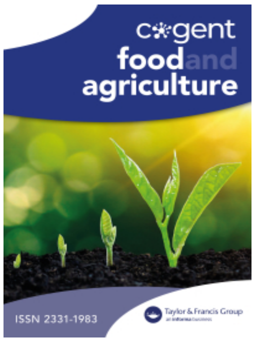

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Heavy and trace metals in Zambian honey: Are consumers at risk?

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ABSTRACT

Honey is globally recognized for its a nutritious and medicinal value, but concerns are increasing over consumer health risks from heavy metal contamination. Therefore, the present study analyzed the levels of Lead (Pb), Nickel (Ni), and Zinc (Zn) in honey samples from five provinces of Zambia and the associated public health risks to men, women and children. An inductively coupled plasma-optical emission spectrometry (ICP-OES) was used to analyse concentration of each of the heavy metal and compared using one way analysis of variance. The results revealed that levels of Pb, Zn and Ni varied significantly among regions with Copperbelt Province having consistently higher levels of heavy metals than the other provinces. All heavy metal concentration values are presented as mean plus or negative standard error (mean ± SE), the concentration detected remained below the WHO permissible limits except for Pb concentration from Copperbelt (1.10 ± 0.12) and Luapula (0.54 ± 0.02) Provinces. However, public health risk assessment indicators including the Estimated Daily Intake (EDI), Target Hazard Quotient (THQ), and Hazard Index (HI) had values <1, suggesting no significant non-carcinogenic health risks. These findings demonstrate that Zambian honey is safe for consumption; continued monitoring and improved harvesting practices are recommended to ensure food-safety and protect public health.

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1. Introduction

Honey is a natural, sugary, and viscous substance produced from the nectar of plants and vegetation (Samuel et al., 2024). It is one of the oldest sweeteners and is used for medicinal purposes as far back as way back as 1550 BC in ancient Egypt (Viktória & Aliz, 2023; Qamar & Rehman, 2020). Honey bees (*Apis mellifera*) collect nectar, mix it with body substances, deposit it into honeycombs, and dehydrate it for maturation (Tibebe et al., 2022). The resulting honey is a gelatinous product rich in carbohydrates (maltose, sucrose, fructose, glucose), organic and inorganic compounds, and water (Kebede et al., 2024). Honey is recognized as a highly nutritious natural bioproduct with both bactericidal and stimulative properties (Adugna et al., 2020). Its quality and value are influenced by factors such as plant species, geographical location, environment, harvesting period, and climatic conditions (Beshaw et al., 2022; da Silva et al., 2025).

Honey production increased by 15.6% between 1961 and 2017, driven by growth in South America, Africa, and Asia (Phiri et al., 2022). In 2022, the global honey market was valued at USD 8.53 billion and

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is projected to reach nearly USD 15 billion by 2031, growing at 5.83% annually (Kumar et al., 2023). In Africa, Ethiopia, Tanzania, and Kenya were the top producers in 2022, with 50,000 MT, 31,345 MT, and 25,000 MT, respectively (Kumar et al., 2023). Honey consumption varies globally due to dietary and cultural differences, though it is produced on every continent, with China and India leading global production (Viktória & Aliz, 2023). Its popularity is largely due to health benefits, including wound and cancer healing, immune support, cardiovascular health, antimicrobial, and respiratory benefits (da Silva et al., 2025; Kaur et al., 2024; Šerevičienė et al., 2022).

However, its quality is threatened by both heavy and trace metals contamination, which can enter the food chain through plant uptake from polluted soil, water, and air, accumulating in nectar and pollen (Mohamed et al., 2024; Palma-Morales et al., 2023; Cempel & Nikel, 2006; Dehkordi et al., 2024; Mehri, 2020). Heavy metals are a specific category of elements characterized by relatively high densities, atomic numbers, and atomic weights on the periodic table, and they can be toxic even at low concentrations (Abdelmonem et al., 2025). In contrast, trace metals have lower densities, atomic numbers, and atomic weights and are required by living organisms in small quantities for normal physiological functions (Das et al., 2023). Bees forage about 7 km^2, increasing exposure to environmental pollutants (da Silva et al., 2025; Komasilova et al., 2021; Sonmez Oskay et al., 2025; Albu et al., 2025; Wu et al., 2022). Heavy metals are common honey contaminants (Kaur et al., 2024), are non-biodegradable, and pose health risks such as kidney, liver, and heart damage (Liu et al., 2024; Wise et al., 2025; Vanisree et al., 2022). They may cause anaemia, cancer, inflammation, and organ failure (Kaur et al., 2024; Morariu et al., 2024). Understanding these contamination risks is vital to safeguard public health.

Honey production in Zambia has been steadily rising, supported by the government and NGOs, with exports valued at $6.1 million in 2022 (Meaton et al., 2021; Kumar et al., 2023; Lombe & Katete, 2024). Beekeepers use both traditional and modern hives, producing over 1,500 metric tonnes annually, of which about 13% is exported (Lowore, 2021; Nyau et al., 2013). Locally, honey is widely traded and used in beer brewing, retail, processing industries, and for direct consumption (Mwalea & Mbewe, 2017). However, no studies to date have assessed the risks associated with consuming honey from the various provinces of Zambia. Previous studies in Zambia have primarily focused on fish (Hasimuna et al., 2022, 2023, 2024, 2025a; Mbewe et al., 2016; Mphande & Chama, 2015; Sihoka et al., 2024), vegetables (Miyanza et al., 2024), plants (Mulwanda et al., 2025), maize (Mwilola et al., 2020) and water and sediments (Hasimuna et al., 2025b, 2021).

Therefore, the present study analyzed the concentration levels of zinc (Zn), lead (Pb), and nickel (Ni)in honey collected from the Copperbelt, Central, Northern, Luapula, and North-Western provinces of Zambia and assessed the health risks for men, women, and children from consuming honey from the five provinces. Pb was assessed because it is a well-known toxic element for humans, capable of causing pathological effects on the skeletal, nervous, endocrine, immune, and circulatory systems, potentially leading to severe or life-threatening conditions such as cancer (Lemessa et al., 2022). Additionally, exposure to Pb during pregnancy may result in significant prenatal developmental impairments in the fetus (Jin et al., 2020; Siame et al., 2025). Ni and Zn were also investigated because, although they are essential trace elements required in small quantities to support physiological and biochemical functions necessary for proper cellular metabolism, they can be toxic to humans when ingested at high doses (Bogdanov et al., 2007; Tahboub et al., 2022; Tuzen et al., 2007; Tolkou et al., 2023). Based on this, we hypothesized that the levels of these metals in honey are below the recommended limits set by the World Health Organization (WHO), and that they do not pose any health risks to men, women, or children consuming honey across these provinces.

2. Materials and methods

2.1. Honey collection

To capture variation within each province, five honey samples, each measuring 500 mL, were randomly purchased from different local beekeepers in the Central, Luapula, North-Western, Northern, and Copperbelt provinces of Zambia (Figure 1). The samples from each province were then mixed and homogenized to create a composite sample, following the procedures described by Adugna et al. (2020) and Beshaw et al. (2022). Sample collection took place between October 2024 and January 2025, and

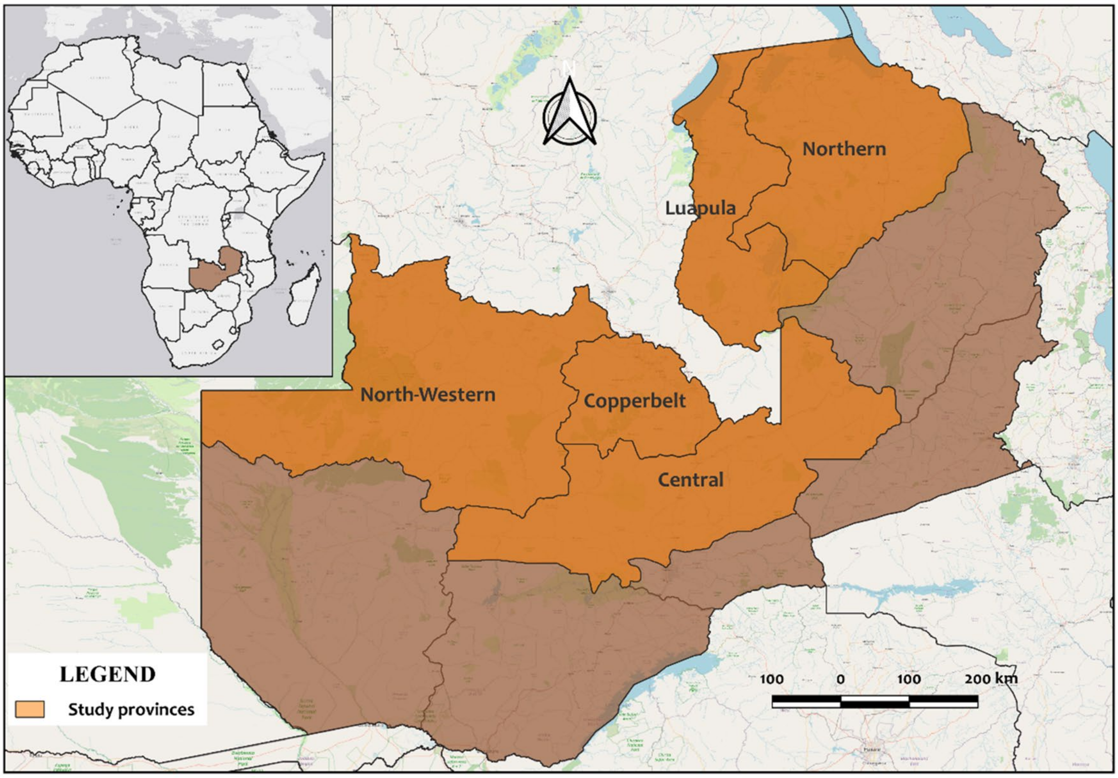

Figure 1. Map showing Central, Luapula, North-Western, Northern and Copperbelt provinces of Zambia where honey samples were collected from October 2024 and January 2025.

Table 1. ICP-OES operating parameters for the quantification of heavy metals in honey samples collected from Central, Luapula, North-Western, Northern, and Copperbelt provinces of Zambia between October 2024 and January 2025.

Parameters	Pb	Zi	Ni kg/m^3
Wavelength (nm)	220.35	213.85	188.98
Relative standard deviation	±5.0%	±2.0%	±5–10%
Limit of detection	1×10^{-8}–$1 \times$ 10–6 kg/m^3	1×10^{-7}–1×10^{-5} kg/m^3	1×10^{-9}–1×10^{-6}

the collected samples were immediately transported to the Zambia Bureau of Standards (ZABS) Laboratory in Lusaka for analysis.

2.2. Reagents and solutions

Two primary reagents were employed in the sample preparation and analysis process. The first was concentrated nitric acid (65%, Kanto Chemical Co., Japan) (Simfukwe et al., 2025; Gashaw et al., 2024), used for digesting the ashed samples, due to its strong oxidative properties, allowing complete dissolution of metals. The second reagent was a multi-elemental standard solution with concentrations ranging from 0 ppm to 5 ppm (0, 0.1, 0.2, 0.3, 0.4, 0.5, 1, 2, 3, 4, and 5 ppm) and the operating parameters for the quantification of heavy metals are shown in Table 1. These standards were essential for the calibration of the ICP-OES machine to ensure accurate detection and quantification of Pb, Ni, and Zn.

2.3. Analytical technique

The core instrument used for the analysis of three heavy metals in honey was the Inductively Coupled Plasma Optical Emission Spectrometer (ICP-OES; Agilent 5110, 2019), known for its high sensitivity and accuracy in multi-elemental detection. Sample preparation followed the protocol described by Thermo Fisher Scientific (2015), with minor modifications to accommodate the study samples. Each sample (10^{-3} Kg) was accurately weighed into a clean, dry crucible and first heated on a hotplate to dryness to remove moisture. After cooling, the dried samples were ashed in a muffle furnace at high temperature for 5 h to eliminate organic matter and isolate mineral content. The ashed material was then digested using 10 cm^3 of concentrated nitric acid to dissolve the inorganic matrix and release the target metals. The digestate was filtered through 0.15 m filter paper and collected into a 0.0001 m^3 volumetric flask, which was then filled to the mark with distilled water, preparing the solution for ICP-OES analysis.

2.4. Validation and quality control

Method validation was performed to ensure the reliability and accuracy of the analytical procedure. The validated method incorporated several statistical parameters. All samples were analysed in triplicate, and the mean, standard deviation (SD), and relative standard deviation (RSD) were calculated to assess precision. The limit of detection (LOD) for Pb and Ni was determined to be 1×10^{-9} kg kg^{-1}, while for Zn, it was 0.01 mg kg^{-1}. The method's specificity, indicated by the interference ratio (IR), was 3.81%, ensuring minimal cross-element interference. Robustness was measured by RSD and found to be 2%, and linearity, reflected by the correlation coefficient (R^2), was 0.997, indicating excellent calibration curve performance.

Quality control measures were stringently observed. A blank sample (containing no analytes) was included and showed no signal, confirming the absence of contamination. Multi-elemental standards were used to calibrate the ICP-OES before every batch analysis to maintain instrument accuracy. The analytical balance was regularly calibrated, and all analyses were conducted using thoroughly cleaned glassware. Importantly, all laboratory procedures were followed strictly in accordance with a standard operating procedure (SOP) to enhance consistency and reliability.

2.5. Health risk assessment

In order to evaluate the health risks from the consumption of honey, the following indices were calculated.

2.5.1. Estimated daily intake

$$EDI = \frac{M \times C}{bw} \ldots\ldots\ldots\ldots\ldots\ldots \quad (1)$$

where M is the quantity of honey consumed daily which is 0.05 kg day^{-1} for adults and 0.021 kg day^{-1} for children (Alaofe et al., 2014) and C is the elemental concentration (μgg^{-1}) and bw is the average body weight 70 kg for men, 65 kg women, and 15 kg for children (Chungu et al., 2019; Miyanza et al., 2024; Mitsunaga & Yamauchi, 2020). To identify the most exposed group, EDI data were calculated for both children and adult men and women, considering the differences in average body weight and food intake.

2.5.2. Estimated weekly intake (EWI)

The estimated weekly intake (EWI) for heavy metals in honey is determined from the equation:

$$EWI = EDI * 7 \ldots\ldots\ldots\ldots \quad (2)$$

The EWI is an index for comparison with the provisional tolerable weekly intake index (PTWI) (Simfukwe et al., 2024).

2.5.3. Chronic daily intake (CDI)

Chronic daily intake (CDI) was calculated using Eq. (3):

$$CDI = \frac{(EDI * ED_{tot})}{bw} \ldots\ldots\ldots \quad (3)$$

where ED_{tot} is the exposure duration (Chebli et al., 2025). The target hazard quotient (THQ) for non- carcinogenic risk was calculated by THQ = CDI/RfD, where RfD is the reference dose, defined as the daily dose that enables consumers to sustain this level of exposure over a long period of time without experiencing any harmful effects. The RfD values for Pb, Zn and Ni are 0.003, 0.0011 and 2×10^{-8} kg bw day^{-1}, respectively (Godebo et al., 2025). THQ > 1 represents adverse non-carcinogenic effects of concern, while THQ < 1 is an acceptable level.

2.5.4. Target hazard quotient (THQ)

The target hazard quotient (THQ) describes the non-carcinogenic health risk posed by exposure to the respective toxic element which was calculated as

$$THQ = \frac{CDI}{RfD} \ldots\ldots\ldots\ldots\ldots\ldots \quad (4)$$

Where RfD is the reference dose, defined as the daily dose that enables consumers to sustain this level of exposure over a long period of time without experiencing any harmful effects. The RfD values for Pb, Zn and Ni are 0.003, 0.0011 and 2×10^{-8} kg bw day^{-1}, respectively (Godebo et al., 2025; Simfukwe et al., 2025). THQ > 1 represents adverse non-carcinogenic effects of concern, while THQ < 1 is an acceptable level (Hasimuna et al., 2023; Simfukwe et al., 2025).

2.5.5. The hazard index (HI)

The hazard index is the sum of the target hazard quotients;

$$HI = \sum THQ_i$$

where ∑THQ is the sum of THQ_{Pb}, THQ_{Zn} and THQ_{Ni}. The assumption is that the magnitude of adverse effect is directly related to the sum of multiple metal exposures (Simfukwe et al., 2024). If the sum of the hazard quotients is <1, the population is at risk. If ΣTHQ is ≥1, the population experience health issues.

2.6. Data analysis

Heavy metal concentration values from each province were entered into Microsoft Excel 2019, cleaned, and exported to the R environment, version 4.4.2 (R Core Team, 2024) for analysis. Data normality was assessed using the Shapiro–Wilk test ($p > 0.05$), and Levene's test confirmed homogeneity of variances. Given these assumptions were met, one-way ANOVA was conducted, followed by Tukey's HSD for pairwise comparisons when significant differences were observed. Univariate statistics and visualizations were also produced in R. Descriptive analysis of human health risk assessments was performed in Excel. To explore similarities in heavy metal concentrations across provinces, Principal Coordinate Analysis (PCoA) was conducted using PRIMER v7 (Clarke & Gorley, 2015) based on Euclidean distances from normalized data. Differences in multivariate structure were assessed using PERMANOVA with 9,999 permutations (Anderson, 2008).

3. Results

3.1. Levels of heavy metals in honey

The distributions of the concentrations of three analyzed heavy metals (Pb, Zn, Ni) in kg wet weight is presented in Figure 2. Results indicate that there were significant differences in the concentrations of Pb, Ni, and Zn among the five provinces ($p < 0.001$). Copperbelt Province had higher concentrations of all heavy metals than the other provinces. The highest mean Pb concentration was recorded in Copperbelt (1.10 ± 0.12), while the lowest was in Northern Province (0.023 ± 0.009). Mean Ni concentration was highest in Copperbelt (0.37 ± 0.04), followed by Central (0.16 ± 0.02), while Luapula recorded the lowest (0.077 ± 0.015). The highest mean Zn concentration was observed in Copperbelt (5.43 ± 0.35), and the lowest in North Western (1.59 ± 0.36).

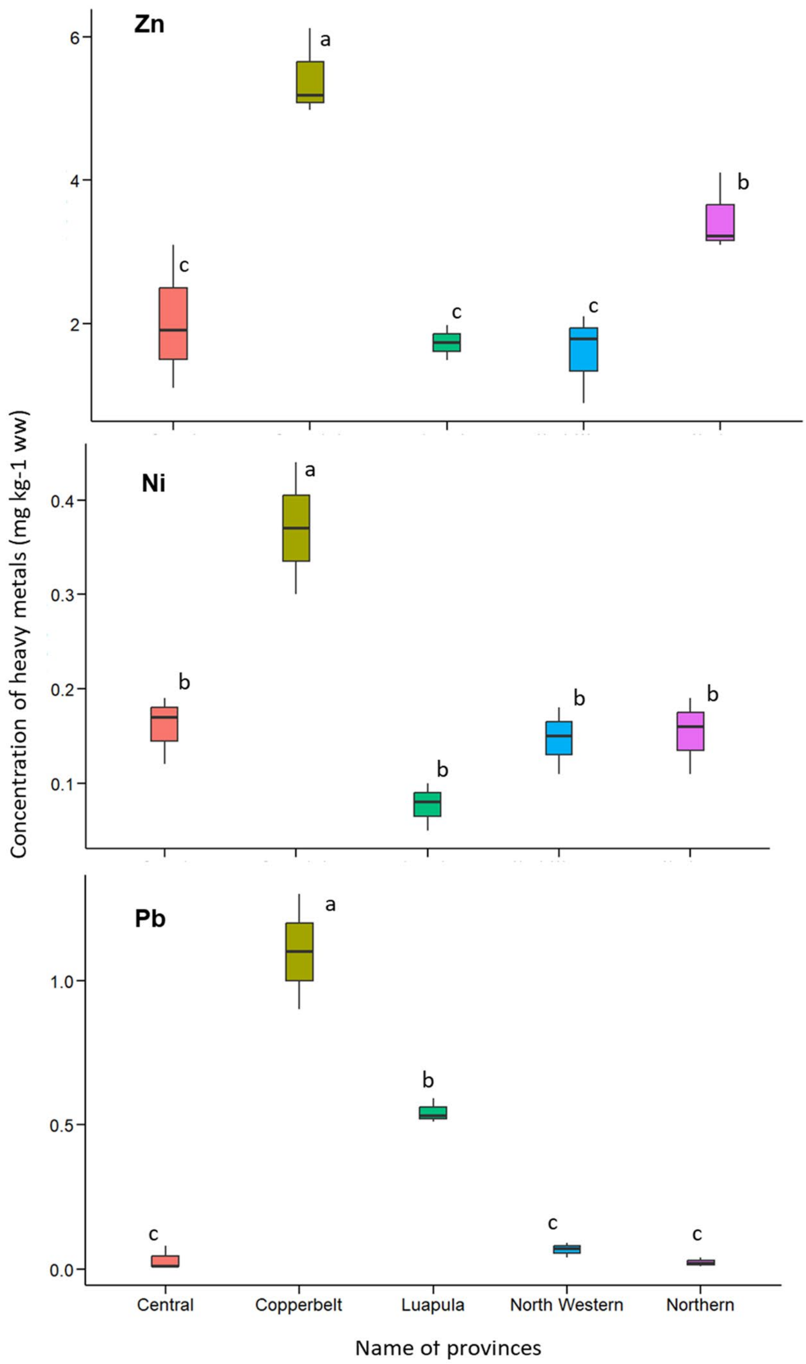

Figure 2. Boxplots showing the median, interquartile range, and data range for the concentrations of Zinc (Zn), Nickel (Ni), and Lead (Pb) in honey from Central, Copperbelt, Luapula, North Western and Northern provinces of Zambia.

3.2. Multivariate analysis

Principal coordinate analysis (PCO) based on a resemblance matrix of normalized data revealed notable dissimilarities in heavy metal concentrations among provinces. PERMANOVA confirmed significant differences among these groups (p(perm) < 0.001; Pseudo-$F = 2550$). Pairwise comparisons indicated that the heavy metal assemblages in Luapula and Copperbelt provinces differed from those in other regions, whereas Central, Northern, and North-Western provinces exhibited similar assemblage patterns. The first two PCO axes explained 95.5% of the total variation ($PCO_1 = 82.9\%$, $PCO_2 = 12.6\%$), highlighting major trends in the dataset (Figure 3).

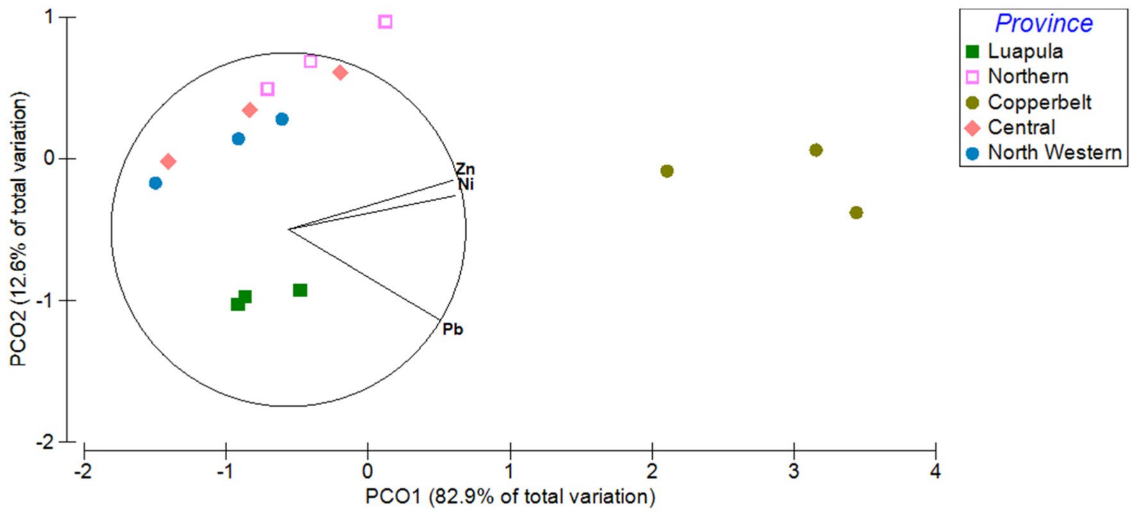

Figure 3. Principal coordinate analysis (PCO) based on a resemblance matrix of normalized data.

Table 2. Estimated daily intake (EDI) of Pb, Zn, and Ni through consumption of honey samples collected from five Zambian provinces (Central, Luapula, North-Western, Northern, and Copperbelt) between October 2024 and January 2025, for men, women, and children.

Province	Heavy metal	Men	Women	Children
Copperbelt	Pb	3.21 × 10–4	3.18×10^{-4}	6.30×10^{-4}
	Zn	3.69×10^{-3}	3.66×10^{-3}	7.24×10^{-3}
	Ni	2.64×10^{-4}	2.62×10^{-4}	5.18×10^{-4}
Central	Pb	3.57×10^{-5}	3.54×10^{-5}	7.00×10^{-5}
	Zn	7.21×10^{-4}	7.15×10^{-4}	1.41×10^{-3}
	Ni	1.14×10^{-4}	1.13×10^{-4}	2.24×10^{-4}
North western	Pb	4.29×10^{-5}	4.25×10^{-5}	8.40×10^{-5}
	Zn	1.26×10^{-3}	1.25×10^{-3}	2.48×10^{-3}
	Ni	7.86×10^{-5}	7.78×10^{-5}	1.54×10^{-4}
Northern	Pb	1.43×10^{-5}	1.45×10^{-5}	2.80×10^{-5}
	Zn	2.29×10^{-3}	2.27×10^{-3}	4.49×10^{-3}
	Ni	1.07×10^{-4}	1.06×10^{-4}	2.10×10^{-4}
Luapula	Pb	3.86×10^{-4}	3.82×10^{-4}	7.56×10^{-4}
	Zn	1.21×10^{-3}	1.20×10^{-3}	2.38×10^{-3}
	Ni	6.43×10^{-5}	6.37×10^{-5}	1.26×10^{-4}

3.3. Potential health risks

The consumptions of honey posed no carcinogenic risk to men, women and children based on Estimated Daily Intake (EDI), Chronic Daily Intake (CDI), Target Hazard Quotient (THQ) and Hazard Index (HI) for Pb, Zn, and Ni from all provinces. All EDI values for the heavy metals were below their respective RfDs and WHO permissible limits: 0.1 mg kg $^{-1}$ for Pb, 3 × 10^{-8}kg for Zn, and 5 × 10^{-8}kg for Ni (Table 2). Similarly, the Estimated Weekly Intake (EWI) and Chronic Daily Intake (CDI) values were also below the permissible limits (Table 3). The Target Hazard Quotient (THQ) and Hazard Index (HI) for all assessed groups were below the WHO threshold of 1 (Table 4).

4. Discussion

The study analysed the concentration of three heavy metals in honey produced in five provinces and their public health risks to men, women and children's consumers. The results showed that heavy metal levels in honey varied among provinces suggesting regional differences in concentrations of the heavy and trace metals. The highest concentrations of analyzed metals in Copperbelt Province are consistent with the region's long-standing role as the center of mining and metallurgical activities in Zambia (Sikamo et al., 2016). Large-scale extraction and smelting operations have historically contributed to elevated metal emissions through dust generation, wastewater discharge, and leaching from mine tailings.

Table 3. Estimated weekly intake (EWI) and chronic daily intake (CDI) of heavy metals through consumption of honey samples collected from five Zambian provinces (Central, Luapula, North-Western, Northern, and Copperbelt) between October 2024 and January 2025 for men, women, and children.

Mean EWI (μgg^{-1})			CDI (μg g^{-1})		
Men	Women	Children	Men	Women	Children
9.30×10^{-4}	1.00×10^{-3}	4.40×10^{-3}	3.20×10^{-4}	3.40×10^{-4}	2.94×10^{-3}
1.07×10^{-2}	1.15×10^{-2}	4.99×10^{-2}	3.69×10^{-3}	3.94×10^{-3}	3.38×10^{-2}
7.70×10^{-4}	8.00×10^{-4}	3.60×10^{-3}	2.60×10^{-4}	28×10^{-4}	2.42×10^{-3}
1.00×10^{-4}	1.00×10^{-4}	5.00×10^{-4}	3.57×10^{-5}	3.81×10^{-5}	3.30×10^{-4}
2.09×10^{-3}	2.20×10^{-3}	9.80×10^{-3}	7.20×10^{-4}	7.70×10^{-4}	6.59×10^{-3}
3.30×10^{-4}	4.00×10^{-4}	1.50×10^{-3}	1.10×10^{-4}	1.20×10^{-4}	1.05×10^{-3}
12.00×10^{-4}	1.00×10^{-4}	6.00×10^{-4}	4.27×10^{-5}	4.58×10^{-5}	3.90×10^{-4}
3.67×10^{-3}	3.90×10^{-3}	1.71×10^{-2}	1.26×10^{-3}	1.34×10^{-3}	1.16×10^{-2}
2.30×10^{-4}	3.00×10^{-4}	1.10×10^{-3}	7.85×10^{-5}	8.38×10^{-5}	7.20×10^{-4}
4.15×10^{-5}	4.15×10^{-5}	2.00×10^{-4}	1.43×10^{-5}	1.52×10^{-5}	1.30×10^{-4}
6.65×10^{-3}	7.10×10^{-3}	3.10×10^{-3}	2.29×10^{-3}	2.45×10^{-3}	2.10×10^{-2}
3.10×10^{-4}	3.00×10^{-4}	1.50×10^{-3}	1.10×10^{-4}	1.10×10^{-4}	9.80×10^{-4}
1.12×10^{-3}	1.20×10^{-3}	5.20×10^{-3}	3.90×10^{-4}	4.10×10^{-4}	3.53×10^{-3}
3.52×10^{-3}	3.80×10^{-3}	1.64×10^{-2}	1.21×10^{-3}	1.29×10^{-3}	$1.11\times^{-2}$
1.90×10^{-4}	2.00×10^{-4}	9.00×10^{-4}	6.43×10^{-5}	6.86×10^{-5}	5.90×10^{-4}

Table 4. Target hazard quotient (THQ) and hazard index (HI) of heavy metals in honey samples collected from five Zambian provinces (Central, Luapula, North-Western, Northern, and Copperbelt) between October 2024 and January 2025 for men, women, and children.

THQ			HI		
Men	Women	Children	Men	Women	Children
1.07×10^{-1}	1.14×10^{-1}	9.80×10^{-1}	0.16	0.16	0.19
3.53×10^{-02}	3.46×10^{-2}	7.53×10^{-2}			
1.32×10^{-2}	1.41×10^{-2}	1.26×10^{-2}			
1.19×10^{-2}	1.27×10^{-2}	1.09×10^{-1}	0.67	0.72	0.74
6.56×10^{-1}	6.10×10^{-1}	5.76×10^{-1}			
5.70×10^{-3}	6.10×10^{-3}	5.22×10^{-3}			
1.43×10^{-2}	1.52×10^{-2}	1.31×10^{-1}	0.17	0.97	**0.95**
1.50×10^{-1}	9.45×10^{-1}	7.79×10^{-1}			
3.90×10^{-3}	4.20×10^{-3}	3.59×10^{-2}			
4.80×10^{-3}	5.10×10^{-3}	4.35×10^{-2}	0.26	0.24	0.69
2.45×10^{-1}	2.24×10^{-1}	5.96×10^{-1}			
5.40×10^{-3}	5.70×10^{-3}	4.90×10^{-2}			
1.29×10^{-1}	1.37×10^{-1}	1.51×10^{-1}	0.24	0.32	**0.92**
1.04×10^{-1}	1.78×10^{-1}	7.43×10^{-1}			
3.20×10^{-3}	3.40×10^{-3}	2.94×10^{-2}			

Similar trends have been reported in other studies assessing soil and water contamination in mining-intensive areas of Copperbelt (Igor Azeuda Ndonfack et al., 2025; Kříbek et al., 2023; Dobrinas et al., 2022; Du et al., 2024). The high levels observed in this province underline the persistent impact of legacy contamination and highlight the need for continued monitoring and targeted mitigation strategies like beekeepers establishing apiaries in uncontaminated areas, preferably far from mining or industrial sites, and regularly inspection of hives and equipment for signs of contamination. Moreover, the use of food-grade, non-metallic containers during harvesting, extraction, and storage is also critical and suggested especial that processing and production methods are known to be one of the sources of heavy metal contamination (Ševičienė et al., 2022). Higher levels of Pb in Luapula and Copperbelt may be due to contamination from industrial mining activities (Mulwanda et al., 2025), including vehicular emissions, and possibly the use of contaminated containers during honey harvesting or processing. Hence, it is important to know how honey is harvested and processed in these provinces to ascertain why Pb levels would be higher in the two provinces which are not known for Pb mining.

Likewise, Central Province had moderately higher concentration of Ni and Zn. This may be attributed to small- to medium-scale mining activities and the use of phosphate fertilizers in agricultural areas. Additionally, the province's location along major transportation corridors could contribute to the accumulation of vehicular emissions and industrial dust, leading to gradual soil contamination. Similar sources contributing to elevated Ni and Mn in the environment have also been reported by Bouaroudj et al. (2024) in honey and Simfukwe et al. (2025) in riverine fish.

The low concentration of heavy metals from Luapula and Northern Provinces could be attributed to limited industrial and mining activities in the areas. These findings align with our hypothesis, given that both regions have low levels of industrial activity and are predominantly rural, which constrains anthropogenic effects (Chola, 2024). Although mining operations have expanded in recent years (Zabré et al., 2021), their relative recency and the province's lower population density may explain the lower levels detected. Similarly, the regions have extensive forest and agricultural areas, which may buffer contaminant accumulation through vegetation uptake and soil retention processes. Wang et al. (2024) stated that soils and vegetations acts as ecological buffer against pollutants. Regarding assessment of human health risk, the values of EDI and EWI were below reference dose for daily and weekly exposure for men, women and children suggesting no potential risk for each age group. Among them, the potential risk was higher in children than in adults in some selected heavy metals. Similarly, non-carcinogenic risks of THQ and HI higher in children compared to men and women. This may be due to differences in metabolism and smaller body sizes in children, which lead to higher intake per kilogram of body weight. This agrees with Mohammed et al. (2023), who also found that children are more at risk from dietary exposure because they eat more food in relation to their body weight. Similar results were reported by Mushtaq et al. (2025), who found that children were more sensitive to food contaminants than adults and Ferreira et al. (2023), who found similar age-based risk patterns and stressed the need to keep checking heavy metals in food for children. However, Zhou et al. (2024) suggested that children and body weight in dietary risk assessment from food consumption should be considered.

Although, age- and sex-specific body weights were used, assumptions about uniform consumption patterns and exposure may still introduce some uncertainty in human health risk estimations (Simfukwe et al., 2025).

However, THQ and HI values for each age group were below 1, meaning that the levels of each heavy metal do not cause serious non-cancer health risks. This is in line with Liang et al. (2019), who also found low THQ values in honey samples from China. On the contrary, our findings differ from those of Morariu et al. (2024) in Sudan, who reported hazard index (HI) values above 1 in honey samples, indicating potential health risks to consumers. This variation may be attributed to differences in the geographical locations where the honey was collected Zambia in the current study versus Sudan in the other highlighting the influence of regional environmental and industrial factors. Furthermore, our results disagree with the finding Chebli et al. (2025), who found that the Children had the HI of above 1 in all heavy metal. This difference could be due to changes in pollution levels, types of plants used by bees, and how much industrial activity there is in different regions (Ajibola et al., 2024). The generally lower THQ and HI values in this study may be because beekeeping in Zambia is done in clean areas, with little industrial activity, and possibly due to the way bees and plants naturally reduce contamination. These results support that Zambian honey is safe to eat for all age groups at the current heavy metal levels.

This study had three main limitations. First, honey samples were collected over a relatively short period, which may not capture seasonal variations. Second, the limited number of samples analysed could affect the representativeness of the results. Third, the study focused only on selected heavy metals and did not assess other potential contaminants including pesticides, radioactive substances, microbial agents, polycyclic aromatic hydrocarbons (PAHs), polychlorinated biphenyls (PCBs), antibiotics, microplastics, and mycotoxins that may also pose health risks.

5. Conclusion and recommendation

This study examined the presence and distribution of heavy metals in honey from five provinces of Zambia, revealing significant regional disparities shaped by industrial, agricultural, and environmental factors. The Copperbelt Province, known for its intense mining activity, recorded the highest contamination levels, while Northern and North Western Provinces exhibited the lowest concentrations. Spatial trends confirm that historical mining and industrial activity are the primary drivers of elevated metal levels in honey, as seen particularly in the Copperbelt. Provinces with less industrial development, such as Northern and North Western, showed lower concentrations, underscoring the influence of land use and anthropogenic pressure. However, unexpected findings emerged in Luapula and Northern Provinces which showed the second-highest lead (Pb) concentration, while Northern Province exhibited the second-highest levels of nickel (Ni) and zinc (Zn). These anomalies, despite the predominantly rural and agriculturally driven land use in these areas, suggest possible contributions from localized geological variability or diffuse contamination sources that warrant further investigation. Risk assessment results indicated that children face higher exposure levels relative to adults. Nevertheless, all Target Hazard Quotient (THQ) and Hazard Index (HI) values remained below the thresholds of concern, suggesting minimal health risks at current exposure levels for all age groups. Based on this, we infer that Zambian honey is generally safe for consumption.

Despite these reassuring findings, the presence of heavy metals even at low levels highlights the importance of regular monitoring and the need to implement regular quality control assessments throughout processing and distribution to ensure that contamination risks are mitigated early.

Additionally, further investigation into honey harvesting and processing practices is recommended to minimize contamination risks. Likewise, future research should include a larger sample size, extend the study to other provinces of Zambia, incorporate longer monitoring periods, and assess a wider range of contaminants, such as pesticides. This would provide a more comprehensive understanding of honey quality and safety, particularly in agriculturally intensive provinces, and help ensure effective consumer protection.

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Data availability statement

Data can be made available upon request from the corresponding author.

References

Abdelmonem, B. H., Kamal, L. T., Elbaz, R. M., Khalifa, M. R., & Abdelnaser, A. (2025). From contamination to detection: The growing threat of heavy metals. *Heliyon*, *11*(1), e41713. https://doi.org/10.1016/j.heliyon.2025.e41713

Adugna, E., Hymete, A., Birhanu, G., & Ashenef, A. (2020). Determination of some heavy metals in honey from different regions of Ethiopia. *Cogent Food & Agriculture*, *6*(1), 1764182. https://doi.org/10.1080/23311932.2020.1764182

Ajibola, F. O., Onyeyili, I. N., Adabra, M. S., Obianyo, C. M., Ebubechukwu, D. J., Auwal, A. M., & Justina, E. C. (2024). Adverse health effects of heavy metal pollution in the Enugu area, Southeastern Nigeria. *World Journal of Biology Pharmacy & Health Sciences*, *20*(3), 10–30574. https://doi.org/10.30574/wjbphs.2024.20.3.0974

Alaofe, H., Kohler, L., Taren, D., Mofu, M. J., Chileshe, J., & Kalungwana, N. (2014). *Zambia food consumption and micronutrient status survey report*. National Food and Nutrition Commission.

Albu, A., Bora, F. D., Cucu-Man, S. M., Stoleru, V., Nistor, C. E., Brumă, I. S., & Rusu, O. R. (2025). Assessing honey quality: A focus on some physicochemical parameters of honey from Iasi County (Romania). *Agriculture*, *15*(3), 333. https://doi.org/10.3390/agriculture15030333

Anderson, M. (2008). *PERMANOVA+ for PRIMER: Guide to software and statistical methods*. Primer-E Limited.

Beshaw, T., Demssie, K., & Leka, I. (2022). Levels and health risk assessment of trace metals in honey from different districts of Bench Sheko Zone, Southwest Ethiopia. *Heliyon*, *8*(9), e10535. https://doi.org/10.1016/j.heliyon.2022.e10535

Bogdanov, S., Haldimann, M., Luginbühl, W., & Gallmann, P. (2007). Minerals in honey: Environmental, geographical and botanical aspects. *Journal of Apicultural Research*, *46*(4), 269–275. https://doi.org/10.1080/00218839.2007.11101407

Bouaroudj, S., Bouasla, A., Bouchetat, F., Rebbah, A. C., Bouchareb, N., & Bounamous, A. (2024). Assessment of heavy metals accumulation in food crops irrigated with water of Boumerzoug River (Constantine, northeast of Algeria). *Global Nest Journal*, *27*(2) 06523. https://doi.org/10.30955/gnj.06523

Cempel, M., & Nikel, G. J. P. J. S. (2006). Nickel: A review of its sources and environmental toxicology. *Polish Journal of Environmental Studies*, *15*(3), 375–382.

Chebli, A. I., Zergui, A., Amziane, A., Zebbiche, Y., & Abdennour, S. (2025). Metals in honey, cow's milk and eggs in North-East Algeria and health risk. *Food Additives & Contaminants: Part B, Surveillance*, *18*(1), 55–64. https://doi.org/10.1080/19393210.2024.2414088

Chola, K. (2024). *Rural development through industrialisation: A case study of Mansa Batteries Limited, 1978–1994* [Doctoral dissertation].

Chungu, D., Mwanza, A., Ng'andwe, P., Chungu, B. C., & Maseka, K. (2019). Variation of heavy metal contamination between mushroom species in the Copperbelt Province, Zambia: Are the people at risk? *Journal of the Science of Food & Agriculture*, *99*(7), 3410–3416. https://doi.org/10.1002/jsfa.9558

Clarke, K. R., & Gorley, R. N. (2015). **PRIMER v7: User manual/tutorial*.

da Silva, B. T. S., Lopes, M. D C., Cruz, A. D S., Borges, C. M., Batista, C. V., Carvalho, F. I. M., Venturieri, G. C., Dantas Filho, H. A., & Fernandes Dantas, K. G. (2025). Determination and human health risk assessment of mercury in honey from the Brazilian eastern Amazon. *Toxicology Reports*, *14*, 101981. https://doi.org/10.1016/j.toxrep.2025.101981

Das, S., Sultana, K. W., Ndhlala, A. R., Mondal, M., & Chandra, I. (2023). Heavy metal pollution in the environment and its impact on health: Exploring green technology for remediation. *Environmental Health Insights*, *17*, 11786302231201259. https://doi.org/10.1177/11786302231201259

Dehkordi, M. M., Nodeh, Z. P., Dehkordi, K. S., Khorjestan, R. R., & Ghaffarzadeh, M. (2024). Soil, air, and water pollution from mining and industrial activities: Sources of pollution, environmental impacts, and prevention and control methods. *Results in Engineering*, *23*, 102729. https://doi.org/10.1016/j.rineng.2024.102729

Dobrinas, S., Soceanu, A., Birghila, S., Birghila, C., Matei, N., Popescu, V., & Constanda, L. M. (2022). Chemical analysis and quality assessment of honey obtained from different sources. *Processes*, *10*(12), 2554. https://doi.org/10.3390/pr10122554

Du, Y., Tian, Z., Zhao, Y., Wang, X., Ma, Z., & Yu, C. (2024). Exploring the accumulation capacity of dominant plants based on soil heavy metals forms and assessing heavy metals contamination characteristics near gold tailings ponds. *Journal of Environmental Management*, *351*, 119838. https://doi.org/10.1016/j.jenvman.2023.119838

Ferreira, S. L., Cerda, V., Cunha, F. A., Lemos, V. A., Teixeira, L. S., dos Santos, W. N., Coutinho, J. D., Porto, I. S. D. A., & de Jesus, R. F. (2023). Application of human health risk indices in assessing contamination from chemical elements in food samples. *TrAC Trends in Analytical Chemistry*, *167*, 117281. https://doi.org/10.1016/j.trac.2023.117281

Gashaw, W., Yohannes, W., Chandravanshi, B. S., & Getachew, N. (2024). Levels of heavy metals and physicochemical properties of honey from four selected areas of Ethiopia. *Bulletin of the Chemical Society of Ethiopia*, *38*(6), 1521–1531. https://doi.org/10.4314/bcse.v38i6.2

Godebo, T. R., Stoner, H., Taylor, P., & Jeuland, M. (2025). Metals in honey from bees as a proxy for environmental contamination in the United States. *Environmental Pollution (Barking, Essex: 1987)*, *364*(Pt 2), 125221. https://doi.org/10.1016/j.envpol.2024.125221

Hasimuna, O. J., Chibesa, M., Ellender, B. R., & Maulu, S. (2021). Variability of selected heavy metals in surface sediments and ecological risks in the Solwezi and Kifubwa Rivers, Northwestern Province, Zambia. *Scientific African*, *12*, e00822. https://doi.org/10.1016/j.sciaf.2021.e00822

Hasimuna, O. J., Chibesa, M., Mumbula, I., Mphande, J., Jere, W. W. L., Phiri, D., Nawanzi, K., Siavwapa, S., Maseko, A. F., Munganga, B. P., Nchima, G., Khalil, H. S., & Maulu, S. (2023). Contamination of selected heavy metals in Limnothrissa miodon (Boulenger, 1906) in the four strata of Lake Kariba, Zambia: Are the consumers at risk? *Journal of Environmental Science & Health. Part B, Pesticides, Food Contaminants, & Agricultural Wastes*, *58*(7), 521–529. https://doi.org/10.1080/03601234.2023.2235262

Hasimuna, O. J., Gweon, H. S., & Yang, H. (2025a). Heavy metal contamination and ecological risk in Kabompo River, Northwestern Zambia. *Environmental Pollutants & Bioavailability*, *37*(1), 2549084. https://doi.org/10.1080/26395940.2025.2549084

Hasimuna, O. J., Jere, W. W., Mtethiwa, A. H., Yabe, J., Chibesa, M., Mphande, J., Mumbula, I., Phiri, C. J., Siavwapa, S., Nawanzi, K., & Simfukwe, K. (2024). Assessment of trace elements (Cu, Fe, and Zn) in Limnothrissa miodon from Lake Kariba, Zambia: Implications for ecological and human health. *Journal of Applied Animal Research*, *52*(1), 2310753. https://doi.org/10.1080/09712119.2024.2310753

Hasimuna, O. J., Jere, W., Mtethiwa, A., Chibesa, M., Mphande, J., Mumbula, I., & Yabe, J. (2025b). Human health risk assessment of cadmium (Cd) and lead (Pb) exposure in limnothrissa miodon fish from the four strata of Lake Kariba, Zambia. *Cogent Food & Agriculture*, *11*(1), 2586830. https://doi.org/10.1080/23311932.2025.2586830

Hasimuna, O. J., Maulu, S., & Chibesa, M. (2022). Assessment of heavy metal contamination in water and largescale yellowfish (Labeobarbus marequensis, Smith 1841) from Solwezi River, North-Western Zambia. *Cogent Food & Agriculture*, *8*(1), 2121198. https://doi.org/10.1080/23311932.2022.2121198

Igor Azeuda Ndonfack, K., Yang, Z., Zhang, J., Whattam, S. A., & Xie, Y. (2025). Geology, geochemistry, and exploration of the Central African Copperbelt: A review. *International Geology Review*, *67*(8), 1098–1131. https://doi.org/10.1080/00206814.2024.2426200

Jin, M., Yuan, H., Liu, B., Peng, J., Xu, L., & Yang, D. (2020). Review of the distribution and detection methods of heavy metals in the environment. *Analytical Methods: Advancing Methods & Applications*, *12*(48), 5747–5766. https://doi.org/10.1039/D0AY01577F

Kaur, K., Arora, P., & Gupta, G. (2024). Contaminants in honey: Safeguarding quality and consumer health. *Uttar Pradesh Journal of Zoology*, *45*(17), 186–199. https://doi.org/10.56557/upjoz/2024/v45i174361

Kebede, I. A., Gebremeskel, H. F., Ahmed, A. D., & Dule, G. (2024). Bee products and their processing: A review. *Pharmacy & Pharmacology International Journal*, *12*(1), 5–12. https://doi.org/10.15406/ppij.2024.12.00425

Komasilova, O., Komasilovs, V., Kviesis, A., & Zacepins, A. (2021). Model for finding the number of honey bee colonies needed for the optimal foraging process in a specific geographical location. *Peer J.*, *9*, e12178. https://doi.org/10.7717/peerj.12178

Křížbek, B., Nyambe, I., Sracek, O., Mihaljevič, M., & Knésl, I. (2023). Impact of mining and ore processing on soil, drainage, and vegetation in the Zambian Copperbelt mining districts: A review. *Minerals*, *13*(3), 384. https://doi.org/10.3390/min13030384

Kumar, A., Singh, D. K., Singh, S., Kumar, V., & Pandey, R. S. (2023). Toxicology of heavy metals in fish: A review on accumulation, biomarker responses, and remedial strategies. *Environmental Toxicology & Pharmacology*, *106*, 104204. https://doi.org/10.1016/j.etap.2023.104204

Lemessa, F., Simane, B., Seyoum, A., & Gebresenbet, G. (2022). Analysis of the concentration of heavy metals in soil, vegetables and water around the Bole Lemi industry park, Ethiopia. *Heliyon*, *8*(12), e12429. https://doi.org/10.1016/j.heliyon.2022.e12429

Liang, G., Gong, W., Li, B., Zuo, J., Pan, L., & Liu, X. (2019). Analysis of heavy metals in foodstuffs and an assessment of the health risks to the general public via consumption in Beijing, China. *International Journal of Environmental Research & Public Health*, *16*(6), 909. https://doi.org/10.3390/ijerph16060909

Liu, H., Wang, Y., Wu, J., Zhang, C., & Li, B. (2024). Assessment of heavy metal pollution and ecological risk in agricultural soils surrounding mining areas in China. *Environmental Science & Pollution Research*, *31*(14), 16984–16999. https://doi.org/10.1007/s11356-023-31654-1

Lombe, A., & Katete, R. S. (2024). Lead remediation techniques: Lessons for sustainable remediation of lead-contaminated sites in Zambia's mining towns. EQA – International Journal of Environmental Quality, *59*, 13–21. https://doi.org/10.6092/issn.2281-4485/17928

Lowore, J. (2021). *Forest beekeeping in Zambia: Analysing the nexus of sustainable forest management and commercial honey trade* [Doctoral dissertation]. http://eprints.hud.ac.uk/id/eprint/35520

Mbewe, G., Mutondo, M., Maseka, K., & Sichilongo, K. (2016). Assessment of heavy-metal pollution in sediments and tilapia fish species in Kafue River of Zambia. *Archives of Environmental Contamination & Toxicology*, *71*(3), 383–393. https://doi.org/10.1007/s00244-016-0295-3

Meaton, J., Lowore, J., & Wood, A. (2021). Assessing value chain interventions in Zambian and Ethiopian forest beekeeping systems. *Business Strategy & Development*, *4*(2), 159–169. https://doi.org/10.1002/bsd2.136

Mehri, A. (2020). Trace elements in human nutrition (II): An update. *International Journal of Preventive Medicine*, *11*(1), 2. https://doi.org/10.4103/ijpvm.IJPVM_48_19

Mitsunaga, A., & Yamauchi, T. (2020). Evaluation of the nutritional status of rural children living in Zambia. *Journal of Physiological Anthropology*, *39*(1), 34. https://doi.org/10.1080/09603123.2023.2229750

Miyanza, F., Ramalepe, T., Monyai, M., Chaúque, E., Nyambe, I., & Chimuka, L. (2024). Determination and risk assessment of heavy metals in raw foodstuffs sold from open markets in Zambia: A comparison of Kabwe, Kitwe, and Lusaka towns. *International Journal of Environmental Health Research*, *34*(3), 1566–1579. https://doi.org/10.1080/09603123.2023.2229750

Mohamed, O. E., El-Shazly, M. M., Hashish, M. E., & Soliman, M. M. (2024). The impacts of cadmium, an environmental pollutant, on honeybees (Apis mellifera, Hymenoptera: Apidae): A review. *Egyptian Journal of Chemistry*, *67*(11), 543–570. https://doi.org/10.21608/ejchem.2024.272472.9384

Mohammed, S. E. A., Dafalla, A. O., El-Niweiri, M., & El Ghazali, G. E. (2023). Comparison of the melissopalynological, antimicrobial, and organoleptic composition of honey samples from *Apis mellifera* L. and *Apis florea* Gaertn. in Sudan. *Grana*, *62*(5–6), 342–351. https://doi.org/10.1080/00173134.2024.2311865

Morariu, I.-D., Avasilcai, L., Vieriu, M., Lupu, V. V., Ioniuc, I., Morariu, B.-A., Lupu, A., Morariu, P.-C., Pop, O.-L., Burduloi, V. M., Starcea, I. M., & Trandafir, L. (2024). A comprehensive narrative review on the hazards of bee honey adulteration and contamination. *Journal of Food Quality*, *2024*(1), 1–13. https://doi.org/10.1155/2024/3512676

Mphande, J., & Chama, L. (2015). Preservation methods and storage period affect the mineral and moisture composition of freshwater fish species. *International Journal of Food Science & Nutrition Engineering*, *5*(3), 147–153. https://doi.org/10.5923/j.food.20150503.06

Mulwanda, C., Namukonde, N., & Nyirenda, V. R. (2025). Effects of heavy metals on insect pollinator diversity in Zambia's Mufulira District mining area. *African Journal of Ecology*, *63*(3), e70052. https://doi.org/10.1111/aje.70052

Mushtaq, A., Khalid, S., Noor, M. J., & Khanoranga (2025). Honey bee products as bioindicator of heavy metals pollution and health risk assessment through the consumption of multifloral honey collected in Azad Kashmir, Pakistan. *Biological Trace Element Research*, *203*(4), 2099–2113. https://doi.org/10.1007/s12011-024-04313-2

Mwalea, N., & Mbewe, G. (2017). Analysis of heavy metals and physicochemical properties in honey along the Ndola-Lusaka Road, Zambia. *International Journal of Multi-Disciplinary Research*, *2, 3471-7102* http://www.ijmdr.net/

Mwilola, P. N., Mukumbuta, I., Shitumbanuma, V., Chishala, B. H., Uchida, Y., Nakata, H., Nakayama, S., & Ishizuka, M. (2020). Lead, zinc and cadmium accumulation and associated health risks in maize grown near the Kabwe mine in Zambia. *International Journal of Environmental Research & Public Health*, *17*(23), 9038. https://doi.org/10.3390/ijerph17239038

Nyau, V., Mwanza, E. P., & Moonga, H. B. (2013). Physico-chemical qualities of honey harvested from different beehive types in Zambia. *African Journal of Food, Agriculture, Nutrition & Development*, *13*(2), 1684–5358. https://doi.org/10.18697/ajfand.57.10730

Palma-Morales, M., Huertas, J. R., & Rodríguez-Pérez, C. (2023). A comprehensive review of the effect of honey on human health. *Nutrients*, *15*(13), 3056. https://doi.org/10.3390/nu15133056

Phiri, B. J., Fèvre, D., & Hidano, A. (2022). Uptrend in global managed honeybee colonies and production based on a six-decade viewpoint (1961–2017). *Scientific Reports*, *12*(1), 21298. https://doi.org/10.1038/s41598-022-25290-3

Qamar, W., & Rehman, M. U. (2020). Brief history and traditional uses of honey. In *Therapeutic applications of honey and its phytochemicals* (Vol. 1, pp. 1–10). Springer. https://doi.org/10.1007/978-981-15-6799-5_1

R Core Team (2024). *RStudio: Integrated development for R (Version 12.1 + 563) [Software]*. RStudio PBC https://posit.co/download/rstudio-desktop/

Samuel, A. T., Akinyemi, F. A., Kolawole, S. A., & Ngor, J. T. (2024). Heavy metal contaminants in honey and dry-cured meat sold in Northern Nigeria markets. *Food Science & Engineering*, *5*(1), 99–111. http://ojs.wiserpub.com/index.php/FSE/ https://doi.org/10.37256/fse.5120243612

Šerevičienė, V., Zigmontienė, A., & Paliulis, D. (2022). Heavy metals in honey collected from contaminated locations: A case of Lithuania. *Sustainability*, *14*(15), 9196. https://doi.org/10.3390/su14159196

Siame, T., Muzandu, K., Mulenga, K. K., & Dzombe, C. B. (2025). Lead-contaminated groundwater exposes residents to health risks in Makululu, Zambia. *Journal of Water & Health*, *23*(5), 615–629. https://doi.org/10.2166/wh.2025.343

Sihoka, C., Wagenaar, I., & Van Dyk, C. (2024). Metal bioaccumulation and histological alterations in Oreochromis andersonii at Itezhi-tezhi Dam downstream of a mining area in the Central Province of Zambia. *Environmental Toxicology and Pharmacology*, *107*, 104394.https://doi.org/10.1016/j.etap.2024.104394

Sikamo, J., Mwanza, A., & Mweemba, C. (2016). Copper mining in Zambia: History and future. *Journal of the Southern African Institute of Mining & Metallurgy*, *116*(6), 491–496. https://doi.org/10.17159/2411-9717/2016/v116n6a1

Simfukwe, K., Jere, W. W., & Msukwa, A. V. (2025). Heavy metal contamination in riverine fish from the Lilongwe River, Malawi: Implications for human health risk. *Environmental Pollution & Management*, *2*, 163–171. https://doi.org/10.1016/j.epm.2025.06.003

Simfukwe, K., Msukwa, A. V., Mphande, J., Hasimuna, O. J., Limuwa, M. M., & Kaunda, E. (2024). Is the concentration of heavy metals in sun-dried Engraulicypris sardella in Malawi a human health risk? *Environmental Chemistry & Ecotoxicology*, *6*, 354–362. https://doi.org/10.1016/j.enceco.2024.08.002

Sonmez Oskay, G., Uygur, G. S., Oskay, D., & Arda, N. (2025). Impact of stress factors internal and external to the hive on honey bees and their reflection on honey bee products: A review. *Journal of Apicultural Research*, *64*(1), 226–241. https://doi.org/10.1080/00218839.2023.2247840

Tahboub, Y. R., Al-Ghzawi, A. A. M. A., Al-Zayafdneh, S. S., & AlGhotani, M. S. (2022). Levels of trace elements and rare earth elements in honey from Jordan. *Environmental Science & Pollution Research International*, *29*(8), 11469–11480. https://doi.org/10.1007/s11356-021-16460-3

Thermo Fisher Scientific. (2015). Sample preparation techniques for AAS, ICP-OES, and ICP-MS for regulated testing laboratories (Technical Note TN44483). Thermo Fisher *Scientific*. https://assets.thermofisher.com/TFS-Assets/CMD/Technical-Notes/tn-44483-aas-icp-oes-icp-ms-sample-prep-regulated-test-tn44483-en.pdf

Tibebe, D., Hussen, M., Mulugeta, M., Yenealem, D., Moges, Z., Gedefaw, M., & Kassa, Y. (2022). Assessment of selected heavy metals in honey samples using FAAS in Ethiopia. *BMC Chemistry*, *16*(1), 87. https://doi.org/10.1186/s13065-022-00878-y

Tolkou, A. K., Toubanaki, D. K., & Kyzas, G. Z. (2023). Detection of arsenic, chromium, cadmium, lead, and mercury in fish: Effects on sustainable and healthy development of aquatic life and human consumers. *Sustainability*, *15*(23), 16242. https://doi.org/10.3390/su152316242

Tuzen, M., Silici, S., Mendil, D., & Soylak, M. (2007). Trace element levels in honeys from different regions of Turkey. *Food Chemistry*, *103*(2), 325–330. https://doi.org/10.1016/j.foodchem.2006.07.053

Vanisree, C. R., Sankhla, M. S., Singh, P., Jadhav, E. B., Verma, R. K., Awasthi, K. K., Awasthi, G., & Nagar, V. (2022). Heavy metal contamination of food crops: Transportation via food chain, human consumption, toxicity, and management strategies. In *Environmental impact and remediation of heavy metals*. IntechOpen. https://doi.org/10.5772/intechopen.101938

Viktória, V., & Aliz, F. F. (2023). Trends in honey consumption and purchasing habits in some European countries. *Applied Studies in Agribusiness & Commerce*, *17*, 1–18. https://doi.org/10.19041/APSTRACT/2023/1/6

Wang, D., Gao, X., Wu, S., Zhao, M., Zheng, X., Wang, Z., Zhang, Y., & Fan, C. (2024). A comprehensive review on ecological buffer zones for pollutants removal. *Water*, *16*(15), 2172. https://doi.org/10.3390/w16152172

Wise, J. P.Jr., Wise, R. M., Hoffert, A., Wise, J. T., & Specht, A. J. (2025). Elevated metal levels in US honeys: Is there a concern for human health*? Biological Trace Element Research*, *203*(4), 1789–1797. https://doi.org/10.1007/s12011-024-04295-1

Wu, Y., Li, X., Yu, L., Wang, T., Wang, J., & Liu, T. (2022). Review of soil heavy metal pollution in China: Spatial distribution, primary sources, and remediation alternatives. *Resources, Conservation & Recycling*, *181*, 106261. https://doi.org/10.1016/j.resconrec.2022.106261

Zabré, H. R., Farnham, A., Diagbouga, S. P., Fink, G., Divall, M. J., Winkler, M. S., & Knoblauch, A. M. (2021). Changes in household wealth near a large-scale copper mine in Zambia. *Resources Policy*, *74*, 102395. https://doi.org/10.1016/j.resourpol.2021.102395

Zhou, L. Q., Wang, H., Fang, J., & Li, Z. (2024). Assessment of ecological risks of heavy metals in urban soils: A case study from central China. *Environmental Monitoring & Assessment*, *196*(4), 253. https://doi.org/10.1007/s10661-024-11176-9