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MOSSES AS A BIOINDICATOR OF AIR POLLUTION ALONG THE LEPENC RIVER IN THE REPUBLIC OF KOSOVO

Adelina Haskaj[1,2], **Sonja Lepitkova**[1*]

[1]*Faculty of Natural and Technical Sciences, "Goce Delcev" University, Stip, Blvd. Krste Misirkov 10A, 2000, Štip, North Macedonia*
[2]*Alma Mater European Campus College "Rezonanca", Glloku te Shelgjet "Veternik", 10 000 Prishtinë, Republic of Kosovo*
*sonja.lepitkova@ugd.edu.mk

A b s t r a c t: This study investigates the distribution and potential impact of heavy metals: cadmium, cobalt, chromium, copper, iron, nickel, lead, and zinc, in moss samples collected from 20 sites along the Lepenc river in Kosovo, by using Inductively Coupled plasma atomic emission spectroscopy (ICP-AES). Statistical analysis (minimum, maximum, mean, median, etc), cluster analysis, principal component analysis (PCA) and pollution indices (Contamination Factor and Pollution Load Index) were performed to better explain the data of metals concentrations in the moss samples. Low levels of contamination were recorded in samples from the Brezovica area, a mountainous area with minimal anthropogenic influence. Samples from the Kaçanik area were notably enriched in Fe, Pb, Zn, Cd, Cr, and Co, possibly reflecting the influence of vehicular emissions, urban dust, and ongoing construction activities. The highest contamination levels were observed in samples 19 and 20, collected from the industrial region of Hani i Elezit. These samples exceeded critical contamination factor (CF) thresholds for multiple elements (Cd, Co, Cr, Ni, and Pb), marking them as pollution hotspots. Furthermore, pollution load index (PLI_{zone}) for entire area was 5.7, confirmed significant pollution at these study locations. These findings underscore the urgent need for targeted environmental monitoring and pollution mitigation strategies, particularly in urbanized zones such as Ferizaj and in industrial centers like Hani i Elezit and Kaçanik.

Key words: heavy metals; mosses; bioindicators; pollution load index (PLI); principal component analysis (PCA)

INTRODUCTION

Air pollution has become one of the most pressing global concerns in recent years. The decline in air quality is largely driven by industrial development and the release of harmful elements into the atmosphere, as evidenced by numerous recent scientific studies. Air quality is assessed using various techniques, including mobile sensors and both stationary and portable monitoring devices. Certain soluble salts of heavy metals contribute to the contamination of air, water, and soil wherever they are present, due to the widespread industrial use of these metals and their compounds in recent decades (Dreshaj Lecaj et al., 2024). Heavy metals are among the most concerning chemical pollutants due to their association with numerous adverse effects on human health. Both prolonged and short-term exposure to air pollutants particularly hazardous metals such as lead, cadmium, arsenic, and mercury can pose serious health risks, as demonstrated by numerous studies and global assessments. Exposure to heavy metals results in several diseases (Paçarizi et al., 2021). As a result of ongoing industrial progress, humans are regularly exposed to potentially harmful substances, including toxic metals released into the environment (Kastrati et al., 2021). Numerous recent studies have shown that mining activities and tailings in Kosovo have contributed to significant soil contamination (Paçarizi et al., 2024; Dreshaj Lecaj et al., 2024; Kastrati et al. 2024), water (Gashi et al., 2010), air (Paçarizi et al., 2023), and food (Sopaj et al., 2025; Kastrati et al.,2023; Pacarizi et al., 2019), further increasing the risk of environmental and human health impacts.

Continuous air monitoring and ongoing research into the harmful effects of these metals are therefore essential. As early as the late 1960s, Rühling and Tyler pioneered the use of mosses as bioindicators to assess air quality and detect atmospheric deposition of heavy metals (Rühling et al., 1970). Due to their specific biological characteristics, mosses are widely used as bioindicators of air pollution. These non-vascular, rootless, and flowerless plants possess a high capacity to accumulate airborne pollutants directly from the atmosphere, making them particularly effective for monitoring air quality (Tyler, 1990).The concentration of elements accumulated in mosses serves as a particularly effective indicator of air pollution, as mosses absorb nutrients and pollutants primarily from the atmosphere rather than through roots (Sopaj et al., 2022). Furthermore, since mosses absorb elements exclusively from the atmosphere, they serve as reliable indicators of air pollution. Their wide geographic distribution, low genetic variability, and stationary nature, combined with the ability to analyze accumulated elements using a variety of analytical techniques, make mosses an excellent choice for air quality biomonitoring (Fernández et al., 2007). Mosses offer several advantages as biomonitors of air quality: they are widely distributed and easy to collect; their lack of true vascular tissue enhances their ability to adsorb airborne pollutants; and their slow growth rate allows for the accumulation of contaminants over extended periods (Zechmeister et al., 2004). Mosses also function as effective accumulators of metals and metal complexes, largely due to their high cation exchange capacity (CEC) (Boev et al., 2022).The significant role that mosses have played in air quality monitoring over recent decades further supports their effectiveness as reliable bioindicators (Tyler, 1990; Demková et al., 2017; Paçarizi et al., 2023). Since 2000, the ICP Vegetation program (http://icpvegetation.ceh.ac.uk) has coordinated the European Moss Survey, providing valuable data on atmospheric deposition of heavy metals and other pollutants across the continent. Numerous studies have been conducted in countries across the region such as North Macedonia within the framework of this program, using mosses and lichens to monitor air quality (Balabanova et al., 2010; Barandovski et al., 2012; Stafilov et al., 2010; Boev et al., 2022).

However, research on the use of mosses for air quality monitoring in Kosovo has only emerged in the last two decades. Alongside other studies, such as Maxhuni et al. (2016), Paçarizi et al. (2021), Sopaj et al. (2022), the current study is a continuation of the use of mosses as bioindicators, but is focused on investigation the impact of industry and settlements along the course of the Lepenc river to the border with the Republic of North Macedonia.

This study further contributes to the understanding of air quality assessment using moss biomonitoring in the region. The purpose of this study is to assess air pollution using mosses as bioindicators. A total of 20 moss samples were collected along the Lepenc river, covering an area of approximately 80 km². Sampling sites were carefully selected to differentiate locations between mountainous and urban areas, thereby allowing for a clearer distinction of pollution sources. The samples were collected in accordance with standardized protocols and analyzed using Inductively Coupled Plasma Optical Emission Spectrometry (ICP-OES) at the Institute of Agriculture, University of Prishtina.

The objective of this study was to evaluate the content of potentially toxic elements in mosses, using pollution indices and statistical analysis as a tool for evaluating the geogenic and anthropogenic origin of these investigated elements.

MATERIALS AND METHODS

Study area

Kosovo is located in the central part of the Balkan Peninsula, between longitudes 41°50′58″ and 43°15′42″, and latitudes 20°01′30″ and 21°48′02″. It has an average elevation of approximately 800 meters above sea level and covers a total area of about 10,900 km² (Paçarizi et al., 2021). The Lepenc river is situated in the southeastern part of the Republic of Kosovo. It belongs to the Aegean Sea basin and is a tributary of the Vardar river. Lepenc originates on the northern slopes of the Sharr Mountains, in the Oshllak area, at an altitude of 2,212 meters. Within the territory of Kosovo, the river is 53 km long, with a catchment area of 607 km². With an average annual flow of 7.9 m^3/s, it serves as a vital water source for nearby communities. Along its course through Kosovo (Figure 1), the river passes through Kaçanik and near Hani i Elezit, where it is used for industrial purposes, agricultural irrigation, and water supply (Bytyçi et al., 2018).

After leaving Kosovo, the Lepenc river flows through North Macedonia before joining the Vardar river, making it a transboundary watercourse. As a result, both countries place significant importance on the management of water resources, particularly in relation to regional development and environmental protection.

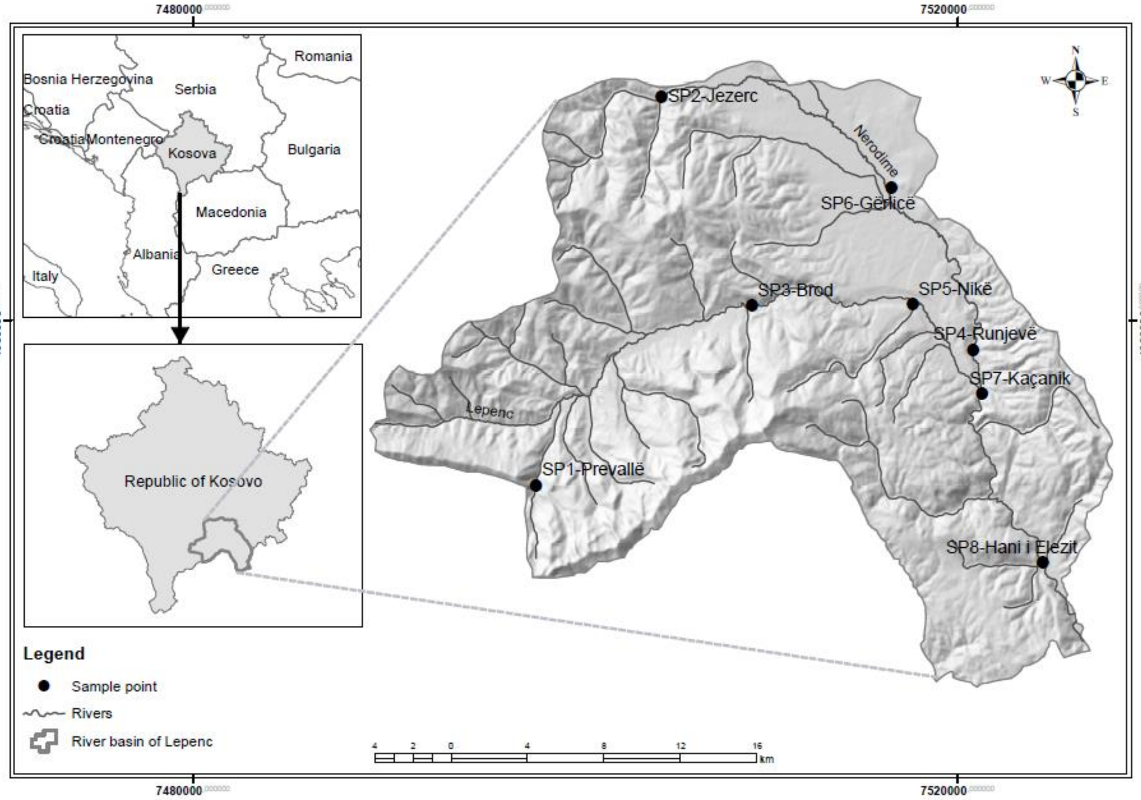

Fig. 1. Study area

Due to the river's ecological and geostrategic significance, various methods such as water quality monitoring, sediment analysis, and air biomonitoring using mosses have been employed to determine heavy metal contamination levels and to assess the ecological status of the area.

The geographic coordinates were recorded in the field using high-precision GPS devices and subsequently processed using GIS software to spatially delineate the sampling sites along the Lepenc river.

These data were used for spatial analysis and to identify potential sources of environmental contamination in the corresponding areas.

The distribution of the sampling locations is shown in Figure 2, which presents their spatial arrangement along the river course, as well as their relationship with the surrounding topography and hydrographic network. The sampling locations (S1–S20) along with their corresponding coordinates (X, Y, Z) within the study area are presented in Table 1.

The samples contain various categories of pollutants, depending on the characteristics of the study area and the geographic locations of the sampling stations. Samples S1–S5 are located in mountainous regions influenced by natural mineral presence, historical mining activities (chrome and nickel), and natural erosion. Samples S6–S14 are affected by waste water discharge, agricultural activities, and minor urban influences. Samples S15–S20 are primarily impacted by industrial pollution, particularly from the "Sharr Cem" Cement Factory, as well as urban sources in the Hani i Elezit area.

Sampling techniques

The sample collection was conducted during the summer of 2024, following the guidelines of the Monitoring Manual of the International Cooperative Programme on Effects of Air Pollution on Natural Vegetation and Crops (2020).The moss sampling procedure involved the collection of *Hylocomium splendens* (Hedw.) moss. In accordance with the protocol, 20 samples were collected in July 2024 from distinct locations distributed across an area of approximately 80 km². Each sampling site consisted of five sub-sampling points within a 50 × 50 m² area. To minimize anthropogenic influence, each sampling site was selected at least 200 meters away from populated areas, 100 meters from minor roads, and 300 meters from major roads. The moss was primarily collected from the ground and, less frequently, from decaying trees or branches. The collected samples were placed in one-liter paper bags and allowed to dry at room temperature (20–25°C).

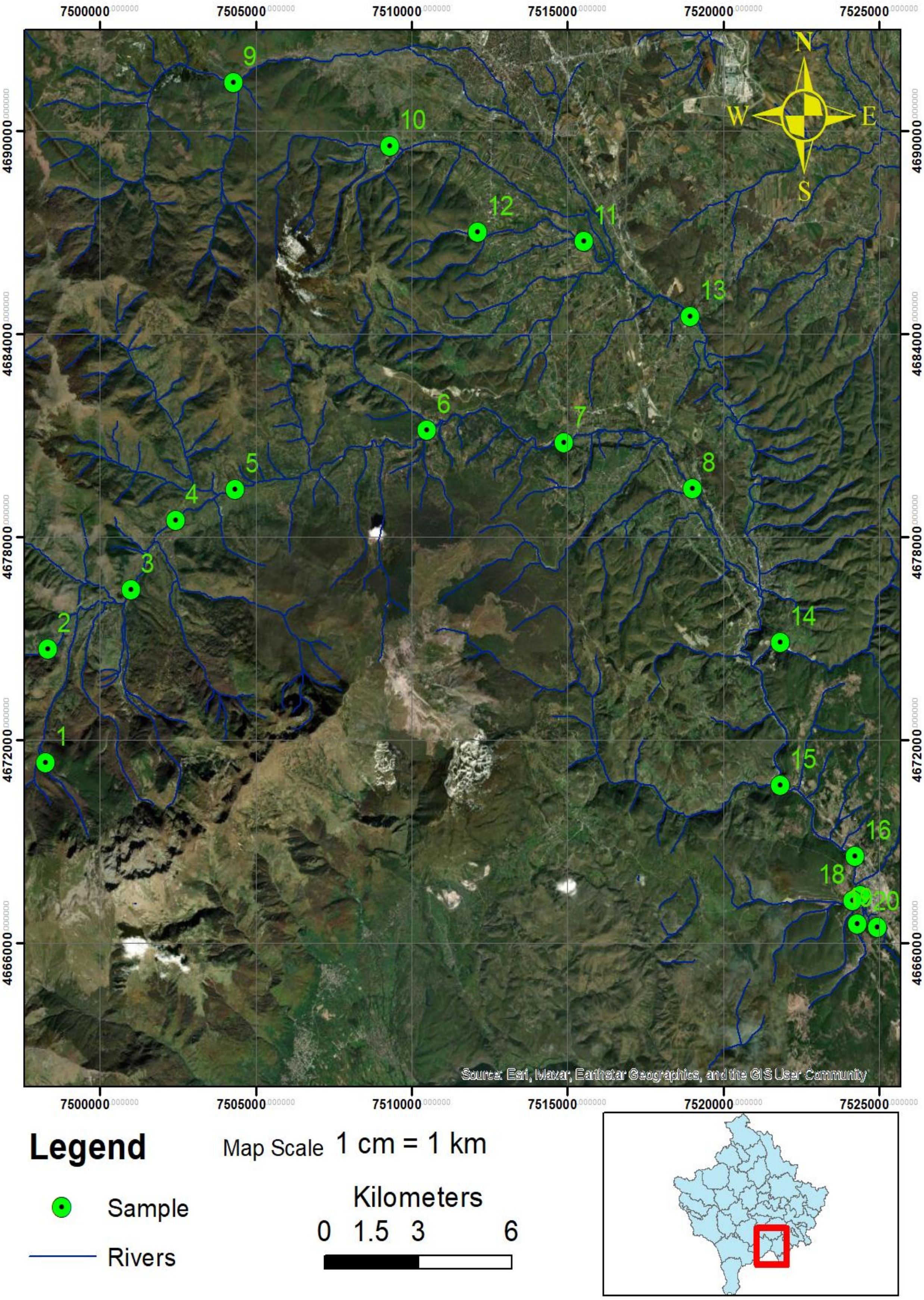

Fig. 2. Map of moss sampling locations

Table 1

The locations of each sample along with the matching coordinates

Sample	X	Y	Z	Sample	X	Y	Z
S1	7498249	4671336	1340	S11	7515527	4686766	549
S2	7498323	4674690	964	S12	7512126	4687042	582
S3	7500996	4676457	885	S13	7518934	4684546	541
S4	7502424	4678500	815	S14	7521827	4674884	554
S5	7504351	4679410	766	S15	7521830	4670665	460
S6	7510500	4681167	646	S16	7524225	4668565	490
S7	7514892	4680797	602	S17	7524407	4667408	406
S8	7519019	4679431	507	S18	7524165	4667262	387
S9	7504281	4691444	678	S19	7524304	4666574	385
S10	7509302	4689584	617	S20	7524952	4666475	382

Digestion of the sample

After weighing 0.5 g of the dried moss sample on an analytical balance, the material was placed in a teflon digestion tube and treated with 7 ml of 65% HNO_3 and 2.5 ml of 30% H_2O_2 to facilitate digestion (Paçarizi et al., 2021). The mixture was then covered with an aluminum cap and left to stand for 10 minutes to initiate decomposition reactions and allow the release of gases. Subsequently, the teflon tubes were placed on a magnetic stirrer (Magnetic Stirrer SH-3) and heated according to the following program: 5 minutes at 170 °C, 10 minutes at 170 °C, 1 minute at 200 °C, 15 minutes at 200 °C, 1 minute at 50 °C, and 23 minutes at 50 °C. After the initial digestion and drying phase, an additional reduced volume of acids was added: 3.5 ml of 65% HNO_3 and 1.75 ml of 30% H_2O_2, and the samples were left to evaporate completely. The digested solutions were then transferred into 25 ml plastic containers, filled with redistilled water up to the mark, and labeled accordingly. At this stage, the samples were ready for shipment to the laboratory for ICP-OES analysis.

Instrumentation

All high-purity chemicals used in this study, including hydrogen peroxide and nitric acid, were supplied by Merck (Germany). Redistilled water was used for the preparation of solutions and for cleaning laboratory equipment. The determination of metals in the prepared solutions was carried out using Inductively Coupled Plasma Optical Emission Spectroscopy (ICP-OES, model ICPE-9800).

Statistical analysis

Statistical analyses were performed using PAST software version 4.11, which provided descriptive statistics such as mean, median, minimum, maximum, coefficient of variation, and standard deviation. Correlation analysis was conducted to assess relationships between element concentrations. Cluster analysis and principal component analysis (PCA) was performed using the same software to identify patterns and associations among the measured elements.

Indices of pollution

The contamination factor (CF) (Carballeira, 2001) is used to calculate the degree of metal contamination in an environment. The mathematical formula:

$$CF = C^i_{metal} / C^i_{reference}$$

is typically used to express it, where C^i_{metal} denotes the amount of the metal present in that location, and C^i_{metal} background denotes the permitted amount of the metal in an uncontaminated area, or clean reference area; in this instance, we use the Norway mosses as a reference because it is thought to be the least polluted area.

According to Carballeira (2001), the following intervals are included in the degree of contamination: $CF < 1$ no contamination, $1 \leq CF \leq 2$ suspected contamination, $2 \leq CF \leq 3.5$ slightly contaminated, $3.5 \leq CF \leq 8$ moderate, $8 \leq CF \leq 27$ severe, and $CF > 27$ extreme contamination factor.

In order to determine metal pollution, this research also calculates the pollution load index

(Tomlinson et al., 1980).This mathematical approach is used to calculate *PLI*.

$$PLI_{site} = \sqrt[n]{CF_1 \times CF_2 \times \cdots \times CF_n}$$

In contrast, the *PLI* of the entire zone – in this case, the area surrounding Kosovo's Lepenc river – is determined using the following formula:

$$PLI_{zone} = \sqrt[n]{PLI_{site1} \times PLI_{site2} \times \cdots \times PLI_{siten}}$$

In this case, n is the number of sampling sites, and site is the sampling location. The pollution level according to Zhang et al. (2011) is calculated to this order: *PLI* zero is the background concentration, $0 < PLI \leq 1$ is unpolluted, $1 < PLI \leq 2$ is moderately to unpolluted, $2 < PLI \leq 3$ is moderately polluted, $3 < PLI \leq 4$ is moderately to highly polluted, $4 < PLI \leq 5$ is extremely polluted, and $PLI > 5$ is very highly polluted.

RESULTS AND DISCUSSION

Eight metals Cu, Cr, Co, Fe, Ni, Cd, Pb, and Zn, were measured at 20 moss sampling locations along the area of the Lepenc river. The statistical data for the concentrations of these metals are presented in Table 2, which includes parameters such as minimum, maximum, median, and other descriptive statistics.

As we shown in the table, nickel has the highest mean concentration (5.15 mg/kg), followed by zinc (4.69 mg/kg), iron (4.14 mg/kg), and lead (4.04 mg/kg), all of which exhibit relatively elevated levels. In contrast, copper (Cu) has the lowest mean concentration (0.04 mg/kg), indicating minimal influence from natural or anthropogenic sources for this element.

The maximum concentration of cadmium (1.13 mg/kg) was lower than the 2020 moss survey of Kosovo (2.10 mg/kg), but the median value were the same 0.36 mg/kg (Paçarizi et al., 2020). The maximum concentration of nickel (17.45 mg/kg) was lower than the 2020 moss survey of Kosovo (79 mg/kg), but the median value (4.05 mg/kg) was higher than the moss survey in Kosovo (1.7 mg/kg). The median values for other metals analyzed were lower compared to the moss survey of Kosovo 2020. These differences can be attributed to variations in the geochemical composition of the regions and the nature of industrial activities related to mineral exploitation.

Table 2

Basic statistics of element concentrations (in mg/kg) in moss samples (n=20)

	Cd	Co	Cr	Cu	Fe	Ni	Pb	Zn
N	20	20	20	20	20	20	20	20
Min	0.17	0.23	0.89	0.02	0.05	0.25	1.80	2.11
Max	1.13	0.87	3.06	0.05	11.60	17.45	6.90	6.90
Mean	0.36	0.55	1.99	0.04	4.14	5.15	4.04	4.69
Stand. dev.	0.13	0.19	0.71	0.01	3.13	4.64	1.67	1.54
Median	0.36	0.55	2.00	0.04	3.34	4.05	4.02	4.67
25 prcntil	0.25	0.36	1.35	0.04	1.64	1.23	2.49	3.34
75 prcntil	0.46	0.72	2.61	0.05	6.76	7.59	5.55	6.19
Coeff. var.	32.37	34.96	35.47	19.43	75.57	90.20	41.23	32.95

According to Kastrati et al. (2021) studies using pollen have also revealed the highest concentrations of Pb, Ni, and Zn.

The coefficient of variation (CV) shows that the spatial distribution of Ni (90.20%) and Fe (75.57%) is relatively high across the samples, indicating multiple source influences and significant geographical heterogeneity in their concentrations. Metals such as Zn, Pb, Cd, Co, and Cr also display considerable variability, whereas Cu exhibits the lowest variability (19.43%) and appears to be more uniformly distributed across the study area.

To assess the relationships between metal concentrations in the analyzed samples, a correlation analysis was conducted using Pearson's correlation coefficient. This statistical approach aids in identifying common sources or similar processes responsible for the distribution of these metals in the environment.

The Pearson correlation coefficient (*r*) and their significance level (*p* values) for eight metals in 20 different locations are presented in Table 3. The absolute value between 0.50 and 0.70 presents a good correlation, and from 0.70 to 1.00 presents a strong correlation (Dreshaj et al., 2024; Sopaj et al., 2022). Cadmium had five strong positive correlations with zinc (0.999), cobalt (0.989), chromium (0.978), lead (0.887) and nickel (0.742) but strong negative correlation with copper (–0.735). Cobalt had three strong positive correlations with zinc (0.991), chromium (0.987) and lead (0.921). Chromium had three strong positive correlations with zinc (0.984), lead (0.961) and iron (0.751). Copper had strong negative correlations with nickel (-0.891) and zinc (–0.733). Three other metals had only one strong positive correlation: Fe-Pb (0.879), Ni-Zn (0.737) and Pb-Zn (0.902). Based on data from Table 3, in total shown 24 associations with absolute values between 0.5 and 0.999, and all of them had significance level below 5% ($p < 0.05$). Strong correlations between Cr and Co have also been discovered in the region, particularly in air investigations carried out in Albania (Lazo et al., 2024).

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Pearson correlation (r) and significance (p) between metal concentrations in mosses

	Cd	Co	Cr	Cu	Fe	Ni	Pb	Zn
Cd		0.000	0.000	0.000	0.005	0.000	0.000	0.000
Co	**0.989**		0.000	0.001	0.002	0.001	0.000	0.000
Cr	**0.978**	**0.987**		0.002	0.000	0.002	0.000	0.000
Cu	–0.735	–0.683	–0.648		0.416	0.000	0.046	0.000
Fe	0.604	0.646	**0.751**	–0.193		0.539	0.000	0.003
Ni	**0.742**	0.695	0.648	–0.891	0.146		0.046	0.000
Pb	**0.887**	**0.921**	**0.961**	–0.450	**0.879**	0.451		0.000
Zn	**0.999**	**0.991**	**0.984**	–0.733	0.633	**0.737**	**0.902**	

To identify the correlations of metals with each other and with locations, we used cluster analysis and principal component analysis (PCA). The hierarchical cluster analysis constructed by Ward's method is presented in Figure 3. Five group of elements could be identified in cluster analysis: the 1st cluster is formed by Ni and impacted highly by locations 19 and 20; the 2nd cluster is formed by Fe and impacted mainly by locations 11 and 13; the 3rd cluster by Cd and Cr; 4th cluster is formed by Pb and Zn, and the 5th cluster formed by Co and Cu. Elements in clusters 1 and 2 have mainly anthropogenic origin, because in this region are located former ferro-nickel factory in Ivaja and cement factory in Hani i Elezit (Dreshaj et al., 2024). Elements in clusters 3, 4 and 5 have a mix geogenic and anthropogenic origin (Paçarizi et al., 2021).

Principal component analysis (PCA) is a statistical method used to explore relationships among multiple variables and to reduce the dimensionality of complex datasets. It transforms the original variables into a smaller set of new variables (principal components) that capture the largest possible variance within the data. As previously mentioned, PAST software version 4.11 was used to perform multivariate statistical analysis, including PCA, in addition to basic statistical computations. Two principal component plots were generated to visualize the distribution of sampling sites and to help identify potentially contaminated areas based on the grouping and variation of metal concentrations.

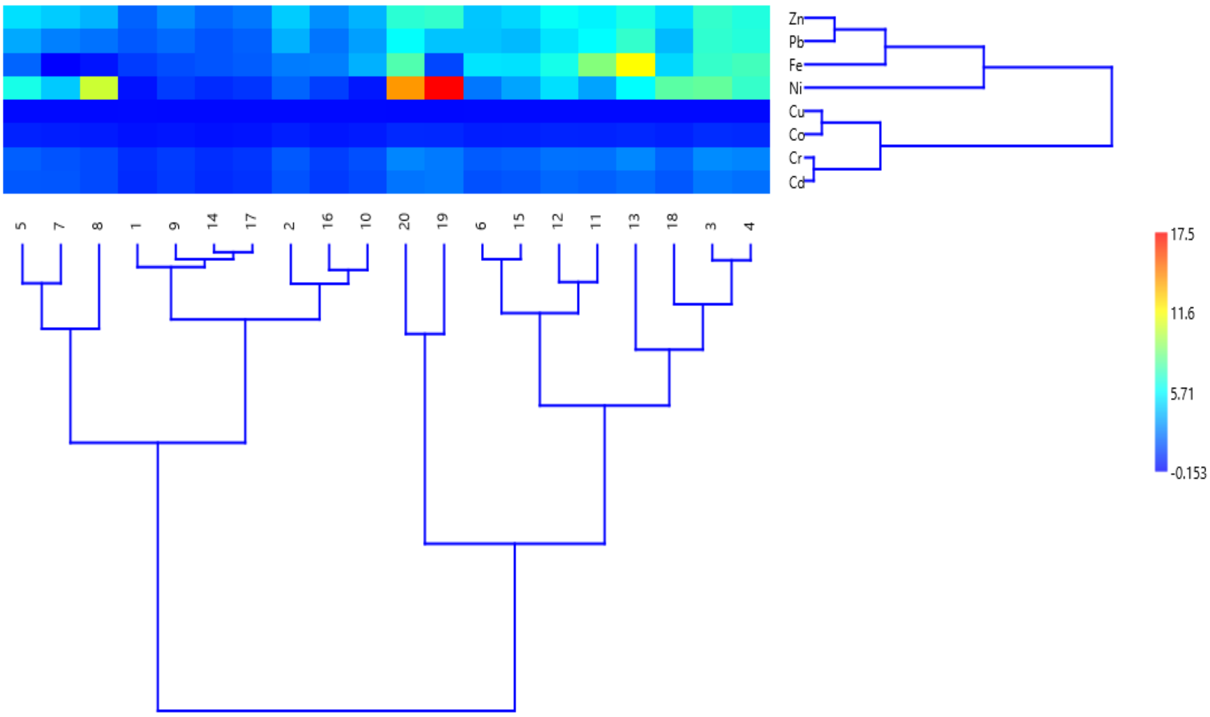

Fig. 3. The hierarchical cluster for eight heavy metals at 20 sampling locations

The results of the PCA analysis are presented in Figure 4, showing that the analysis produced two principal components (PCs). As we shown PC1 contributed 67.57% and PC2 with 30.65% of total variables (98.22%). The circle of correlations indicates that nickel (Ni) plays a significant role in sample differentiation along PC1, as evidenced by its long and isolated vector. Location 19 and 8 have a large vector in PC1 and PC2 and was affected by anthropogenic factors, and impacted in the level of concentration of nickel in moss samples. Location 20 has a large vector in PC1 but has not impacted in PC2. Locations 13 (Kaçaniku i vjetër) and 11 (Gërlica) have high vector in PC2 and impacted in the level of iron in moss samples. Other elements (Pb, Zn, Cr, Co, and Cu) were concentrated in locations 3, 4, 12 and 15 which are mainly located in the area of mountains.

Copper (Cu), however, displays distinct behavior in the PCA plot, setting it apart from the other elements and implying a different origin or mechanism of pollution. The samples from sites 1 to 5 in the PCA plot are located near the center of the graph (PC1 ≈ 0), indicating a natural distribution of metals with generally low concentrations. In the correlation circle, these samples are not strongly associated with any specific metal. Geographically, they correspond to a mountainous region near Brezovica, an area distant from industrial and urban activities, and thus serve as a reference site with minimal anthropogenic influence. Samples 6 to 10 represent the Ferizaj and Shtime regions. In the PCA, these samples are more spread along PC2. In the correlation circle, copper (Cu) is oriented in a distinct direction, suggesting that Cu pollution in this region originates from local sources such as agricultural activities (primarily due to the use of various pesticides), infrastructure development, and urban emissions. Furthermore, samples 11 to 13 are associated with metals such as Fe, Pb, Zn, Cd, Cr, and Co, which cluster together in the correlation circle, indicating a common source of pollution in this area. These samples correspond to the municipality of Kaçanik. Given that the sampling sites are located along the national road and within residential zones, the primary sources of contamination are likely related to urban emissions, road dust, traffic, and construction activities. Samples 14–20, based on their coordinates, are located near major industrial sources such as cement factories (e.g., SharrCem) and mineral processing facilities. As a result, this area is influenced by industrial and metallurgical waste. These sites are situated in Hani i Elezit, a region near the border with North Macedonia. Notably, these samples exhibit the highest concentrations of nickel (Ni).The high results of metals in this area are also given in this work (Paçarizi et al., 2023). In the PCA plot, these samples are positioned at the extreme end of PC1, indicating a strong influence on this component.

Meanwhile, in the correlation circle, nickel (Ni) is represented by a long and isolated vector, highlighting the significant impact of industrial pollution in the Hani i Elezit area.

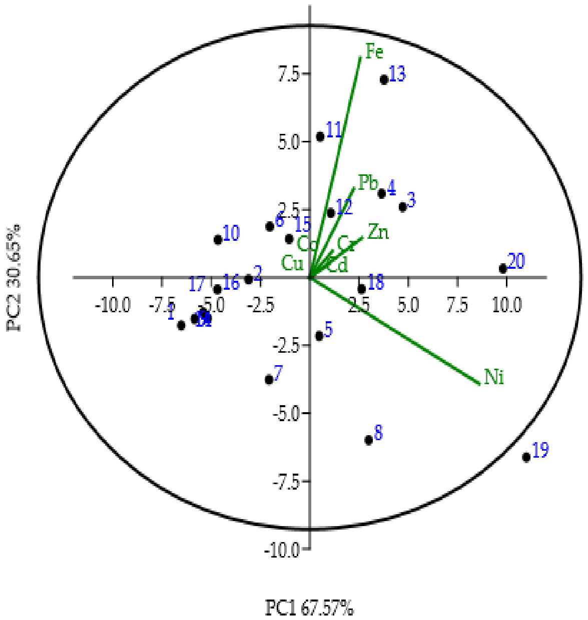

Fig. 4. Multivariate component analysis (PCA), for eight heavy metals at 20 sampling locations

Indices of pollution

Additionally, to assess the levels of air pollution, the contamination factor (CF) and pollution load index (PLI) values were calculated and are presented in Table 4.

According to Carballeira (2001), the contamination factor (CF) results from the 20 sampling sites show that many samples contain one or more heavy metals with CF values exceeding the critical threshold of 3, indicating widespread pollution across multiple locations. Samples 3, 4, 11–13, and 19–20, in particular, exhibit the highest levels of contamination, with four or five heavy metals, such as cadmium (Cd), cobalt (Co), chromium (Cr), nickel (Ni), and lead (Pb), surpassing the critical limit.

The concentrations of Pb and Ni in these samples are exceptionally high, reaching values of up to 138.00 and 15.86, respectively, suggesting significant contamination from industrial or urban sources. As reported by Sopaj et al. (2022), CF values are among the highest near industrial facilities. Additionally, samples 5, 11, 12, 15, and 18 exhibit high levels of contamination, exceeding the threshold for three distinct elements, including cadmium (Cd), nickel (Ni), and lead (Pb). These contaminants are attributed to anthropogenic activities in the surrounding environment. Samples in locations 19, 20 and 8 have higher CF of Ni, as: 15.86, 12.68, and 9.46, respectively. While samples 3, 4, and 13 show significant contamination with Cd and Pb. In contrast, samples 1, 9, 10, 14 and 16, do not exceed the CF threshold for any metal, indicating lower pollution levels and suggesting that these areas are less impacted by human activities. According to the results, the metals that most frequently exceed the critical CF values are Cd, Cr, Co, Ni, and Pb, suggesting that these elements are the primary pollutants in the studied location.

Figure 5 presents the pollution load index (PLI) values for eight heavy metals: Cd, Co, Cr, Cu, Fe, Ni, Pb, and Zn, based on the PLI classification proposed by Zhang et al. (2011). As shown in the figure below, there are significant variations in the pollution load from one location to another, reflecting the wide range of PLI values among the sampling points.

The PLI data indicate the presence of both anthropogenic pollution (e.g., urban or industrial sources) and geogenic pollution (i.e., derived from the natural geology of the rocks) in the study areas. Therefore, the region encompassing samples 1 through 5 is characterized by mountainous terrain with minimal industrial influence, although its natural geological composition may contribute to elevated concentrations of metals such as Cd, Pb, and Ni.

PLI for eight metals in some locations: 3 (1.22) and 4 (1.18) have PLI values greater than 1. In this case, the elevated values are attributed to natural geological enrichment rather than anthropogenic pollution. This interpretation is supported also by the cluster analysis (Figure 3) and PCA results (Figure 4).

Furthermore, the PLI values for the five priority metals Cd, Cr, Co, Ni, and Pb are notably high in samples 3 (10.41) and 4 (9.66). However, these elevated values reflect natural background levels, particularly for Cd and Pb, and do not indicate contamination from industrial sources.

According to Georgievski et al. (2025), the geological structure of the rocks in the mountainous region also contributes to the elevated concentrations of cadmium (Cd).

Table 4

Heavy metal pollution factor (CF) values in 20 moss samples

	Cd	Co	Cr	Cu	Fe	Ni	Pb	Zn
1	2.075	1.245	1.286	0.013	0.004	0.231	37.500	0.066
2	4.325	2.750	2.714	0.011	0.009	1.955	78.400	0.142
3	6.525	4.325	4.371	0.009	0.022	7.273	136.000	0.216
4	6.075	4.025	4.150	0.010	0.023	6.318	131.000	0.202
5	4.675	3.050	2.914	0.010	0.007	5.682	74.800	0.156
6	4.213	2.625	2.793	0.012	0.016	2.350	87.100	0.137
7	4.563	2.650	2.521	0.010	0.000	4.073	55.900	0.142
8	3.813	2.268	2.179	0.010	0.001	9.455	49.500	0.124
9	2.913	1.683	1.721	0.012	0.005	1.095	45.500	0.093
10	3.750	2.230	2.386	0.011	0.013	0.335	70.200	0.124
11	5.138	3.200	3.514	0.011	0.028	3.277	114.000	0.170
12	5.550	3.275	3.529	0.009	0.020	4.532	102.000	0.183
13	5.813	3.675	4.257	0.010	0.037	5.227	138.000	0.197
14	2.075	1.165	1.271	0.012	0.006	0.755	35.900	0.070
15	4.550	2.775	2.964	0.009	0.016	3.291	82.400	0.150
16	2.975	1.658	1.836	0.010	0.009	1.168	50.700	0.098
17	2.438	1.420	1.521	0.011	0.006	0.959	41.200	0.081
18	4.613	3.000	3.050	0.007	0.016	7.091	82.600	0.154
19	6.588	3.775	3.786	0.005	0.005	15.864	86.900	0.216
20	6.288	3.900	4.171	0.006	0.024	12.682	116.000	0.209
Min	*2.075*	*1.165*	*1.271*	*0.005*	*0.000*	*0.231*	*35.900*	*0.066*
Max	*6.588*	*4.325*	*4.371*	*0.013*	*0.037*	*15.864*	*138.000*	*0.216*
Mean	*4.448*	*2.735*	*2.847*	*0.010*	*0.013*	*4.681*	*80.780*	*0.146*
Median	*4.556*	*2.763*	*2.854*	*0.010*	*0.011*	*3.682*	*80.400*	*0.146*

According to Boev (Boev et al., 2022), further explains that erosion processes significantly increase the levels of chromium (Cr) and nickel (Ni) in clastic deposits. The urban area of Kaçanik, which includes sampling sites from 6 to 10, is affected by anthropogenic pollutants, national roads and urban activities.

For all eight metals, the pollution load index (PLI) is generally below or close to 1, indicating moderate levels of pollution. However, for the four main metals: cadmium, cobalt, chromium, nickel, and lead, the PLI values are moderately high in location 7 (5.87) and 8 (6.15), suggesting a mixed influence of both urban and geological sources.

The Ferizaj region and its surroundings, including sample sites 11–15, represent urban-industrial zones with intensive construction activity and high traffic density. Urban emissions from the city of Ferizaj, as discussed by Duan & Tan (2013), affect these sampling locations. The PLI values for eight metals exceed 1 in samples 11 (1.01) and 13 (1.22), clearly indicating urban pollution. Furthermore, the PLI values for the five priority metals are particularly high in locations 11 (7.36), 12 (7.84), 13 (9.19), and 15 (6.33), reflecting significant contamination from construction activities and vehicular emissions.

The Hani i Elezit area – considered the most polluted zone and it is located near cement factories, mining operations, and metallurgical sources. This region includes samples 16–20. For all eight metals, the PLI value in sample 20 is 1.22, indicating ongoing industrial impact. Notably, the highest PLI values in the study are found in locations 19 (10.54) and 20 (10.84) for five potentially toxic elements, highlighting extremely high levels of industrial and metallurgical pollution, mainly resulting from mine waste and emissions from industrial facilities.

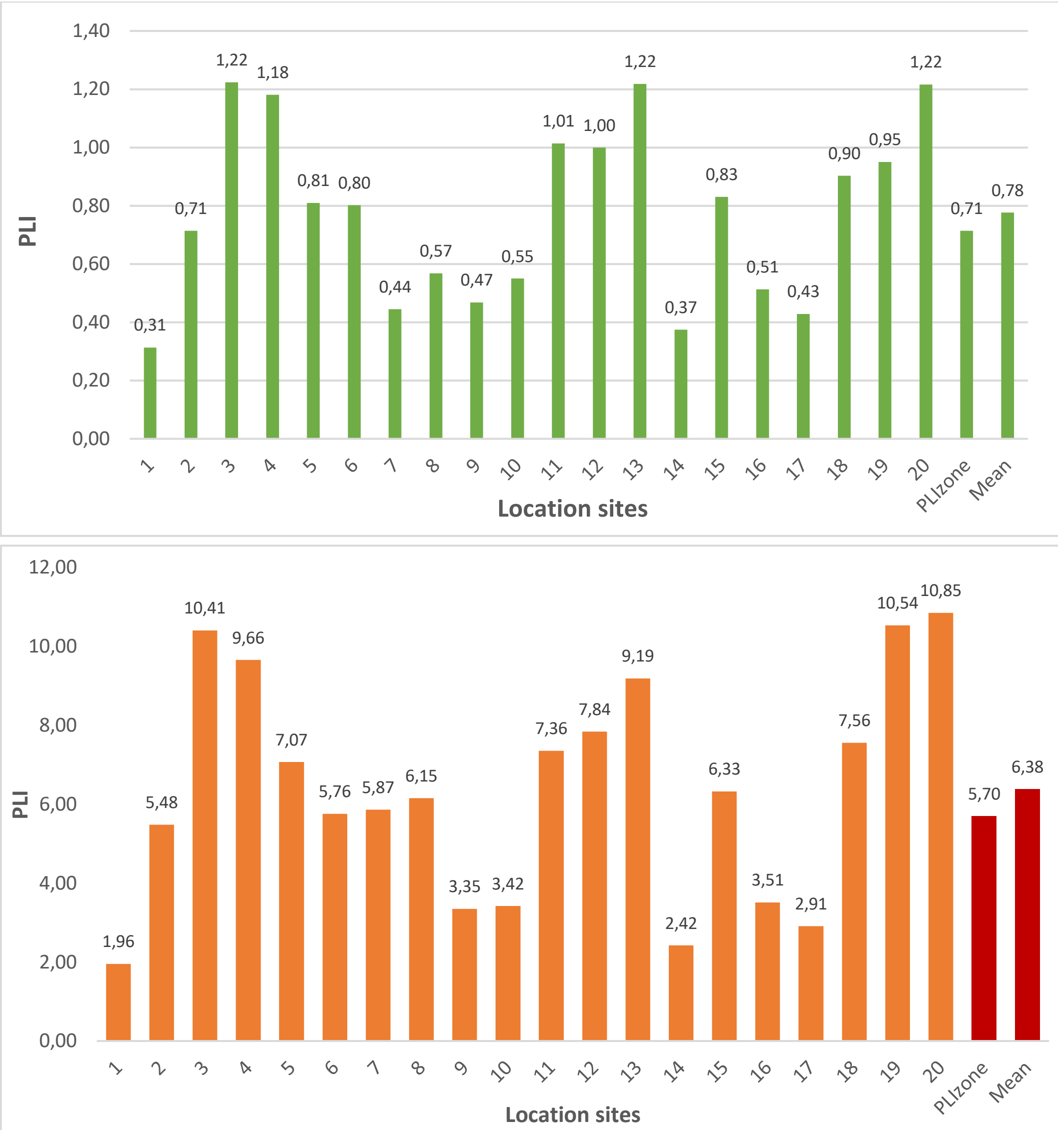

Fig. 5. Pollution load index (PLI) for (a) eight heavy metals and (b) five heavy metals (Cd, Co, Cr, Ni, and Pb).

CONCLUSIONS

This study evaluated the concentration levels and spatial distribution of eight heavy metals: cadmium, cobalt, chromium, copper, iron, nickel, lead, and zinc, in moss samples collected from 20 locations along the Lepenc river in Kosovo. The findings revealed significant contamination by several heavy metals, particularly Cd, Pb, Ni, and Cr, indicating notable anthropogenic pressure in specific areas.

Pearson correlation analysis revealed strong associations between specific metal pairs, particularly Zn–Cd, Zn–Co, and Co–Cd. These correlations suggest shared pollution sources or similar environmental dispersion mechanisms.

Principal component analysis (PCA) was employed to identify the most contaminated regions along the Lepenc river. The samples from the Brezovica region (1–5) were characterized by low metal concentrations and minimal anthropogenic influence, reflecting natural background conditions. In the Kaçanik area (6–10), Cu pollution was evident, likely due to urban activity and pesticide use. In the Ferizaj–Shtime area (11–13), contamination was primarily attributed to urban emissions and traffic-related pollution. The most severely polluted area was Hani i Elezit (14–20), where proximity to cement production and mineral processing industries contributed to elevated Ni concentrations.

The Ferizaj region (S11–S15) demonstrated clear signs of urban-industrial pollution. PLI values exceeded 1 in most sites, while values for priority metals reached up to 9.19 in location 13, reflecting the influence of urbanization and construction activities.

Hani i Elezit (16–20) was identified as the most heavily polluted region. PLI values for five heavy metals peaked at locations 19 (10.54) and 20 (10.85), clearly indicating severe contamination from industrial emissions, particularly from cement plants and mining operations.

Based on the overall contamination factors for the five potentially toxic elements (Cd, Co, Cr, Ni, and Pb), the PLI of entire study area (PLI_{zone}) was 5.70, and indicate the high pollution area with these metals.

Based on these findings, it is concluded that industrial activities in Hani i Elezit and urban development in Kaçanik and Ferizaj are the primary contributors to heavy metal contamination along the Lepenc river. To protect both the environment and public health, continued monitoring and targeted mitigation measures are strongly recommended for these critical zones.

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Р е з и м е

МОВОВИТЕ КАКО БИОИНДИКАТОРИ НА ЗАГАДУВАЊЕТО НА ВОЗДУХОТ ПО ТЕКОТ НА РЕКАТА ЛЕПЕНЕЦ ВО РЕПУБЛИКА КОСОВО

Аделина Хаскај[1,2], Соња Лепиткова[1*]

[1]*Факултет за природни и технички науки, Универзитет „Гоце Делчев“, Штип,*
Бул. „Крсте Мисирков“ 10А, 2000 Штип, Северна Македонија
[2]*Alma Mater Европски кампус колеџ „Резонанца“, Глококте Шелгјет „Ветерник“,*
10000 Приштина, Република Косово
*sonja.lepitkova@ugd.edu.mk

Клучни зборови: тешки метали: мовови; биоиндикатори: индекс на оптовареност со загадување (PLI); анализа на главни компоненти (PCA)

Оваа студија ја истражува дистрибуцијата и потенцијалното влијание на тешките метали (Cd, Co, Cr, Cu, Fe, Ni, Pb, Zn) во примероци мов собрани на 20 локации по текот на реката Лепенец во Косово, со употреба на индуктивно спрегната плазма – атомска емисиона спектроскопија (ICP-AES). За подобро објаснување на податоците за концентрациите на метали во мововите беа спроведени статистичка анализа (минимална, максимална, средна вредност, медијана итн.), кластерска анализа, анализа на главни компоненти (PCA) и индекси на загадување (фактор на контаминација и индекс на оптовареност со загадување).

Ниски нивоа на контаминација беа забележани во примероците од областа Брезовица, планински регион со минимално антропогено влијание. Примероците од областа

Качаник покажаа значително збогатување со Fe, Pb, Zn, Cd, Cr и Co, што веројатно го одразува влијанието на емисиите од возила, урбаната прашина и тековните градежни активности.

Највисоки нивоа на контаминација беа регистрирани во примероците 19 и 20, собрани од индустрискиот регион Хан и Елезит. Овие примероци ги надминаа критичните прагови на факторот на контаминација (CF) за повеќе елементи (Cd, Co, Cr, Ni и Pb), што ги означува како жаришта на загадување. Понатаму, индексот на оптовареност со загадување (PLI) за целата област изнесуваше 5,7, што потврдува значително загадување на овие локации.

Овие наоди ја нагласуваат итната потреба од насочена стратегија за мониторинг на животната средина и ублажување на загадувањето, особено во урбанизираните подрачја како што се Урошевац и индустриските центри Хан и Елезит и Качаник.