrations (mg/kg) of Cd, Cu, Pb, and Zn measured by inductively coupled plasma optical emission spectrometry (ICP-OES) in leafy vegetables—particularly *Spinacia oleracea* (Cd: 4.02;

Pb: 1.44; Cu: 25.27; Zn: 136.21)—exceeded the maximum permissible limits established by the Food and Agriculture Organization and the World Health Organization. Health risk assessment revealed elevated non-carcinogenic and carcinogenic risks, with target hazard quotient (THQ) and hazard index (HI) values exceeding 1. Target cancer risk (TCR) for cadmium exceeded the acceptable range (10^{-6}–10^{-4}) in *Spinacia oleracea* (9.98×10^{-3}), *Manihot esculenta* (8.11×10^{-3}), and *Amaranthus vulgaris* (5.6×10^{-3}). Survey data showed that, despite awareness of contamination risks, consumers continued to prefer high-risk vegetables, particularly *Manihot esculenta*. Logistic regression analysis indicated that awareness significantly predicted knowledge, risk perception, and adoption of safer practices. More than half of respondents expressed willingness to pay a premium for safer food options, including hydroponically produced vegetables. These findings highlight a critical disconnect between contamination levels, consumer behavior, and risk awareness, underscoring the need for integrated food safety policy interventions in mining-impacted urban settings.

Keywords: Heavy metals, market vegetables, Health risk assessment, consumer perception, mining contamination

1. Introduction

The risk of heavy metal contamination is rising on a global scale (Luo et al., 2021; Rizwan et al., 2021). Contamination of ecosystems with heavy metals is one of the main and most widely discussed ecotoxicological problems (Hema et al., 2022). In food crops, heavy metal contamination has become a serious global public health and environmental issue worldwide (Boahen, 2024; Gupta et al., 2022). Vegetables, crucial to a healthy diet, are notably prone to accumulating toxic heavy metals like copper, arsenic, and lead, which can enter the food chain through soil, water, and atmospheric deposits (Mputu Malolo et al., 2024; Nie et al., 2023). These contaminants may cause serious health problems, such as kidney damage, increased cancer risk, and neurological disorders, because of extended exposure (Feyisa et al., 2025; Mputu et al., 2024; Hema et al., 2022).

The sustainability of food security for everyone, particularly the poor, depends on food availability, consumption trends, and projections (Anyimah et al., 2020). The fresh vegetables market in the Democratic Republic of the Congo (DRC) is projected to generate US$270.53

million in revenue in 2025. It is expected to grow at a compound annual growth rate (CAGR) of 3.72% from 2025 to 2030 (FAO Statista, 2025).

In the DRC, the fresh vegetable market is predicted to have an average volume per person of 12.0 kg in 2025 (FAO Statista, 2025). Nevertheless, the safety of these vegetables is jeopardized due to the ongoing intensive mining operations in Lubumbashi, located in the southeastern region of the DRC, and recognized as the copper production hub, which accounted for 69% of global cobalt production in 2020 (Gulley, 2022). It is concluded that trace metals are disseminated throughout Lubumbashi's environment, and the nearness of mineral processing plants to agricultural and residential areas amplifies the population's vulnerability to pollution caused by mining activities (Shengo & Mansoj, 2008; Pourret et al., 2016; et al., 2023). Thus, vegetables can contain heavy metals and toxic elements, such as copper, cobalt, cadmium, lead, zinc, and aluminum (Kalonda et al., 2016; Muimba-Kankolongo et al., 2021).

In Lubumbashi, a variety of vegetables are grown and sold in the markets, including kale, sweet potato leaves, head cabbage, amaranth, Chinese cabbage, marrow leaves, cassava leaves, and spinach (Mputu et al., 2024; Mushagalusa, 2019). The majority of vegetables in Lubumbashi's markets are sold by the sides of the roads, exposing them to heavy metal emissions from vehicles and other environmental pollutants. Additionally, these vegetables are typically grown in backyard gardens near mining areas, where mining effluents are occasionally utilized as organic amendments (Mputu et al., 2024). One of the primary ways people are exposed to heavy metals is by consuming contaminated foods, such as vegetables (Zakir et al., 2021).

Aside from environmental matrices in Lubumbashi, biomonitoring studies show high urinary metal levels among residents, and reports link metal exposure to adverse maternal and child outcomes, underscoring the relevance to public health (Van Brusselen et al., 2020; Kayembe et al., 2019; Song, 2015). Investigations in Lubumbashi have previously documented elevated levels of Co, Cu, Cd, and Pb in soil, irrigation water, and vegetables, which frequently exceeded health-based regulatory values (Michel et al., 2013; Kalonda et al., 2016; Muimba-Kankolongo et al., 2021; Mpanga & Lutandula, 2022; Mununga et al., 2023; Mununga et al., 2024; Mputu et al., 2024).

However, these works are not synthesized to demonstrate what remains unresolved. The novelty of the present study lies in bridging this established environmental evidence with quantitative health risk assessment and consumer perceptions, which are still poorly explored but very critical. Furthermore, the concentration of uranium in the urine of the population in the mining city of Lubumbashi is abnormally high, which causes health professionals to be more concerned (Banza et al., 2009; Cheyns et al., 2014). Thus, the residents of Lubumbashi and the surrounding area are currently experiencing a health catastrophe (Mununga et al., 2023). Human exposure to mining contamination in Lubumbashi constitutes a grave public health concern stemming from the elevated population density in contaminated areas and the community's further exposure to mining waste (Balasha, 2025).

Consumer perception significantly affects food choices and can impact public health outcomes (Cheng et al., 2016). In Lubumbashi, where mining is extensive, the lack of attention to heavy metal contamination in vegetables stems from inadequate awareness and deficient risk communication. As a result, consumers may be without dependable information regarding the safety of locally sourced vegetables, potentially increasing their exposure to heavy metals based on their purchasing choices (Mensah et al., 2014; Parveen et al., 2023; Macready et al., 2020). Research spearheaded in Lubumbashi has underscored the necessity of evaluating heavy metal contamination levels within vegetables sold and consumed (Michel et al., 2013; Mputu et al., 2024; Muimba-Kankolongo et al., 2021; Mununga et al., 2023). Nonetheless, consumer perceptions concerning this contamination remain under-researched. This has resulted in a knowledge gap among consumers, providing little to no information availability for policymakers in designing strategies to ensure the safety of the vegetable industry, especially in heavy metals mining-contaminated zones (Owusu-Sekyere et al., 2014).

Consequently, consumers' perception of the risk of contamination and related actions will lead to changes in behavior around prevention and mitigation, namely by avoiding contaminated areas, seeking information and endorsing quality policies to address the challenge (Lahino & Salami, 2025). Recent agronomic trials have indicated that soil amendments can only mitigate the transfer of contaminants under light pollution levels (Mununga et al., 2023). This suggests that risks to consumers may persist in heavily polluted soils.

Due to the toxicity of heavy metals to public health, the FAO and WHO have established recommended limits for these metals in food (Codex Alimentarius, 2001; WHO, 2011). Nevertheless, three crucial gaps require attention: firstly, the current market-derived data is fragmented and lacks alignment with a cohesive, multi-metal protocol laboratory covering the widely consumed leafy and fruiting vegetables, which impedes temporal comparisons. Secondly, limited research has integrated measurement with quantitative dietary risk standards, specifically calculated in accordance with local consumption patterns.

The existence of this gap highlights the need for intervention prioritization. Thirdly, it is unclear how consumers perceive risks, what their hygiene practices are and which sources of information they use to inform themselves; this has led to a mismatch between the recorded exposure and communication of risk/ policymaking within an urban food chain affected by mining (Mununga et al., 2024).

This study addresses these gaps by (i) measuring multi-metal concentrations in commonly consumed vegetables sold in the main Lubumbashi markets using a standard protocol, (ii) performing a probabilistic health risk assessment applied to locally relevant intake scenarios, and (iii) exploring consumer perceptions and hygiene practices to inform communication needs of policy levers. By combining laboratory evidence with risk analysis and consumer perceptions, we offer actionable information for municipal and national authorities about market surveillance, risk communication, and viable intervention initiatives in mining-impacted cities.

2. Materials and Methods

2.1 Study area

The study was conducted in Lubumbashi, the administrative capital of Katanga province, which is located in the southeast of the DRC. With a population of 2.58 million, it is the second-largest city and the mining capital of the country (Tshibanda et al., 2024). It is situated at an elevation of 1220 to 1240 meters and spans an area of approximately 747 km² (Mushagalusa, 2019). The average yearly temperature is around 20 °C; July is the coolest month (15 °C), while October is the warmest (23 °C). The average annual rainfall is 1270 mm, and the rainy season, which lasts from November to March, averages 118 days (Erens et al., 2015). The town has high exposure to various toxic metals due to mining, posing a serious risk to public health (Balasha, 2025). Additionally, mining activities contribute to air pollution and deforestation (Peša, 2022; Van Brusselen et al., 2020). Six markets were chosen as vegetable sampling sites: Kenya, Zambia, Karavia/Golf, Mzee Kabila, Matshipisha, and Kasapa Moise (Figure 1). These are among the largest and most open markets in Lubumbashi.

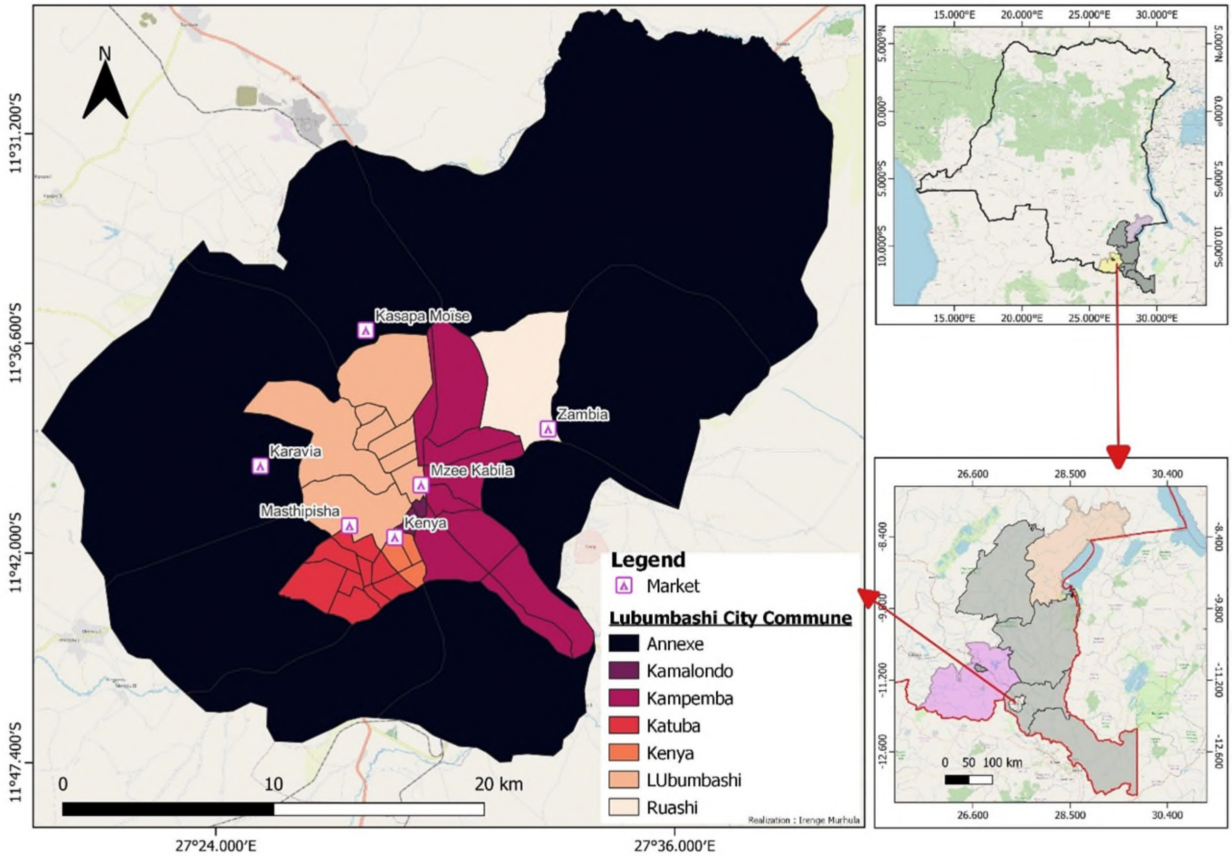


Figure 1. Map of the vegetable sample collection area (Markets) in the mining city of Lubumbashi, DRC.

2.2 Sample collection

Vegetable samples were collected from the six markets in Lubumbashi listed in Section 2.1, including *Spinacia oleracea*, *Brassica chinensis, Amaranthus vulgaris, Manihot esculenta*, *Allium cepa*, *and Solanum lycopersicum*. The common names of these vegetables were spinach, Chinese cabbage, amaranth, onions, and tomatoes, respectively (Table S1, Supplementary file). A total of 216 samples were collected in June 2025, with each sample taken in triplicate, representing 1 kg of each edible part. Before making a purchase, vendors were questioned about the origin of the vegetables, a process conducted randomly in each market. These vegetables are the most commonly grown and consumed (Mubemba et al., 2014; Mushagalusa, 2019). All vegetables, except onions, were cleaned with tap water to remove dust and then placed in seal-top bags. The samples were labelled and transferred directly to the University of Lubumbashi's Faculty of Agronomy Agro-Pedologique Laboratory at room temperature for further analysis.

2.3 Vegetable preparation and heavy metals determination

To determine the concentration of heavy metals such as Cadmium (Cd), Cobalt (Co), Copper (Cu), Iron (Fe), Lead (Pb), and Zinc (Zn) in vegetable species, the method used followed Van Ranst et al., (1999). The leafy, bulb, and fruit vegetables were cut and air-dried in an oven to remove all moisture at 44-65°C. The leaves were then ground into a fine powder using a grinder. A weight of 0.5g of the powdered sample was measured and transferred to a clean flask, with the addition of 10 mL of 6N nitric acid. The flask was gently heated to approximately 70-80°C until a complete reaction and the sample was fully digested. After cooling, the mixture was filtered to remove any undissolved particulate matter. The filtrate was then transferred to a 100 mL volumetric flask, and distilled water was added to fill it. The concentration of heavy metals (Cd, Co, Cu, Fe, Pb, and Zn) in the vegetables was determined in (mg/kg) per dry weight through acid mineralization with HNO_3 and $HClO_3$ using the Inductively Coupled Plasma Optical Emission Spectrometry (ICP-MS).

2.4 Consumer health risk assessment

The following indices, which are frequently used to evaluate the potential health risk of heavy metal exposure through food intake, were utilized to assess the health risk to consumers in Lubumbashi from ingesting heavy metals through the vegetables (FAO/WHO, 2011).

2.4.1 Estimation of daily metal intakes (EDI)

The EDI is the estimated daily intake of these heavy metals (mg/day/kg body weight) through the consumption of vegetables. The average estimated daily intake of these heavy metals for Congolese consumers through the consumption of vegetables was calculated according to equation (1), as provided by the Food and Agriculture Organization of the United Nations Codex Alimentarius (2014) and Habte et al. (2023).

$$EDI= [D_{\text{vegetable intake}} \text{ (kg/day)} \times C_{\text{metal}} \text{ (mg/kg)}] / \text{body weight (kg)}. \qquad (1)$$

Where: $D_{vegetable\ intake}$ is the average daily vegetable consumption of a Lubumbashi person, estimated to be 0.0235 kg per person (Mputu et al., 2024). C_{metal} is the concentration of heavy metals in the vegetable sample. The average body weight of a Congolese adult is 57.8 kg (Tuakuila et al., 2012).

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

The target hazard quotient (THQ) is the ratio of a contaminant's exposure to the level at which exposure to that contaminant is not expected to pose a health risk (Sultana et al., 2022). The equation (2) below was used to calculate the THQ (Feyisa et al., 2025; Mputu et al., 2024).

$$THQ = EDI/RfD. \qquad (2)$$

Where the EDI has already been described in section 2.4.1, the reference dose (RfD) is the oral reference dose of the metal of interest (mg kg^{-1} day^{-1}). RfD is the acceptable daily exposure of a particular contaminant without any risk to health effects for the lifetime of an individual (Sultana et al., 2022). The RfD values in mg/kg day unit for the specific heavy metals are: Cd (0.001), Co (0.043), Cu (0.04), Fe (0.70), Pb (0.004), and Zn (0.30) (Feyisa et al., 2025; Julius et al., 2024; Mputu et al., 2024; Ren et al., 2025). If the THQ value is less than one, there are no possible health risks. When the HQ is greater than 1, however, it indicates that exposure to any particular contaminant may pose health risks (Bermudez et al., 2011; Chary et al., 2008).

The hazard index (HI) is used to assess the potential health risks associated with consuming multiple contaminants simultaneously. Since different contaminants can have comparable detrimental effects on human health, it is frequently appropriate to combine the targeted hazard quotients of various substances (Al-Jassir et al., 2005; Sharmin et al., 2020). The HI will be calculated by using the formula in equation (3) as proposed by Zakir et al. (2021).

$$HI = THQ_1 + THQ_2 + THQ_3 \ldots THQ_n . \qquad (3)$$

Similar to the hazard quotient, possible health risks are indicated by an HI value higher than 1.

2.4.3 Target cancer risk (TCR)

The cancer risk (CR) from the ingestion of carcinogenic metals was assessed using the equation (4) proposed by Mputu et al. (2024).

Annual excess lifetime cancer risk (AELCR) = EDI × SF/DL ×365 days (4)

Where: the estimated daily intake (EDI) refers to the amount of substances consumed daily. The cancer slope factor (SF) Cd is 6.1, and for lead (Pb), it is 0.0085 (Mao et al., 2023). In the DRC, the average human life expectancy is 60.7 years (Tuakuila et al., 2012). Regulatory agencies typically set acceptable risk levels for exposure to carcinogens between 10^{-6} and 10^{-4} (Mao et al., 2023).

2.5 Survey of consumer perception

2.5.1 Study design

A cross-sectional survey with a structured questionnaire interview was conducted between September 2025 to December 2025 to assess the knowledge, attitude and practices of 353 consumers regarding heavy metal contamination in vegetables in Lubumbashi.

2.5.2 Sample size and sampling technique

The sample size of consumers was determined using Cochran's sampling formula (Cochran, 1977). The formula used for determining the sample size of a large indefinite population is shown in equation (5).

$$n= Z^2 . p(1-p) / E^2 \quad (5)$$

Based on a 95% confidence level (Z=1.96), with an estimated population proportion (p=0.5, if unknown), and a 5% margin of error (E), the initial population size was determined to be 384. Nevertheless, due to incomplete data, the final sample consisted of 353 consumers. To select consumers, a simple random sampling technique was implemented (Abass et al., 2016), with initial selection occurring at the markets where the vegetable samples were collected, focusing on those observed purchasing any of the sampled vegetables.

2.5.3 Questionnaire and data collection

A structured questionnaire was prepared to interview consumers. The questionnaire was originally drafted in English and subsequently translated into French for in-person consumer interviews. To improve the validity and reliability, the questionnaire was tested with 10 consumers to assess its clarity and consistency (Mensah et al., 2014). The questionnaire was structured into five sections. The initial section presented the consumers' sociodemographic data, encompassing gender, age, educational attainment, duration of residence in Lubumbashi, and prior awareness of heavy metal contamination. Three questions made up the second section, which was created to determine consumers' knowledge of mining contamination and heavy metals in vegetables. The third section evaluated consumer perceptions and attitudes regarding the health risks associated with heavy metal-contaminated vegetables, employing three questions. The fourth section evaluated consumer practices related to vegetable safety, encompassing their perspectives on vegetable cultivation, the avoidance of vegetables from potentially contaminated regions, and their washing practices in response to contaminant exposure. Finally, the fifth section also investigated consumers' cooking methods for vegetables, their interest in soilless/hydroponic vegetable produce, their willingness to pay for such produce, and their primary sources of food safety information. The questionnaire was digitized in Kobo Toolbox (https://kf.kobotoolbox.org). The interviews were conducted in both French and Swahili, and participation was voluntary. After the interviews, the data were entered, exported, and compiled into a single dataset for further analysis.

2.6 Statistical analysis

All data analysis was conducted using R Studio (Version 4.4.2) after extraction and preprocessing with Microsoft Excel. Descriptive statistics were used to present the concentration of the heavy metals. Following a non-normal distribution, the Kruskal-Wallis test was used to determine the statistical difference in heavy metals among the vegetable species. Dunn's post-hoc test with Bonferroni correction was used for pairwise comparison to adjust p-values. Spearman's correlation and visualization through heatmaps using their mean concentration. To examine the variability of heavy metals within the vegetables and different markets, Principal Component Analysis (PCA) was performed. Descriptive statistics (frequencies and percentages) were used to summarize the consumer survey data. The Chi-square ($\chi 2$) test was used to explore the relationship between sociodemographic characteristics of consumers, while ordinal logistic regression analysis was used to identify factors associated with knowledge, attitudes and practices of consumers. Statistical significance was set at $p < 0.05$ with 95% confidence intervals.

3. Results

3.1 Concentration of heavy metals in vegetables

The concentrations of heavy metals (Cd, Co, Cu, Fe, Pb, and Zn) in vegetable samples from six markets in Lubumbashi are presented in Table 1, revealing significant variation. Notably, Cd, Fe, and Zn showed statistically significant differences among the vegetable species ($P < 0.05$), while Co, Cu, and Pb did not. *Spinacia oleracea* consistently exhibited the highest mean concentrations of Cd (4.02 mg/kg), Fe (287.43 mg/kg), and Zn (136.21 mg/kg). In contrast, the levels of Cd were notably lower in *Allium cepa* and *Solanum lycopersicum*. In comparison to the permissible limits set by the FAO/WHO, Cd levels exceeded the threshold (0.2 mg/kg) in all species except for *Allium cepa* and *Solanum lycopersicum*. Pb levels also surpassed the permissible limit (0.3 mg/kg). At the same time, Cu concentrations exceeded the allowable limit of 10 mg/kg in all species, with the highest concentration of 25.27 mg/kg found in *Spinacia oleracea*. Additionally, lead surpassed the guideline of 0.30 mg/kg across all species, with *Amaranthus vulgaris* showing the highest level at 4.52 mg/kg. Consequently, Zn levels also exceeded the 50 mg/kg threshold, with concentrations of 136.21 mg/kg, 65.60 mg/kg, and 53.50 mg/kg observed in *Spinacia oleracea*, *Amaranthus vulgaris*, and *Manihot esculenta*, respectively. However, Co and Fe levels remained within the recommended limits.

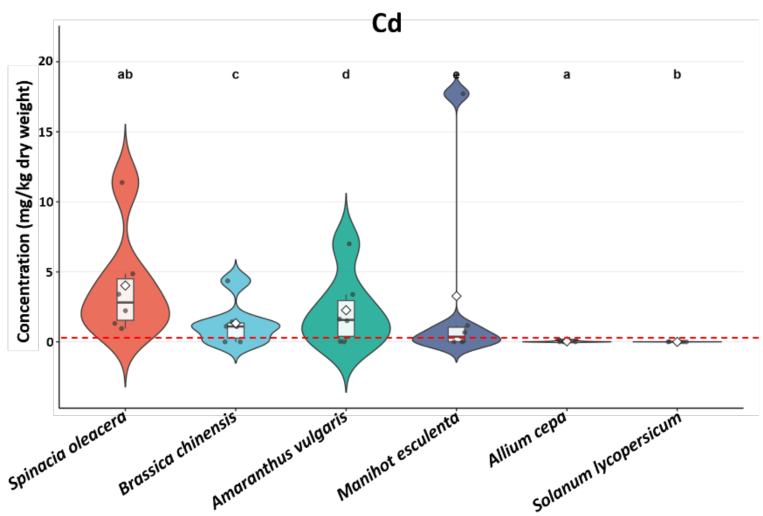
Table 1. Concentration of heavy metals (mg/kg) in vegetable species

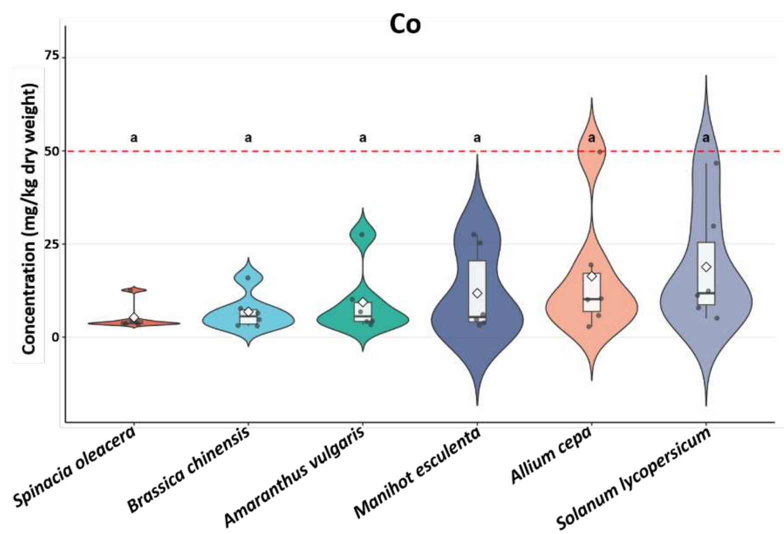
Vegetables species	Index	Cd	Co	Cu	Fe	Pb	Zn
Spinacia oleacera	Mean ± SD	4.02 ± 3.88^{ab}	5.28 ± 3.61^{a}	25.27 ± 4.36^{a}	287.43 ±190.60^{a}	1.44 ± 3.53^{a}	136.21±88.96^{ab}
	Median	2.81	3.77	25.51	205.50	0.00	121.34
	(range)	(0.95-11.38)	(3.48-12.60)	(20.04-30.47)	(185.10-671.20)	(0.00-8.65)	(27.97-288.10)
Brassica chinensis	Mean ± SD	1.33 ± 1.60^{c}	6.82 ± 4.82^{a}	18.18 ±10.59^{a}	163.92 ± 96.91^{b}	1.59 ± 2.45^{a}	46.84 ± 36.53^{c}
	Median	1.10	5.59	20.45	174.10	0.31	36.02
	(range)	(0.00-4.36)	(3.01-15.91)	(3.91-33.58)	(46.56-293.00)	(0.00-6.05)	(12.02-109.50)
Amaranthus vulgaris	Mean ± SD	2.26 ± 2.64^{d}	9.40 ± 9.22^{a}	19.96 ± 11.53^{a}	306.31 ±241.06^{c}	4.51 ± 11.06^{a}	65.60 ± 48.40^{d}
	Median	1.57	5.57	21.56	298.85	0.00	68.54
	(range)	(0.00-7.00)	(3.38-27.53)	(4.97-36.83)	(66.04-663.20)	(0.00-27.09)	(11.51-130.30)
Manihot esculenta	Mean ± SD	3.27 ± 7.09^{e}	11.79 ± 11.39^{a}	16.99 ± 9.84^{a}	160.70 ±112.35^{d}	0.58 ± 1.43^{a}	53.54 ± 56.06^{e}
	Median	0.37	5.41	15.45	119.90	0.00	23.67
	(range)	(0.00-17.71)	(3.21-27.53)	(6.92-31.72)	(51.98-336.20)	(0.00-3.50)	(8.88-130.30)
Allium cepa	Mean ± SD	0.04 ± 0.06^{a}	16.37 ± 17.28^{a}	13.54 ± 8.0^{a}	77.34 ± 51.22^{a}	2.75 ± 2.97^{a}	12.51 ± 2.61^{a}
	Median	0.00	10.21	12.36	70.50	2.42	13.33
	(range)	(0.00-0.16)	(2.82-49.73)	(4.98-25.68)	(13.04-160.30)	(0.00-6.55)	(9.31-15.24)
Solanum lycopersicum	Mean ± SD	0.00 ± 0.01^{b}	18.84 ±16.16^{a}	18.51 ±18.27^{a}	100.12±79.84^{e}	0.69 ± 0.89^{a}	13.78 ± 3.25^{b}
	Median	0.00	11.78	8.86	72.72	0.25	12.66
	(range)	(0.00-0.02)	(5.10-46.70)	(6.39-51.22)	(47.95-259.50)	(0.00-1.85)	(11.17-20.07)

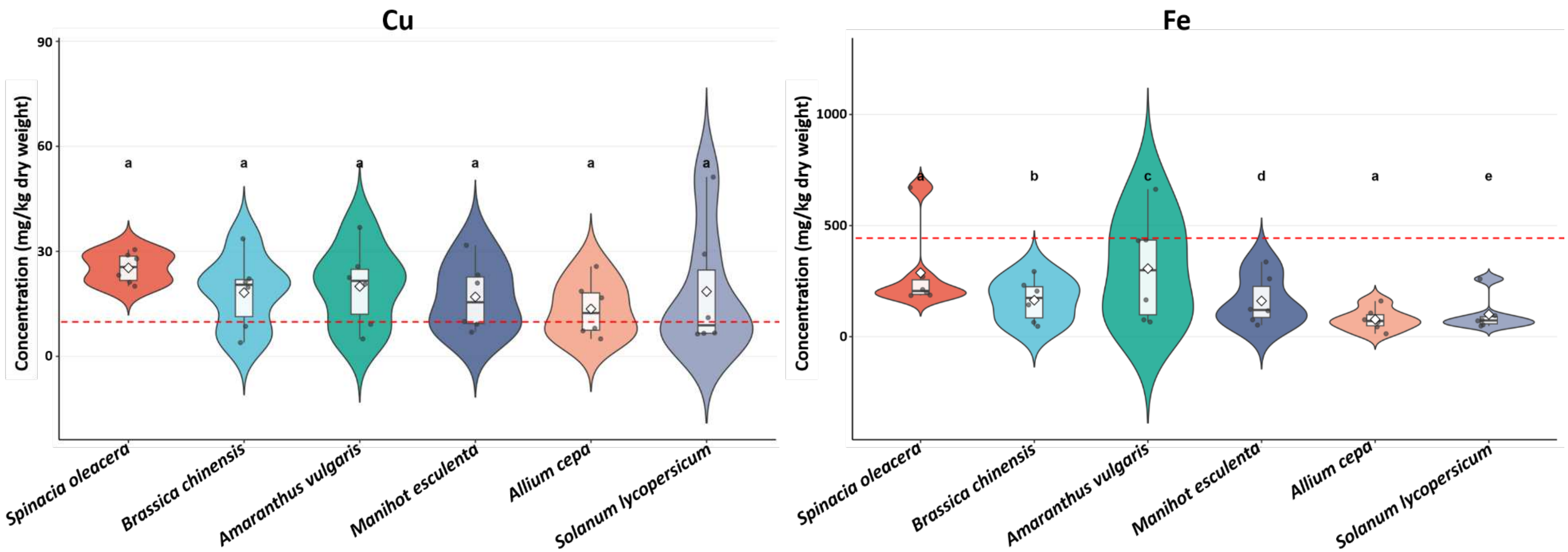
P value	**0.007**	0.184	0.429	**0.047**	0.465	**0.005**
Maximum permissible limits (mg/kg)	**0.2**	**50**	**10**	**450**	**0.30**	**50**
	FAO/WHO (2001)	Feyisa et al. (2025; Gupta et al. (2022)	FAO/WHO (2011)	FAO/WHO (2007)	FAO/WHO (2011)	FAO/WHO (2011)

Rows with different superscript letters and bold *p values* indicate a significant difference ($p < 0.05$) among vegetable species, Dunn's test with a Bonferroni correction was performed following a Kruskal–Wallis analysis; see the supplementary Excel file for the values.

The distribution and variability of heavy metal concentrations are further illustrated in violin plots for each metal across the vegetable species (Figure 2). These plots demonstrate a pronounced right-skewed distribution for Cd, Cu, and Pb, particularly in the leafy vegetables *Spinacia oleracea* and *Amaranthus vulgaris*, indicating sporadic high-level contamination events. Also, Zn showed a right-skewed distribution in *Spinacia oleracea*, while Fe and Co exhibited symmetric distributions that were relatively wide in *Allium cepa* and *Solanum lycopersicum*


Cd
Concentration (mg/kg dry weight)
20
15
10
5
0
ab
c
d
e
a
b
Spinacia oleacera
Brassica chinensis
Amaranthus vulgaris
Manihot esculenta
Allium cepa
Solanum lycopersicum


Co
Concentration (mg/kg dry weight)
75
50
25
0
a
a
a
a
a
a
Spinacia oleacera
Brassica chinensis
Amaranthus vulgaris
Manihot esculenta
Allium cepa
Solanum lycopersicum


Cu
Fe
Concentration (mg/kg dry weight)
90
60
30
0
1000
500
0
a
a
a
a
a
a
a
b
c
d
a
e
Spinacia oleacera
Brassica chinensis
Amaranthus vulgaris
Manihot esculenta
Allium cepa
Solanum lycopersicum

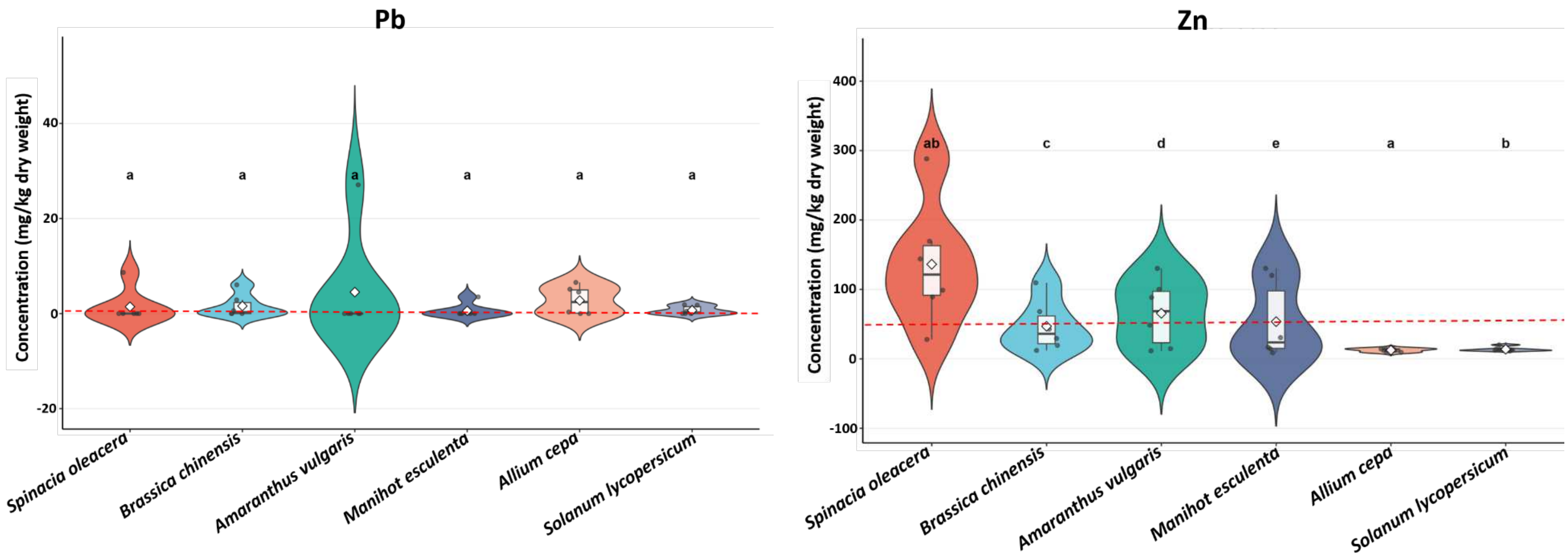


Figure 2. Heavy metal levels in Lubumbashi market garden vegetables. Violin plots exhibiting distributions of Cd, Co, Cu, Fe, Pb and Zn concentrations in the samples analyzed expressed as mg/Kg dry weight. Boxplots in violins display interquartile range with median line. White diamonds represent mean values. Letters above violins are statistical groupings based on Dunn's test with Bonferroni correction following a Kruskal–Wallis analysis ($p < 0.05$); vegetables that share the same letter do not differ significantly. Dashed lines indicate the maximum permissible limits set by FAO/WHO (Cd: 0.2, Cu: 10, Fe: 450, Pb: 0.3, Zn: 50 mg/kg), except for Co according to Feyisa et al. (2025) and Gupta et al. (2022).

3.1.1 Correlation analysis among heavy metals

The analysis of Spearman's correlation indicated a considerable positive association between various metals (Figure 3). Precisely, Cd, Zn, Fe, and Cu established a highly interconnected cluster, showing correlations ranging between r = 0.58 and 0.80, suggesting comparable accumulation patterns. Significant associations were found between Cd-Zn and Fe-Cd, with r = 0.80 and r = 0.75, respectively (Figure 2b). A positive correlation was also found between Cu and Fe (r = 0.70) as well as Zn (r = 0.58). In contrast, Co exhibited negative correlations with most metals, including Co-Cd (r = -0.61) and Co-Zn (r = -0.41). Consequently, Pb displayed a weak correlation with the other metals, with r values between -0.08 and 0.26. The metal co-occurrence network shows a dense cluster involving Cd, Zn, Fe, and Cu, with an antagonistic connection to Co, while Pb is in a separate node shown in Figure 3(b).

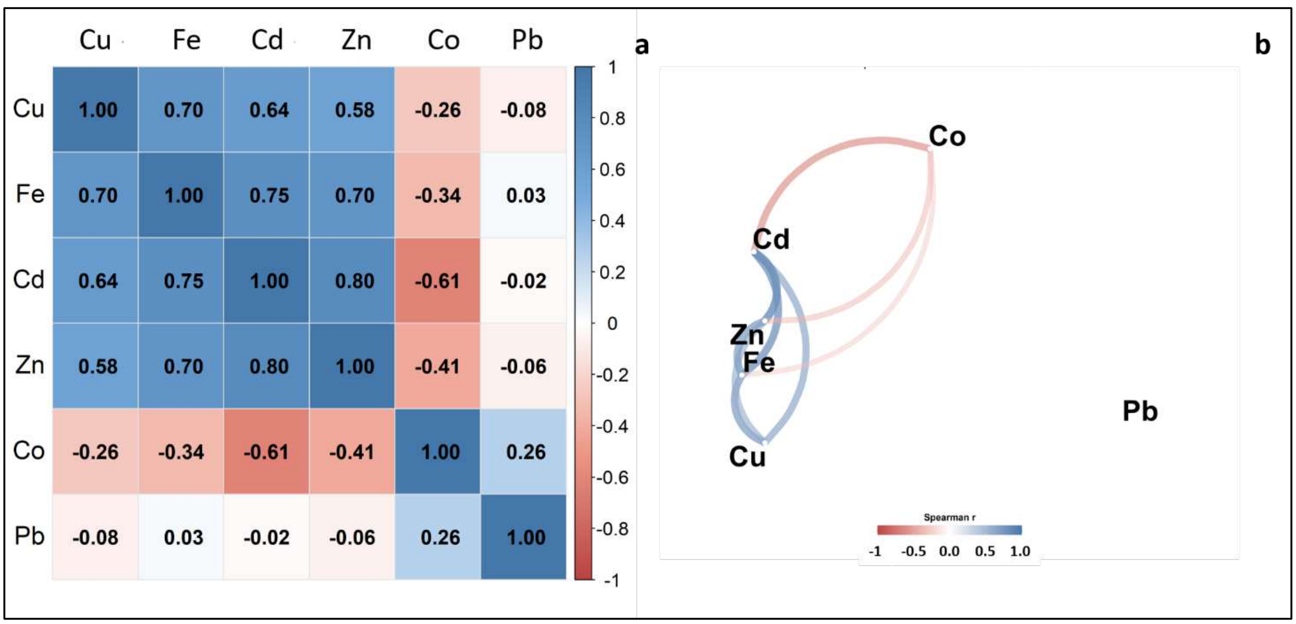


Figure 3. Correlation matrix of heavy metal concentrations. Part (a) Spearman correlation matrix of heavy metals and part (b) Co-occurrence network of heavy metals. The criteria used are Spearman's $\rho > 0.3$ and $p < 0.05$.

3.1.2. Heavy metal levels in vegetable species across the markets

Principal Component Analysis (PCA) was applied to the mean concentrations of heavy metals across vegetables and markets (Figure 4), explaining 65.73% of the total variance. PC1 (45.65%) was mainly associated with Pb, Cu, Fe, Cd, and Zn, whereas Co showed a weak association with the principal component, contributing very little to both PC1 and PC2. *Amaranthus vulgaris* drove PC2 (20.08%), which showed higher Pb, Cu, Fe, and Zn levels in Kenya. Conversely, *Solanum lycopersicum* and *Allium cepa* from Machipisha and Kenya markets aligned positively with the PC2 axis, showing elevated Co levels. Most vegetables from Zambia, Kenya, and Kasapa markets clustered near the negative PC1, suggesting relatively low levels of heavy metals. These patterns highlight species- and market-related variations in metal accumulation.

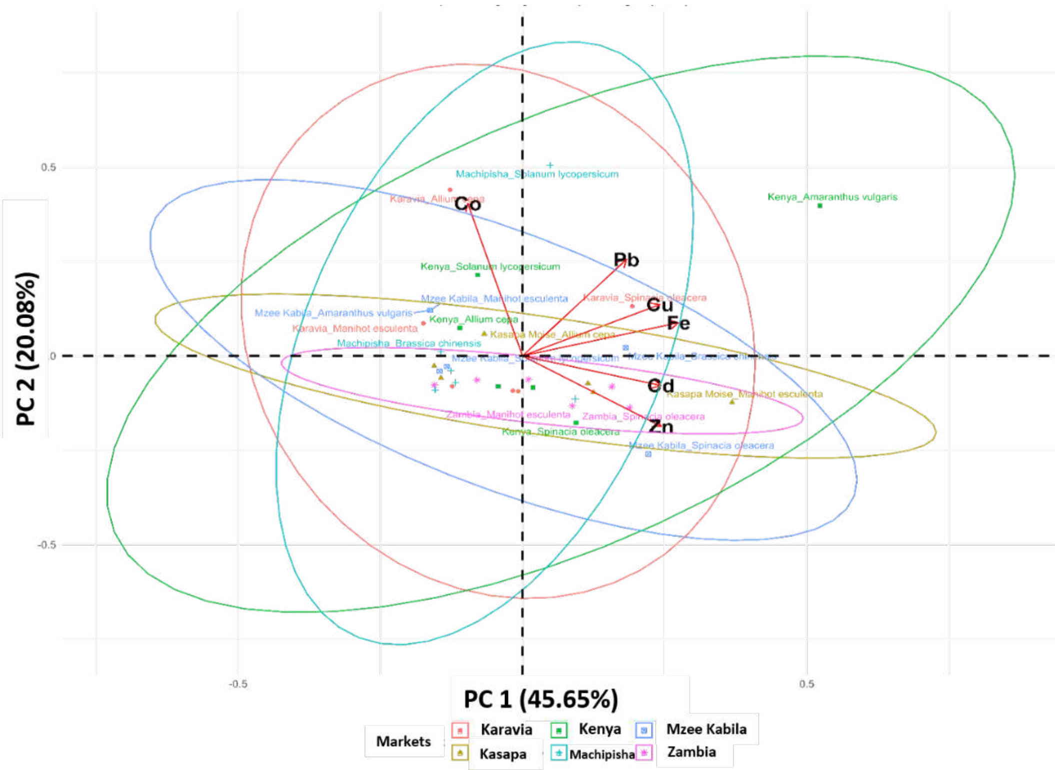


Figure 4. PCA biplot of heavy metals in vegetables across the markets

3.2 Consumer health risk assessment

3.2.1 Estimated daily intake (EDI)

Table 2 summarizes the EDI of the mean concentrations of heavy metals in various vegetables. The EDI was below the recommended limits set by the FAO/WHO for all metals and species. *Spinacia oleracea* had the highest intake of Cd, Cu, and Zn, with EDIs of 1.64×10^{-3}, 1.03×10^{-2}, and 5.54×10^{-2}, respectively. *Amaranthus vulgaris* recorded the highest intake of Fe at 1.25×10^{-1} and Pb at 1.84×10^{-3}. *Solanum lycopersicum* also contributed to the highest intake of Co at 7.66×10^{-3}, while *Allium cepa* had the lowest values for Cd and Zn.

Table 2. The EDI of heavy metals through the consumption of vegetables

Vegetable species	EDI (mg/kg/day/ body weight)					
	Cd	Co	Cu	Fe	Pb	Zn
Spinacia oleacera	1.64×10^{-3}	2.14×10^{-3}	1.03×10^{-2}	1.17×10^{-1}	5.86×10^{-4}	5.54×10^{-2}
Brassica chinensis	5.41×10^{-4}	2.77×10^{-3}	7.39×10^{-3}	6.66×10^{-2}	6.47×10^{-4}	1.90×10^{-2}
Amaranthus vulgaris	9.18×10^{-4}	3.82×10^{-3}	8.11×10^{-3}	1.25×10^{-1}	1.84×10^{-3}	2.67×10^{-2}
Manihot esculenta	1.33×10^{-3}	4.79×10^{-3}	6.91×10^{-3}	6.53×10^{-2}	2.37×10^{-4}	2.18×10^{-2}
Allium cepa	1.59×10^{-5}	6.65×10^{-3}	5.51×10^{-3}	3.14×10^{-2}	1.12×10^{-3}	5.09×10^{-3}
Solanum lycopersicum	1.52×10^{-6}	7.66×10^{-3}	7.53×10^{-3}	4.07×10^{-2}	2.80×10^{-4}	5.60×10^{-3}
Recommended limit	0.046[a]	0.21[a]	2.0[b]	17.0[b]	0.214[c]	20.0[b]

Source: a=FAO/WHO, 2003; b= FAO/WHO, 2011; c= FAO/WHO, 2012.

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

Among the analyzed metals, Cd exhibited the highest level of the THQ, with *Manihot esculenta* and *Spinacia oleracea* exceeding the safe limit (THQ > 1) (Figure 5). Conversely, all other vegetable species had THQ values below 1 for Co, Cu, Fe, Pb, and Zn. The Hazard Index (HI) was notably high for all vegetable species, except for *Allium cepa* and *Solanum lycopersicum*. *Spinacia oleracea* and *Amaranthus vulgaris* recorded the highest HIs, with values of 2.44 and 1.94, respectively.

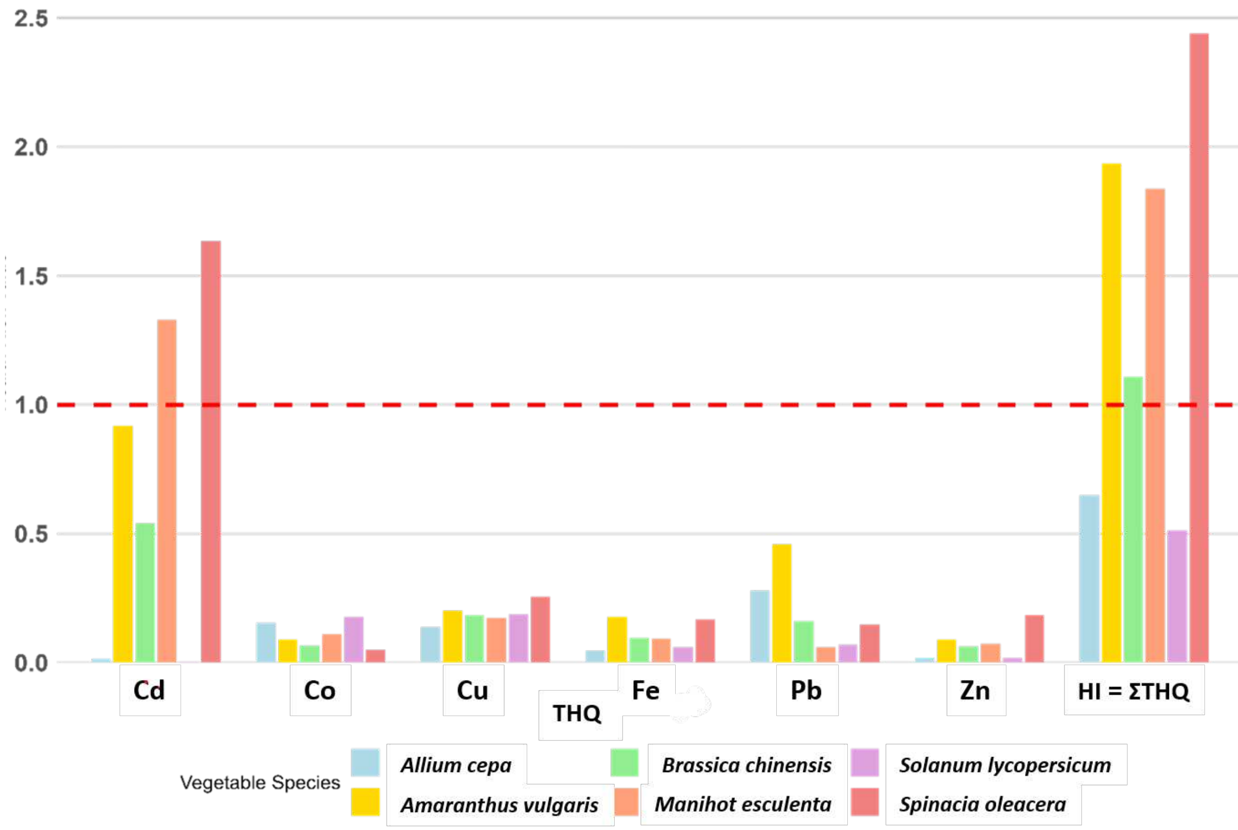


Figure 5. THQ and HI from the consumption of vegetable species.

3.2.3 Target cancer risk (TCR)

Table 3 presents the TCR assessment, which revealed that Cd presented the most significant carcinogenic hazard for all the vegetables, with *Spinacia oleracea* (9.98×10^{-3}), *Manihot esculenta* (8.11×10^{-3}), and *Amaranthus vulgaris* (5.6×10^{-3}) notably exceeding the acceptable risk threshold (10^{-6}-10^{-4}). *Brassica chinensis* presented a Cd risk of (3.3×10^{-3}), whereas *Allium cepa* and *Solanum lycopersicum* were within or close to the acceptable limit. In contrast, the TCR from Pb exposure in all the vegetables was minimal, with the values falling within the safe range.

Table 3. Cancer risk for Cd and Pb associated with the consumption of vegetables

Vegetable species	Cd	Pb
Spinacia oleacera	9.98×10^{-3}	4.98×10^{-6}
Brassica chinensis	3.3×10^{-3}	5.5×10^{-6}
Amaranthus vulgaris	5.6×10^{-3}	1.56×10^{-5}

Manihot esculenta	8.11×10^{-3}	2.02×10^{-6}
Allium cepa	9.69×10^{-5}	9.51×10^{-6}
Solanum lycopersicum	9.3×10^{-6}	2.38×10^{-6}

3.3 Consumer survey

3.3.1 Consumers' socio-demographic characteristics and vegetable preferences

There was significant variation across socio-demographic characteristics (Table 3). Females recorded the majority of 63.5% female whiles 36.5% were males, with a significant difference ($\chi^2 = 25.567$, $p < 0.0001$). Consumers' age also varied significantly ($\chi^2 = 394.21$, $p < 0.0001$), with the majority (67.42%) aged 18-29 years, and 1.13% aged ≥ 60 years. Education levels varied, with the majority (72.52%) having a university education. There was also a significant difference in educational category ($\chi^2 = 459.16$, $p < 0.0001$). Most (37.68%) of the consumers worked in the private sector, more than half (59.49%) had lived in Lubumbashi for more than 10 years, and only 26.35% had heard of heavy metal contamination before.

Manihot esculenta was the most preferred vegetable by consumers (30.6%), followed by *Amaranthus vulgaris* (20.7%) and *Solanum lycopersicum* at 17.3%. The lowest preferred was *Allium cepa* with 8.8% (Fig 1, supplementary file).

Table 4. Socio-demographic characteristic of consumers

Variable	**Category**	**N (%)**	**χ^2**	**P-value**
Gender	Female	224 (63.5)	25.567	**<0.0001**
	Male	129 (36.5)		
Age (years)	18-29	238 (67.42)	394.21	**<0.0001**
	30-44	95 (26.91)		
	45-59	16 (4.53)		
	≥60	4 (1.13)		
Education level	None	8 (2.27)	459.16	**<0.0001**
	Primary	12 (3.40)		
	Secondary	77 (21.81)		
	University	256 (72.52)		

Main occupation	Farmer	35 (9.92)	156.45	**<0.0001**
	Government worker	32 (9.07)		
	Private sector	133 (37.68)		
	Student	123 (34.84)		
	Unemployed	30 (8.50)		
Length of stay in Lubumbashi	1-5 years	69 (19.55)	108.79	**<0.0001**
	10 years	74 (20.96)		
	10 > years	210 (59.49)		
Have heard of heavy metal contamination before	Yes	260 (73.65)	79.006	**<0.0001**
	No	93 (26.35)		

3.2 Consumers' knowledge, perception, and practice on the safety of vegetable consumption in Lubumbashi

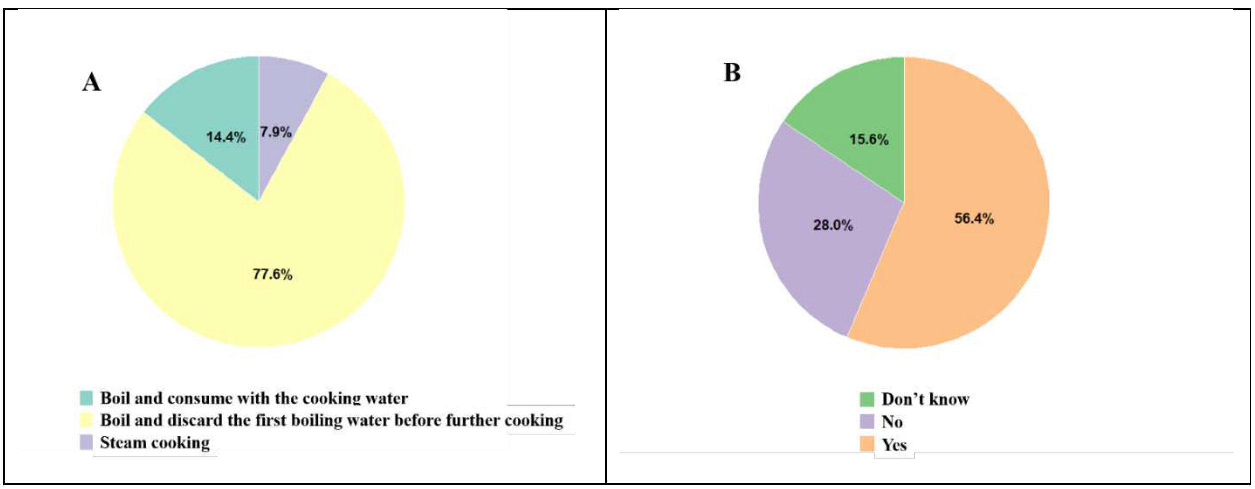
Table S2 (supplementary file) illustrates consumer understanding, perception, and actions regarding heavy metal contamination in vegetables. For the knowledge section, the majority (66.9%) of consumers were aware that vegetables can absorb metals such as Pb, Cu, and Co from contaminated soils or water; 24.4% were unaware, and 8.8% responded negatively. The activities of mining were found to be the main contributor to contamination, accounting for 46.2%, industrial waste at 36.8%, road traffic/dust at 5.95% and the use of pesticides at 2.27%. Furthermore, 41.4% did not know that vegetables sold at the markets were cultivated near mining/industrial sites, whereas 30% knew.

Consumer perception indicated that most respondents (73.6%) strongly agreed that the consumption of vegetables contaminated with heavy metals can lead to significant health issues, with 13.3% agreeing and only 4.25% disagreeing. The most prevalent health issues linked to heavy metal exposure were pains/diarrhea (49.6%), cancer (21.0%), kidney/liver problems (11.0%), and developmental issues in children (9.07%). Approximately 9.35% of consumers did not know the implications of health (Table S2, supplementary file).

Consumers' practices revealed that the origin of cultivation of vegetables was always considered for 20.96% of consumers when purchasing vegetables, whereas 22.10% never considered it. The study revealed that 66.29% of individuals would avoid purchasing vegetables from a contaminated source, while 19.83% indicated they would not. Contamination concerns influenced the vegetable washing practices of consumers, with the majority (72.24%) washing "very much" and 56.94% washing 3–4 times before consumption (Table S2, supplementary file).

3.2.1 Consumers' vegetable cooking practices, preferences and source of food safety information in Lubumbashi

Figure 6 presents consumers' vegetable cooking practices, preferences, and their source of food safety information in Lubumbashi. Most consumers (77.6%) discard the first boiling water after boiling the vegetables, while 14.4% consume the vegetables with the boiling water, and 7.9% use steam cooking. The majority (56.4%) of consumers showed interest in vegetables cultivated using soilless/hydroponic methods. Concerning willingness to pay for such products, 55% would pay <5,000 FC per kg, and 37.1% receive their food safety information from radio/Tv, next by health workers (21.2%).



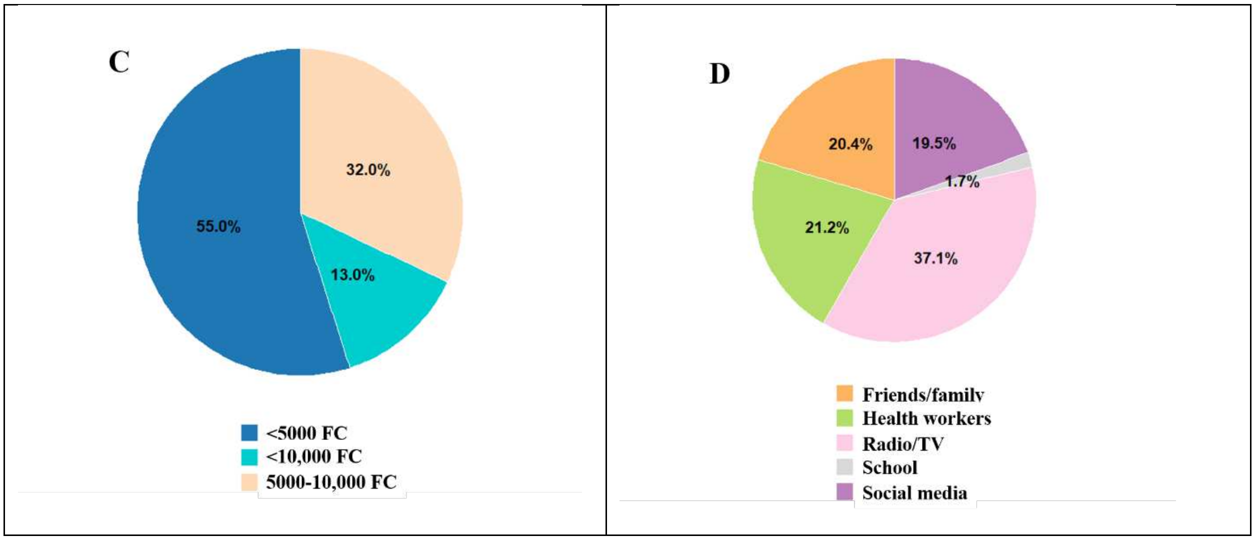


Figure 6. Consumers' vegetable cooking methods, source preference, and food safety information. A) Consumers' usual cooking practices of vegetables; B) Consumers' interest in vegetables produced from soilless/hydroponics; C) Consumers' willingness to pay for 1 kg of such vegetables and (FC= Francs Congolese, 1 USD= 2270 FC) D) Consumers' main source of food safety/contamination information.

3.3. Factors associated with consumers' knowledge, perception and practices with respect to heavy metal contamination in vegetables

Table S3, Supplementary file, shows the ordinal logistic regression analysis, which revealed that gender and prior awareness predicted the knowledge of heavy metal contaminations. Females were twice as likely to know compared to males (ORa = 1.91, 5% CI: 1.28–2.86, $p = 0.002$). Lower odds of knowledge were associated with older age (≥60 years) (ORa = 0.07, 95% CI: 0.01–0.45, $p = 0.005$). Reduced knowledge was also associated with reduced education, with primary education presenting the strongest negative association (ORa = 0.05, 95% CI: 0.01–0.30, $p = 0.001$). Consumers who had not heard about the contamination of heavy metals before were more than seven times more likely to lack knowledge (ORa = 7.22, 95% CI: 4.34–12.02, $p < 0.001$).

Consumers' health risk perception was strongly influenced by prior awareness. Consumers who had not heard about heavy metal contamination were 3.87 times more likely to have a poor perception (ORa = 3.87, 95% CI: 2.38–6.29, $p < 0.001$). Gender, age and education were predictors of perception with statistically significant ($p > 0.05$).

Consumer practice patterns, such as avoiding contaminated vegetables/ washing habits, were significantly related to occupation prior awareness. Unemployed consumers recorded the highest odd of good practices (ORa = 5.58, 95% CI: 2.16–14.39, $p < 0.001$), next by students (ORa = 3.87, 95% CI: 1.75–8.57, $p = 0.001$) and workers in the private sector (ORa = 2.98, 95% CI: 1.40–6.33, $p = 0.005$). Prior awareness predicted better practices as well (ORa = 2.20, 95% CI: 1.37–3.55, $p = 0.001$) (Table S3, Supplementary file).

4.0 Discussion

4.1 Concentration of heavy metals in vegetable species.

Significant variations in heavy metal concentrations were observed among the six-vegetable species analyzed in Lubumbashi. Our results reveal significantly elevated concentrations of Cd, Cu, Pb, and Zn in numerous leafy vegetable species, specifically *Spinacia oleracea, Amaranthus vulgaris* and *Manihot esculenta*. Comparable research has revealed considerably elevated concentrations of these metals in vegetables, surpassing FAO/WHO thresholds within Lubumbashi (Michel et al., 2013; Mputu et al., 2024; Muimba-Kankolongo et al., 2021). Higher levels of heavy metals in Lubumbashi vegetables might be associated with a range of environmental and anthropogenic sources (Hosen et al., 2024).

Mining operations in Lubumbashi result in the release of significant amounts of metals such as Cd, Co, and Pb into the soil and water, which subsequently may be absorbed by crops (Che et al., 2024; Mpanga & Lutandula, 2022; Ocansey, 2013). Leafy vegetables have been commonly reported as effective accumulators of heavy metals, they are more sensitive to external contamination or uptake of soil metal due to factors such as transpiration rate, the large surface area of their leaves and the presence of a great number of available binding sites for metals in leaf tissue (Mao et al., 2023; Zhou et al., 2016). Cd can be found in soil and water due to different processes, including the use of phosphate fertilizers in agriculture (Al-Shammari 2025). For instance, Cd frequently penetrates the plant through carriers of Ca^{2+}, Fe^{2+} and Zn^{2+}, as this toxic metal might chemically resemble these essential elements (Mpanga & Lutandula, 2022). This process accounts for the high Cd levels always found in *Spinacia oleracea* (4.02mg/kg), a plant with the ability to upregulate Zn, Fe and permease transporter genes under nutrient stress status, which indirectly enhances the uptake of Cd (Iddrisu et al., 2026).

Cu and Pb levels consistently surpass safe limits across all vegetable species examined in these studies, highlighting the persistent and extensive environmental contamination in the Copper Belt mining zone of Lubumbashi. The soils in this region are well-documented to contain elevated concentrations of Cu and Pb, a consequence of prolonged cobalt mining that has enriched the area's pedogeochemical background (Lwalaba et al., 2019; Muimba-Kankolongo et al., 2021; Mununga et al., 2024). The Cu levels align with the geological characteristics of the Copper Belt, known for its richness in copper, as well as emissions from smelting operations. The bioavailability of Cu may be increased due to the presence of acidic soils and the degradation of organic matter, particularly in gardens that are often irrigated with wastewater from nearby mining activities (Mununga Katebe et al., 2023; Peša, 2022). Notably, Cu concentrations have been found to exceed recommended levels in Lubumbashi, with significant accumulation observed in leafy vegetables in previous studies (Mpanga & Lutandula, 2022; Mununga et al., 2024).

Pb exceedance levels in vegetables primarily stem from airborne Pb particles resulting from artisanal ore processing, smelting activities, and vehicular emissions (Julius et al., 2024). Previous research conducted in Lubumbashi has demonstrated Pb accumulation in the surface soil and leaves of vegetables situated near smelting and mining operations (Muimba-Kankolongo et al., 2021). This is consistent with the higher Pb accumulation in *Amaranthus vulgaris* and *Spinacia oleracea* in our study where vegetables are obtained from the markets. Hence, Pb contamination in Lubumbashi (especially in leafy vegetables where dust is directly deposited on the edible tissues) might not be only caused by the root uptake but mostly due to atmospheric deposition (Ajiwe et al., 2018).

Although Co concentrations in the samples investigated were found below the threshold limit, they were high in *Amaranthus vulgaris, Manihot esculenta* and *Solanum lycopersicum*. Lubumbashi, known as a major centre of some of the world's most significant Cu-Co deposits, is influenced by both artisanal mining and industrial activities, which to a large extent are responsible for Co dispersal through dust, soils and irrigation water (Mununga Katebe et al., 2023). In contrast to the proposed Co concentrations, our study agrees with Muimba-Kankolongo et al. (2021), Mununga et al. (2024), and Mununga Katebe et al. (2023) that the levels of Co can be time variable. In Lubumbashi, Cu and Cu commonly occur in soil together and plants uptake Co mainly through non-specific divalent metal transporters which are also used for iron (Fe^{2+}) and manganese (Mn^{2+})

(Lwalaba et al., 2019; Mpanga & Lutandula, 2022). This process may explain why plant species with a high preference for Fe uptake (*Spinacia oleracea* and *Manihot esculenta*) also exhibit higher Co accumulation. The PCA indicated that market-related variations in Pb, Cu, Fe, Cd, and Zn suggest that the type of vegetable and the source of the market can influence contamination patterns. Likewise, the levels of Cd, Co, and Pb were found to be higher in Tanzanian leafy vegetables collected from local markets (Magesa et al., 2025). Showing that markets can also be a source of heavy metals contaminations.

While our results show that the concentrations of Co are still under recommended values, this contributes to potentially serious environmental effects. The mobility of Co in the Cu-Co soil matrix of Lubumbashi is a threat to its accumulation over the years, in particular on vegetable gardens located close to smelters and tailings, as well as artisanal ores processing areas (Mununga et al., 2024). Zn concentration was found above the recommended limits in some species, mainly in *Spinacia oleracea, Amaranthus vulgaris* and *Manihot esculenta*. This may be due to the fact that Zn is an essential nutrient for vegetable growth, readily absorbed by roots and transported to the aerial parts of the plants (Zhou et al., 2016; Ren et al., 2025). As a result, the elevated Zn concentrations may be linked to the extensive mining and industrial activities in Lubumbashi (Mputu et al., 2024).

4.2. Consumer health risk assessment and perception of heavy metal contamination in vegetables

Our study is the first study offering an integrated approach to food and health, combining laboratory analysis of heavy metal contamination in vegetables with an assessment of consumer health risks and a socioeconomic survey of consumer perceptions. Consumers may face health risks when eating vegetables (Mao et al., 2023). These risks depend on the amount and type of heavy metals present (Manegabe et al., 2025). The EDI, THQ, HI and cancer risk were used to assess the health risk of consumers. The amount of heavy metal exposure is closely related to daily intake (Osae et al., 2023). The EDI was within the recommended limits set by the FAO/WHO for all metals and species. *Amaranthus vulgaris* recorded the highest EDI of Fe, while *Spinacia oleracea* had the highest intake of Cd, Cu, and Zn. The daily intake of Cd and Cu in *Amaranth sp*. was within the recommended limit in Tanzania, confirming that eating this vegetable poses no potential health risk (Julius et al., 2024). However, a comparative study conducted in Kinshasa and Lubumbashi indicated a higher level of EDI for Pb, Cd, Cu and Zn in Amaranthus species and Brassica oleracea in Lubumbashi compared to Kinshasa (Mputu et al., 2024).

The THQ is recognized as an important factor for assessing the risk linked to the consumption of food crops that are contaminated with metals (Zakir et al., 2021), while the HI calculates the overall THQ when several heavy metals are present (Sharmin et al., 2020). The THQ level for Cd was highest in *Manihot esculenta* and *Spinacia oleracea*. This indicates that there is a potential health risk due to Cd when consuming these vegetables. Cd has no essential or beneficial roles in plants, humans, or animals, as it lacks nutritional value and is toxic (Asrade & Ketema 2023). Cd exposure is associated with damage to the kidneys and loss of bone minerals. Chronic exposure can result in serious health issues that include osteoporosis and renal failure (Mitra et al., 2022). Consumers in Lubumbashi are not faced with Cd/Pb but instead every day with a combination of mining-related metals (Cd, Pb, Cu, Zn, Co). This is supported by the HI accumulation to non-carcinogenic risk among metals, which surpasses the safe limit (HI > 1) on key leafy vegetables such as *Spinacia oleracea* (HI = 2.44) and *Amaranthus vulgaris* (HI = 1.94). This suggests an apparent risk of non-carcinogenic systemic effects from the cumulative metal body burden, through the individual EDI values. HI was not found to be lower in *Allium cepa* and *Solanum lycopersicum*. The findings of this study comply with studies by Nie et al. (2023), Ren et al. (2025) and Asrade & Ketema (2023).

Among the carcinogenic metals, Cd was above the acceptable threshold limit set by USEPA (2011), and it was present in *Spinacia oleracea*, *Manihot esculenta* and *Amaranthus vulgaris*; however, Pb levels were within the threshold limit. The findings of this study show that consumers may pose a certain degree of carcinogenic risk from Cd. Similar findings in carcinogenic levels of Cd in *Amaranth sp* have been reported in Julius et al. (2024) and by Hosen et al. (2024). In Lubumbashi, there is a reality of multi-pathway exposure, including the inhalation of contaminated dust and eating other locally produced foods, such as fish that come from contaminated water and grains (Banza 2009). This situation would increase the total body burden, reflecting the broader environmental challenges that are present in the area (Mputu et al., 2024).

The analysis that we conducted shows a clear relationship that exists between how consumers perceive contamination and the levels of contamination that were observed in the vegetables from the markets in Lubumbashi. Many of the consumers expressed strong agreement that the contamination of heavy metals presents a serious health risk, in line with a similar study (Mensah et al., 2014). Laboratory analysis confirmed these concerns and showed that there were elevated levels of Cd, Cu, Pb, and Zn in various vegetable species, including *Spinacia oleracea* and *Amaranthus vulgaris*. The survey results indicated that *Manihot esculenta* was the vegetable that consumers preferred the most. However, this vegetable also had one of the highest HI and showed higher levels of cancer risk. This finding highlights the complexity of food safety in Lubumbashi, where the choices made by consumers are influenced by cultural and dietary preferences Michel et al. (2013); Mushagalusa (2019), but these same choices can unintentionally lead to increased exposure to harmful contaminants. Most consumers agreed that heavy metal contamination levels are concerning and that even with awareness, knowing does not necessarily lead to effective risk mitigation. Similar to Ghana, knowledge of consumers does not guarantee action (Abass et al., 2016; Owusu-Sekyere et al., 2014).

4.3. Policy implications

In line with the IPBES nexus summary for policymakers, our study points out the presence of heavy metal contamination in vegetables, presenting the challenges for food and health, as well as for biodiversity (IPBES, 2024). It suggests the need for combined efforts in environmental and public health governance in Lubumbashi, DR Congo.

Mining environmental obligations relates to food safety surveillance in urban agriculture. The Mining Code in the DRC, ‘Code Minier', has been amended and completed by decree number 18/024 on the 8th of June in the year 2018, and has recently enforced actions in Lubumbashi following an incident involving the spill of industrial effluent (Code Minier, 2018). This incident demonstrated that the authority can suspend operations, impose penalties, and require remediation in accordance with the code. These rules should be clearly linked to the monitoring of food safety downstream, including the mandatory testing of irrigation waters and vegetable produce in markets that are near mining and processing locations, so that compliance with mining regulations can lead to agricultural safety checks when incidents occur.

At the national level, the Animal and Vegetable Quarantine Service (SQAV), implements sanitary and phytosanitary (SPS) measures under the Ministry of Agriculture. The enforcement of standards and the capacity of laboratories are irregular. The DRC mainly depends on Codex Alimentarius, but there is limited application of these standards domestically. A policy that would be enacted locally by the provincial health and agriculture departments should include requirements for traceability of farms and water sources that are located near mining areas. It should also set up regular market surveillance to check for heavy metals in vegetables, establish specific threshold incidents that would trigger market advisories, and ensure integration with the SQAV border and SPS protocols to create uniform testing methods. Fair market competition, lower trade barriers, and support the development of market infrastructure are crucial for establishing favorable conditions for vegetable producers to access local, national, and global markets (Frank & Mohamed, 2024).

Vegetable safety policies required a combination of contamination monitoring from both heavy metals and pesticide regulations. Studies from Kinshasa and Lubumbashi reveal that market gardeners often use toxic or prohibited pesticides without proper training, risking consumers' health when mixed with metals exposure from mining (Ndelo, 2023). A regulatory framework locally should link testing of metals along with pesticide compliance, keeping of records and mandatory training to ensure food safety holistically.

It is critical to take advantage of consumer interest in hydroponics/soilless systems through a certification and standards approach. Over half of consumers are interested in hydroponic vegetables and are willing to pay for it. This will also increase the competitiveness of producers in the fresh vegetable market (SEFO et al., 2025). With laboratory confirmation, Office Congolese Control/SQAV and publishing of results to be publicly transparent, this essentially leverages the willingness to pay against exposure to contaminated soil, water or deposition of dust.

5.0. **Limitations of the study**

Although this study is among the few to combine laboratory-based analysis and household survey data to assess health risks related to food-chain contamination by heavy metals in the DRC Copperbelt, several limitations should be acknowledged. First, the analysis focused on the most consumed vegetables, thereby excluding other food crops whose availability is seasonal, which may not fully capture seasonal variability or farm-specific contamination pathways. Moreover, because vegetable samples were collected from open markets that are exposed to dust, and where water of uncertain quality is used for washing and freshening produce, the study could not disentangle contamination originating from agricultural fields from contamination occurring during post-harvest handling and market conditions. Second, the health risk assessment relied on standard assumptions regarding average consumption rates and body weights, which may underestimate exposure among high-consumption groups or vulnerable populations such as children and pregnant women. Third, consumer perceptions were assessed using a one-time cross-sectional survey, limiting the ability to capture temporal changes in risk awareness, perceptions, and behavioral responses.

6.0. Conclusion

The current study provides constructive evidence for policymakers and researchers as a whole. It is one of the few studies conducted in Lubumbashi regarding consumer well-being and heavy metal contamination in vegetables. The findings of this study reveal that the mining city of Lubumbashi requires collective efforts from everyone to bring about transformative change, especially as it is a rapidly growing city. There are several ways to mitigate heavy metal contamination in Lubumbashi, such as Phytostabilization methods that have already been underway. However, this study addresses the gap by emphasizing the importance of connecting environmental monitoring with consumer health and examining perceptions to inform targeted interventions aimed at reducing exposure and improving food safety in mining-affected regions.

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