Disentangling legacy and ongoing industrial metal pollution using honey as a bioindicator in Kosovo

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ABSTRACT

Environmental contamination by heavy metals remains a persistent ecological concern in regions with a history of mining and metallurgical activity. In Kosovo, historical Pb-Zn-Cd smelting in the Mitrovica region and ongoing ferronickel production in Drenas provide a relevant framework for distinguishing between legacy and active sources of metal pressure. Although primary lead production ceased in 2000, legacy contamination may persist in soils and enter the food chain. This study investigated the spatial distribution of Pb, Cd, Zn, Ni, and Cu in honey samples (n = 24) collected from different local sampling points in industrial, rural, and mountainous regions of Kosovo. Element concentrations were determined using ICP-MS in an ISO/IEC 17025 accredited laboratory, and statistical evaluation was performed using Welch's robust ANOVA followed by Games-Howell post-hoc comparisons. Significant spatial differences were observed for Pb and Ni (p < 0.001) and for Cd (p < 0.001 in Welch's robust test), whereas Zn and Cu did not differ significantly among zones. Elevated Pb concentrations near historically industrialized areas indicate the persistence of legacy contamination, whereas the distribution of Ni reflects the combined influence of ongoing industrial activity and local environmental variability. All measured concentrations remained below the current European Union maximum level established for Pb in honey. The results demonstrate that honey can effectively differentiate between legacy contamination associated with historical Pb-Zn smelting and ongoing industrial metal emissions from ferronickel production. This study provides the first spatially resolved assessment of heavy metal pressure in Kosovo using honey as a bioindicator, contributing to regional environmental monitoring and food safety evaluation.

Keywords: honey, heavy metals, bioindicator, post-industrial contamination, Kosovo.

INTRODUCTION

Environmental contamination by heavy metals represents a persistent ecological and public health challenge, particularly in regions with a long history of mining and metallurgical activity [Šerevičienė et al., 2022; Kelmendi et al., 2018]. Trace metals such as lead (Pb), cadmium (Cd), zinc (Zn), nickel (Ni), and copper (Cu) can accumulate in soils, sediments, and vegetation and may remain in the environment for decades due to their persistence and limited biodegradability. As a result, these elements can enter terrestrial food chains and pose long-term risks to ecosystems and human health through bioaccumulation and chronic exposure. In Kosovo, the Mitrovica and Drenas areas have been historically associated with intensive extraction and processing of Pb, Zn, and Cd, primarily through the activities of the Trepça mining and smelting complex [Kelmendi et al., 2018]. The lead smelter operating near Zveçan functioned until 2000, when its activity was suspended due to critically elevated blood lead levels detected in children living in the surrounding area. Although industrial production of Pb, Cd, and Zn has ceased since then, large quantities of metallurgical waste and contaminated tailings remain deposited in soils, representing a long-term environmental burden [Kelmendi et al., 2023]. Such legacy contamination is known to persist in terrestrial ecosystems long after industrial activity has ceased, particularly in post-smelting

environments where contaminated dust, tailings, and soil particles continue to influence surrounding vegetation and agricultural land.

Previous investigations in the Bajgora agricultural region have confirmed elevated heavy metal concentrations in soils resulting from decades of metallurgical emissions, indicating that contamination persists long after industrial activity has stopped [Kelmendi et al., 2023]. Similarly, assessments of the Sitnica River, which drains major industrial zones, have reported poor ecological status due to physicochemical pollution and metal discharge from mining and energy production sites [Kelmendi and Aliu, 2023]. In contrast, Ni production continues in Drenas through ferronickel industry, representing an active source of potential environmental exposure. The coexistence of legacy contamination from historical Pb-Zn-Cd metallurgy and ongoing industrial emissions associated with ferronickel production creates a complex environmental setting in Kosovo, making it a particularly relevant case for investigating how different metal pressures may be reflected in biological monitoring matrices. Previous studies in Kosovo have also shown that environmental conditions in industrial areas such as Drenas and Kastriot are reflected in the trace-element composition of bee products, supporting the use of honey in regional biomonitoring studies [Aliu et al., 2020]. A recent study from Kosovo also reported heavy metals in honey samples from Istog, Drenas, and Kastriot, further supporting the use of honey as a regional bioindicator [Demaku et al., 2023]. In addition, studies on bee products from other regions have shown that honey generally contains lower concentrations of heavy metals than wax, pollen, and propolis, while still remaining a useful and practical matrix for pollution monitoring [Formicki et al., 2013].

Honey bees (*Apis mellifera*) are widely recognized as effective bioindicators of environmental quality because their foraging activity integrates exposure from air, soil, water, and vegetation within a radius of several kilometers [Bogdanov, 2016; Stankovska et al., 2008]. During nectar and pollen collection, bees accumulate atmospheric particles and trace elements, allowing honey to reflect local contamination patterns [Bogdanov, 2016]. Numerous studies have demonstrated that concentrations of Pb, Cd, Zn, and Ni in honey may serve as proxies for regional environmental pollution [Godebo et al., 2025; Šerevičienė et al., 2022]. Honey is increasingly considered a

low-cost biomonitoring tool because bees integrate environmental contamination over their foraging range, allowing the matrix to reflect average local pollution levels [Passarella et al., 2026].

In addition, variations in trace metal concentrations in honey have been linked not only to industrial emissions but also to geological background, botanical origin, and local environmental conditions [Pohl, 2009; Moujanni et al., 2017]. The selected metals (Pb, Cd, Zn, Ni, and Cu) were chosen because they represent the most environmentally relevant trace elements associated with historical and ongoing industrial activity in Kosovo. Pb, Cd, and Zn are strongly linked to the legacy of mining and smelting in the Mitrovica region, whereas Ni reflects the influence of current ferronickel production in Drenas. Cu was included as an additional essential trace element to enable comparison between potentially toxic metals and a metal influenced by both natural and anthropogenic sources.

Despite previous environmental studies conducted in Kosovo, systematic comparative investigations integrating industrial, rural, and mountainous environments within a unified statistical framework remain limited. Although heavy metals have been reported in environmental matrices and bee products from Kosovo, a statistically supported comparison among industrial, rural, and mountainous zones using independent local sampling points has not been clearly established. In particular, the extent to which honey can distinguish between legacy contamination from historical Pb-Zn-Cd metallurgy and ongoing Ni-related industrial pressure has not been adequately evaluated. This gap is important because post-industrial regions may continue to influence food products long after primary production has ceased, while active industrial sources may create different contamination patterns that require separate interpretation [Kelmendi et al., 2023; Kelmendi and Aliu, 2023].

We hypothesized that honey collected from industrially influenced areas would show distinguishable heavy metal patterns compared with honey from rural and mountainous environments, reflecting differences between historical and ongoing sources of contamination. Therefore, the aim of this study was to evaluate the concentrations of Pb, Cd, Zn, Ni, and Cu in honey samples collected from industrial, rural, and high-altitude areas of Kosovo and to assess their spatial distribution in order to examine the persistence of

legacy contamination and the suitability of honey as a bioindicator of environmental metal pollution. More specifically, the study was designed to test whether honey can serve not only as a general indicator of environmental contamination, but also as a bioindicator capable of differentiating between legacy and ongoing heavy metal pressure in Kosovo.

MATERIALS AND METHODS

Study Area and Sampling Design

The study was conducted in the Republic of Kosovo, where honey samples were collected from 24 different local sampling points representing areas with different environmental exposure levels. The sampling design included three categories: industrial zones (n = 8), rural areas surrounding these industrial zones (n = 8), and a high-altitude mountainous region considered as a background environment (n = 8). The sample size was determined based on field accessibility, availability of locally produced honey, and the need to ensure spatial coverage of areas with contrasting environmental exposure.

Industrial samples were obtained from villages/localities located in the vicinity of historically industrialized municipalities of Mitrovica and Drenas, regions characterized by long-term mining, metallurgical, and energy production activities associated primarily with lead, zinc, cadmium, and nickel processing. Rural samples were collected from agricultural areas surrounding these municipalities, representing zones with limited direct industrial influence. Mountain samples were obtained from villages/localities located in the high-altitude region of Peja, representing a relatively low anthropogenic impact environment. This sampling design was intended to compare honey metal profiles among zones affected by historical metallurgical activity, ongoing industrial emissions, and relatively low-impact background conditions. In this way, the three-zone structure provided a framework for testing whether honey can differentiate between legacy contamination and current metal pressure in environmentally contrasting areas of Kosovo.

The selection of industrial and rural locations was based on their contrasting environmental exposure patterns and on previous regional studies that identified these areas as relevant for assessing metal contamination in environmental and biological matrices [Aliu et al., 2020; Kelmendi et al., 2023]. Sampling sites were selected according to known villages and beekeeping locations within the industrial, rural, and mountainous study zones. Honey was collected from private households and local apiaries in each selected location. The coordinates of the sampling sites were obtained using Google Earth Pro based on the identified villages and apiary locations. These coordinates were then transferred to QGIS 3.40 for spatial visualization and preparation of the sampling map shown in Figure 1. Elevation was considered in the study design because altitude may influence environmental metal deposition, vegetation types, and the foraging behavior of honey bees, potentially affecting trace metal concentrations in honey.

Honey samples were obtained from local residents or beekeepers in the selected villages and were provided in glass jars, which represent the common traditional storage form for honey in Kosovo. Approximately 500 g of honey was collected from each location, and the 24 samples were gathered within a 10-day field period. After collection, the samples were delivered to the responsible person for preparation and shipment to the accredited laboratory in Bulgaria. For laboratory purposes, 250 g of each sample was used for analysis, while the remaining portion was retained. According to the information provided by the local beekeepers, the sampled honey originated from the 2025 production season, although the exact storage duration of individual samples was not independently verified.

Each sampling point was treated as an independent observational unit for the purposes of statistical comparison among zones. Independent local sampling points were intentionally selected in order to avoid pseudo-replication and to ensure that each honey sample represented a separate sampling unit for subsequent statistical analysis.

The geographical coordinates and altitudes of the sampling stations are presented in Table 1 and Figure 1.

Sample preparation and digestion

The honey samples were transported under controlled conditions to the ISO/IEC 17025:2018 accredited laboratory, Alimenti-Omnilab (D &V Consult JSC), in Plovdiv, Bulgaria. For the determination of trace elements, approximately 0.5 g of

Table 1. Description of the sampling sites, coordinates, and altitude

| Sample ID	Location	Latitude (N)	Longitude (E)	Altitude (m)	Zone
M1	Mitrovica – near industrial waste dump	42°54′11.65″	20°52′17.57″	504	Industrial
M2	Rudar	42°54′37.24″	20°51′36.08″	538	Industrial
M3	Zveçan	42°54′44.11″	20°50′6.66″	526	Industrial
M4	Zhitkovci	42°55′32.27″	20°49′19.20″	508	Industrial
M5	Zhazhë	42°56′43.26″	20°51′55.87″	754	Rural
M6	Rahovë	42°56′12.86″	20°53′54.46″	829	Rural
M7	Dedi	42°59′30.72″	20°54′16.89″	855	Rural
M8	Bajgorë	42°57′23.90″	20°59′27.38″	1125	Rural
M9	Drenas – near industrial waste dump	42°38′12.15″	20°54′6.33″	588	Industrial
M10	Çikatovë	42°39′14.44″	20°53′41.13″	640	Industrial
M11	Bletar	42°38′52.09″	20°52′12.64″	608	Industrial
M12	Krojkovë	42°36′5.70″	20°51′7.94″	647	Industrial
M13	Kishnarekë	42°33′1.53″	20°53′5.30″	638	Rural
M14	Likoc	42°40′0.37″	20°45′36.23″	766	Rural
M15	Makermal	42°40′57.91″	20°48′35.15″	634	Rural
M16	Izbica	42°45′18.14″	20°39′16.28″	667	Rural
M17	Loxhë	42°37′52.42″	20°19′34.14″	498	Mountain
M18	Vitomiricë	42°41′28.67″	20°19′23.73″	521	Mountain
M19	Novosellë	42°43′42.50″	20°20′5.32″	496	Mountain
M20	Ozdrim	42°42′5.16″	20°22′54.11″	462	Mountain
M21	Bogë	42°44′22.67″	20°3′25.60″	1380	Mountain
M22	Koshutani	42°44′14.28″	20°5′41.60″	1510	Mountain
M23	Kuqishtë	42°41′29.54″	20°4′22.71″	1216	Mountain
M24	Drelaj	42°42′8.95″	20°7′25.83″	1055	Mountain
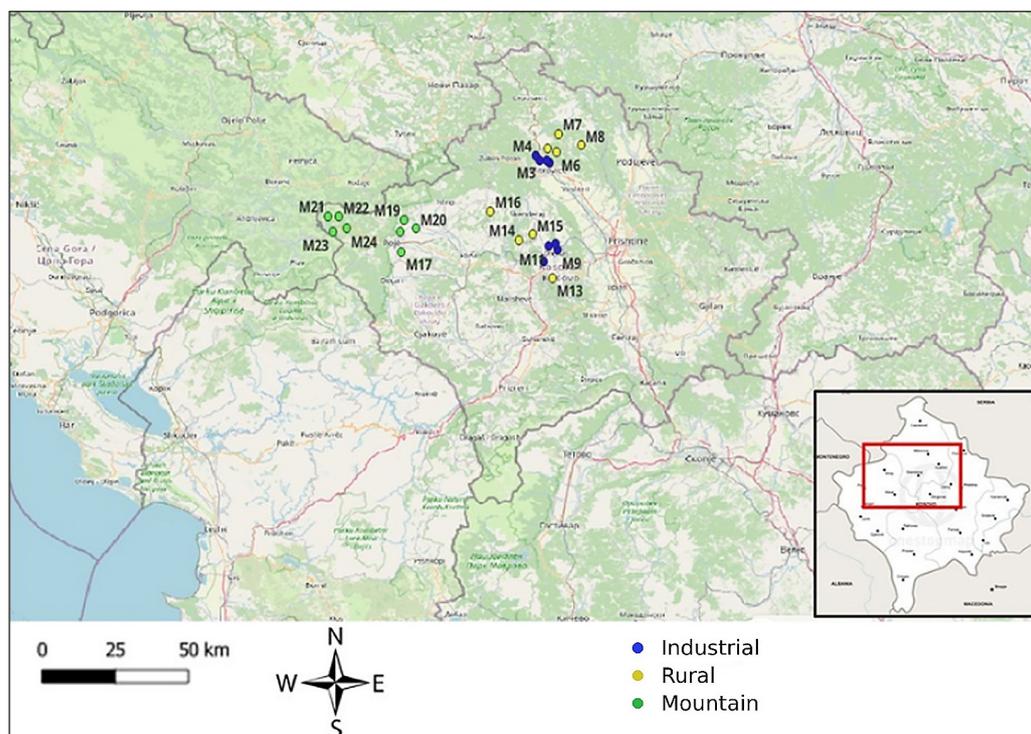
Figure 1. Geographic distribution of honey sampling sites across industrial, rural and mountainous zones in Kosovo

each homogenized honey sample was accurately weighed and digested using ultra-pure concentrated nitric acid (HNO_3) and hydrogen peroxide (H_2O_2) in a closed-vessel microwave digestion system (Milestone ETHOS X, Milestone Srl, Italy). The digestion was performed under controlled temperature and pressure according to the manufacturer's protocol and the requirements of the BDS EN 15763:2010 and VLM-IM-ICP/MS-05:2015 methods to ensure complete mineralization of the organic matrix.

ICP-MS analysis and quality control – the concentrations of trace metals (Pb, Cd, Zn, Ni, Cu, and Cr) were determined using an inductively coupled plasma mass spectrometer (ICP-MS, Agilent 7900, Agilent Technologies, USA). The instrument was operated in standard mode using helium collision gas to minimize polyatomic interferences. The monitored isotopes included ^{206}Pb, ^{208}Pb, ^{111}Cd, ^{66}Zn, ^{60}Ni, and ^{63}Cu. Instrumental parameters were optimized with an RF power of 1550 W, plasma gas flow of 15 L/min, auxiliary gas flow of 1.0 L/min, and nebulizer gas flow of 1.05 L/min.

Quality control procedures included the use of procedural blanks, calibration verification standards, and spiked recovery samples. The analysis for Pb and Cd followed the BDS EN 15763:2010 standard, while Cu, Ni, Zn, and Cr were analyzed using the validated laboratory method VLM-IM-ICP/MS-05:2015. The limit of quantification (LOQ) for Cr was established at 0.02 mg/kg. Recovery rates for the analyzed elements ranged from 95% to 105%, and the relative standard deviations (RSD) for triplicate measurements were below 5%. All concentrations are reported in mg/kg on a fresh weight basis.

Statistical analysis

All statistical analyses were performed using IBM SPSS Statistics (version 26.0, IBM Corp., Armonk, NY, USA). Metal concentrations were summarized as mean ± standard deviation (SD), together with minimum and maximum values. The use of inferential statistics was justified because the study design included 24 independent local sampling points (8 per zone), with each honey sample representing a separate observational unit. This design enabled the comparison of metal concentrations among industrial, rural, and mountainous environments without pseudo-replication. One-way analysis of variance (ANOVA) was initially applied separately for Pb, Cd, Zn, Ni, and Cu to test differences among the three zones (industrial, rural, mountainous). Because the assumption of homogeneity of variances was not satisfied according to Levene's test, Welch's robust ANOVA was additionally applied, followed by Games-Howell post-hoc comparisons, which are appropriate when group variances are unequal. Statistical significance was set at $p < 0.05$. The results of Welch's robust ANOVA were used as the primary basis for statistical interpretation in the revised manuscript.

Supporting analytical and statistical documentation, including a sample laboratory report and SPSS output tables, was retained as supplementary evidence for the revised submission.

RESULTS

Heavy metal concentrations

The concentrations of Pb, Cd, Zn, Ni, and Cu in honey samples collected from industrial, rural, and mountainous zones are presented in Table 2, while mean concentrations (±SD) by sampling zone are summarized in Table 3 and illustrated in Figure 2. All analyzed metals were detected in all samples, although their spatial distribution patterns differed considerably among the three environmental zones. All measured concentrations remained below the current European Union maximum level established for Pb in honey, indicating compliance with the applicable food safety criterion for this metal.

Welch's robust ANOVA revealed significant spatial variation for Pb, Cd, and Ni, whereas Zn and Cu did not show statistically significant differences among zones (Table 4). Welch robust ANOVA was used because Levene's test indicated unequal variances among groups.

Lead (Pb) concentrations ranged from 0.0020 to 0.0369 mg/kg. Mean Pb values were higher in industrial (0.0279 ± 0.0093 mg/kg) and rural samples (0.0176 ± 0.0152 mg/kg) than in mountainous samples (0.0020 ± 0.0000 mg/kg). Welch's robust ANOVA indicated a significant effect of sampling zone on Pb concentrations (Welch = 72.247, $p < 0.001$). Games-Howell post-hoc comparisons showed a significant difference between industrial and mountainous samples ($p < 0.001$), whereas the rural–mountain comparison was borderline ($p = 0.052$) and the industrial–rural comparison was not

Table 2. Concentrations of Pb, Cd, Zn, Ni and Cu in individual honey samples (mg/kg, fresh weight basis)

Sample ID	Pb	Cd	Zn	Ni	Cu	Zone
M1	0.0364	0.0072	0.97	0.073	0.43	Industrial
M2	0.036	0.007	0.97	0.07	0.41	Industrial
M3	0.0368	0.0071	0.99	0.074	0.43	Industrial
M4	0.0369	0.0072	0.98	0.07	0.42	Industrial
M5	0.029	0.0085	0.39	0.28	0.55	Rural
M6	0.034	0.009	0.35	0.27	0.53	Rural
M7	0.032	0.0084	0.37	0.25	0.56	Rural
M8	0.032	0.0086	0.38	0.27	0.53	Rural
M9	0.02	0.0025	0.17	0.16	0.51	Industrial
M10	0.018	0.0025	0.16	0.14	0.49	Industrial
M11	0.018	0.0053	0.18	0.15	0.50	Industrial
M12	0.021	0.0061	0.18	0.165	0.51	Industrial
M13	0.002	0.0025	3.51	0.13	0.35	Rural
M14	0.002	0.0025	3.46	0.11	0.34	Rural
M15	0.005	0.0025	3.49	0.13	0.35	Rural
M16	0.0051	0.0025	3.46	0.11	0.32	Rural
M17	0.002	0.009	0.67	0.37	0.46	Mountain
M18	0.002	0.011	0.65	0.39	0.46	Mountain
M19	0.002	0.009	0.67	0.36	0.48	Mountain
M20	0.002	0.010	0.68	0.37	0.49	Mountain
M21	0.002	0.010	0.76	0.32	0.45	Mountain
M22	0.002	0.010	0.78	0.29	0.43	Mountain
M23	0.002	0.009	0.74	0.30	0.44	Mountain
M24	0.002	0.009	0.75	0.31	0.44	Mountain

Note: EU maximum level for Pb in honey: 0.10 mg/kg (Commission Regulation (EU) 2023/915). No specific maximum levels are established for the other metals in honey. Analysis performed using ICP-MS according to BDS EN 15763:2010.

Table 3. Mean concentrations (± SD) of heavy metals in honey samples by sampling zone (mg/kg)

Metal	Industrial (n=8)	Rural (n=8)	Mountain (n=8)
Pb	0.0279 ± 0.0093	0.0176 ± 0.0152	0.0020 ± 0.0000
Cd	0.0056 ± 0.0020	0.0056 ± 0.0033	0.0096 ± 0.0007
Zn	0.5750 ± 0.4304	1.9263 ± 1.6611	0.7125 ± 0.0501
Ni	0.1128 ± 0.0444	0.1938 ± 0.0796	0.3388 ± 0.0380
Cu	0.4625 ± 0.0437	0.4413 ± 0.1091	0.4563 ± 0.0207

Note: Values expressed in mg/kg (fresh weight basis).

significant ($p = 0.273$). These findings suggest that Pb remains the metal most clearly associated with the historical industrial legacy of the study area.

Cd concentrations varied from 0.0025 to 0.0110 mg/kg. Mountain samples showed the highest mean concentration (0.0096 ± 0.0007 mg/kg), whereas industrial and rural samples exhibited comparable values (0.0056 ± 0.0020 and 0.0056 ± 0.0033 mg/kg, respectively). Welch's robust ANOVA confirmed significant spatial differences (Welch = 38.471, $p < 0.001$), and Games-Howell comparisons showed that mountainous samples had significantly higher Cd concentrations than both industrial ($p = 0.020$) and rural samples ($p = 0.012$), whereas industrial and rural zones did not differ significantly ($p = 0.999$). This pattern indicates that factors other than direct industrial proximity may influence Cd distribution.
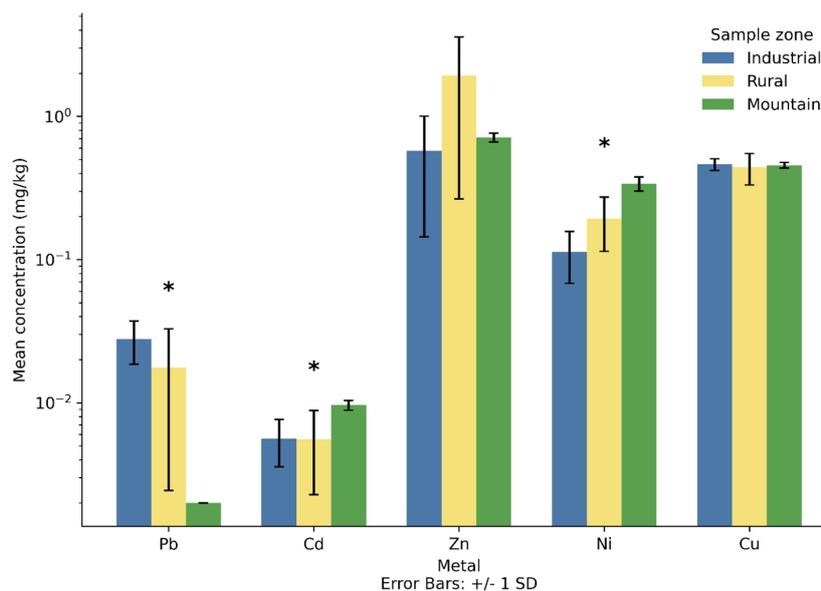
Figure 2. Mean (± SD) concentrations of Pb, Cd, Zn, Ni and Cu in honey samples from industrial, rural and mountainous zones

Table 4. Welch robust ANOVA results for heavy metal concentrations among industrial, rural and mountainous zones

Metal	Welch statistic	p-value	Interpretation
Pb	72.247	< 0.001	Significant
Cd	38.471	< 0.001	Significant
Zn	2.418	0.146	Not significant
Ni	72.662	< 0.001	Significant
Cu	0.309	0.739	Not significant

Zinc (Zn) concentrations ranged from 0.160 to 3.510 mg/kg. Rural samples exhibited the highest mean Zn concentration (1.9263 ± 1.6611 mg/kg), followed by mountainous (0.7125 ± 0.0501 mg/kg) and industrial samples (0.5750 ± 0.4304 mg/kg). Although the classical ANOVA suggested a significant difference, this pattern was not confirmed by Welch's robust ANOVA (Welch = 2.418, p = 0.146), and Games-Howell post-hoc comparisons did not identify statistically significant pairwise differences. The relatively large standard deviation observed in rural samples indicates substantial local variability among sites.

Ni concentrations demonstrated a clear spatial gradient, increasing from industrial (0.1128 ± 0.0444 mg/kg) to rural (0.1938 ± 0.0796 mg/kg) and reaching the highest levels in mountainous samples (0.3388 ± 0.0380 mg/kg). Welch's robust ANOVA indicated a significant effect of sampling zone on Ni concentrations (Welch = 72.662, p < 0.001). Games-Howell post-hoc

comparisons showed that mountainous samples differed significantly from both industrial (p < 0.001) and rural samples (p = 0.006), whereas the industrial–rural comparison was not significant (p = 0.069). Thus, the strongest Ni contrast involved the mountainous zone rather than a full separation among all three zones.

In contrast, Cu concentrations ranged from 0.320 to 0.560 mg/kg and mean Cu concentrations were comparable in industrial (0.4625 ± 0.0437 mg/kg), rural (0.4413 ± 0.1091 mg/kg), and mountainous samples (0.4563 ± 0.0207 mg/kg). Welch's robust ANOVA did not indicate significant differences among zones (Welch = 0.309, p = 0.739), and Games-Howell comparisons likewise showed no significant pairwise differences. This relatively uniform pattern suggests that Cu was less sensitive to zonal environmental differences than Pb, Cd, or Ni.

The observed spatial variability supports the applicability of honey as a practical and

accessible matrix for environmental biomonitoring in regions affected by both legacy and ongoing metal pressures.

Overall, the results indicate clear spatial variability in the distribution of Pb, Cd, and Ni among the three sampling zones, whereas Zn and Cu remained relatively stable. The logarithmic representation in Figure 2 allows clearer visualization of differences among metals with widely varying concentration ranges. Taken together, the observed patterns support the interpretation that honey can capture both legacy and ongoing metal pressure in environmentally contrasting areas of Kosovo.

DISCUSSION

The present study revealed distinct spatial patterns in heavy metal concentrations in honey collected from industrial, rural, and mountainous regions of Kosovo, supporting the hypothesis that honey can differentiate between legacy and ongoing sources of environmental metal pressure.

Lead – legacy contamination

The significantly higher Pb concentrations observed in industrial and rural zones compared with mountainous areas suggest the persistence of legacy contamination in regions historically influenced by the Trepça mining and smelting complex. Although lead production ceased in 2000, decades of metallurgical activity resulted in the accumulation of contaminated tailings and airborne particulates in surrounding soils. Because Pb is characterized by low mobility and long environmental persistence, it may remain in soil matrices for extended periods and continue to enter the food chain. The absence of significant differences between industrial and rural zones may indicate that contamination has dispersed beyond the immediate industrial perimeter over time.

Nickel – spatial gradient and combined industrial/geogenic influence

Nickel exhibited a clear spatial gradient (industrial < rural < mountainous). Welch's robust ANOVA confirmed significant zonal differences, and Games-Howell comparisons showed that mountainous samples differed significantly from both industrial and rural samples, whereas the industrial–rural comparison was not statistically significant. Unlike Pb, the distribution of Ni did not follow a simple proximity-to-industry pattern. This may reflect the combined influence of natural geogenic background, local soil composition, and atmospheric transport processes. In addition, ferronickel production in Drenas represents a potential ongoing source of Ni emissions. However, the highest concentrations detected in mountainous samples suggest that geological background and broader environmental dispersion processes may also play an important role.

Cadmium – enrichment in mountainous areas

Mountain samples showed significantly higher Cd concentrations than industrial and rural samples. This pattern may indicate geochemical background enrichment or localized soil characteristics affecting plant uptake. Cadmium is known to be relatively mobile under certain soil conditions, particularly in acidic environments, and may accumulate in specific ecological niches independently of direct industrial emissions. Thus, the observed pattern suggests that Cd distribution in honey may be influenced by both natural environmental conditions and local bioavailability.

Zinc – rural variability

Rural samples exhibited the highest Zn concentrations descriptively. However, because the significance pattern for Zn was not confirmed by Welch's robust ANOVA, these differences should be interpreted cautiously. Because Zn is an essential element widely present in soils and plants, its variability may be associated with agronomic practices, fertilizer use, or natural soil heterogeneity rather than direct industrial emissions alone. The high standard deviation observed in rural samples also indicates considerable local variability among sampling sites.

Copper – relatively uniform distribution

Copper concentrations did not differ significantly among zones, indicating relatively stable background levels across the study area. As Cu is an essential micronutrient with both natural and anthropogenic sources, its relatively homogeneous distribution suggests limited spatial differentiation in the investigated environments. Comparable Cu patterns and relatively stable metal concentrations in honey have also been reported

in previous regional and international studies [Sitarz-Palczak et al., 2015; Zenunović et al., 2020]. Recent studies have also shown that multivariate statistical approaches can improve the interpretation of heavy metal patterns in honey and help distinguish possible environmental sources of contamination [Gelaye et al., 2024].

Environmental and food safety implications

Importantly, all measured concentrations remained below the current European Union maximum level established for Pb in honey. Compliance with food safety standards is particularly relevant in the context of international trade, as chemical contaminants remain among the principal causes of honey-related alerts in the European food safety system [Eissa et al., 2023]. This finding is consistent with previous research showing that honey generally contains lower concentrations of heavy metals than other bee products, while still remaining a useful matrix for environmental pollution monitoring [Formicki et al., 2013]. These findings indicate that honey produced in the investigated areas does not pose an immediate food safety concern with respect to the analyzed metals. Nevertheless, the persistence of elevated Pb in historically industrialized areas and the marked spatial variability of Ni highlight the importance of continued environmental monitoring, particularly in post-industrial regions where contamination legacies may remain environmentally relevant for decades after industrial cessation. Recent studies from other countries have similarly emphasized that, even when heavy metal concentrations in honey remain within acceptable safety limits, honey still provides valuable information on environmental contamination and consumer exposure [Naccari et al., 2025; Wise et al., 2025].

Study limitations

Although the present study provides statistically supported evidence of spatial variation in heavy metal concentrations, several limitations should be acknowledged. First, the sample set, although balanced across zones (n = 8 per zone), represents a single harvesting season, and temporal variability was not assessed. Seasonal changes may influence metal uptake into nectar and pollen and, consequently, into honey. Second, although independent local sampling points were included to ensure spatial representation, parallel analyses of soil, plants, or atmospheric deposition were not performed, limiting direct source attribution. Third, the unequal variances observed for certain metals indicate natural heterogeneity within zones, which may reflect localized environmental conditions.

Despite these limitations, the use of independent sampling sites and inferential statistical analysis strengthens the reliability of the spatial comparisons and supports the interpretation of honey as an environmental bioindicator.

CONCLUSIONS

This study demonstrated that honey collected from different environmental zones of Kosovo reflects spatial variability in heavy metal concentrations associated with both historical and ongoing anthropogenic influences. Significant differences were found for Pb, Cd, and Ni, whereas Zn and Cu did not show robustly significant zonal differences.

Elevated Pb concentrations in industrial and rural areas indicate the persistence of legacy contamination linked to past metallurgical activity in Mitrovica, despite the cessation of lead production in 2000. The distinct spatial pattern observed for Ni suggests a combined influence of geological background and ongoing industrial processes. Although Zn showed descriptive variability, this pattern was not confirmed by robust variance-insensitive testing, indicating that Zn differences should be interpreted with caution. Variability in Cd further highlights the complexity of environmental metal dynamics beyond simple proximity to industrial sources.

Importantly, all measured concentrations remained below the current European Union maximum level established for Pb in honey. These findings support the suitability of honey as a practical bioindicator for assessing long-term environmental metal pressure and emphasize the need for continued monitoring in post-industrial regions in order to better understand contamination persistence and ecosystem recovery processes.

More specifically, the study demonstrates that honey can be used not only to detect environmental metal contamination in Kosovo, but also to distinguish between legacy industrial contamination and ongoing metal pressure, thereby filling an important regional knowledge gap in post-industrial biomonitoring.

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