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AIR DEPOSITION OF HEAVY METALS IN THE PRISHTINA REGION USING MOSSES AND LICHENS AS BIOINDICATORS

Abstract: Heavy metal pollution is an important environmental issue in urban and industrial areas because these elements persist in the environment and may cause ecological and health problems. The aim of this study was to investigate the atmospheric deposition of heavy metals (Cu, Mn, Ni, Pb, Zn, and Cr) in the Prishtina region (Kosovo) using mosses and lichens as bioindicators. A total of 24 moss samples (*Hypnum cupressiforme*) and 9 lichen samples (*Cladonia portentosa*) were collected between June and August 2025. The plant samples were digested using aqua regia and analysed by Inductively Coupled Plasma Atomic Emission Spectroscopy (ICP-AES). Multivariate statistical methods, including basic statistics, Pearson correlation, and principal component analysis (PCA), together with spatial distribution analysis of heavy metals, were applied to facilitate clearer data interpretation. To evaluate the degree of heavy metal contamination at individual sites and across the entire region, four pollution indices (*CF*, *PLI*, *Eri*, and *PERI*) were calculated. The results indicate that the study area is contaminated with nickel, chromium, and lead, mainly due to mining activities at the open-pit ferronickel mines in Golesh, emissions from the ferronickel smelter in Drenas, and heavy traffic along the Prishtina-Peja highway. The ecological risk index (*Eri*) for nickel in moss samples ranged from 6.00 to 336, while in lichen samples it ranged from 6.00 to 42.0. Copper showed *Eri* values of 6.67-16.67 in mosses and 3.33-5.00 in lichens. For lead, *Eri* values in moss samples ranged from 3.33 to 53.33, whereas in lichens they were below the detection limit. Based on moss data, 9 locations (39.1 %) were classified as moderately polluted, while 14 locations (60.9 %) fell into the unpolluted to moderately polluted category. In lichen samples, 3 locations (37.5 %) were classified as unpolluted and 5 locations (62.5 %) as unpolluted to moderately polluted. Overall, both the concentrations and pollution indices of heavy metals in mosses were 2-7 times higher than those observed in lichens at the same sampling locations. The smaller number of lichen samples compared with moss samples reflects their limited presence at several sampling sites, which represents a limitation of the study.

Keywords: heavy metals, mosses, lichens, pollution indices, ferronickel mine, Kosovo

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Introduction

Environmental pollution is one of the biggest and most complex challenges facing society [1, 2]. As a result of the expansion and great intensity of anthropogenic activities, urban environments are facing profound and dynamic changes. Within these environments, metals and metalloids represent one of the main categories of urban pollutants [3, 4]. Heavy metals pose a serious environmental problem, due to their high level of toxicity and their harmful impacts on both living organisms and the functioning of ecosystems [5, 6]. The main sources of these elements are considered to be natural and anthropogenic. Natural sources such as natural erosion of the crust, erosion, volcanic activity while anthropogenic activity such as agricultural, urban runoff and industrial activities and many others [7, 8]. These metals are often described as “silent killers” when their density exceeds 5 g/cm^3 [9]. Heavy metals are pollutants that do not dissolve and spread easily in the environment. They persist for a long time and pass from one trophic level to another through biomagnification. Some of them, such as lead (Pb), cadmium (Cd), mercury (Hg) and nickel (Ni), are toxic in their divalent form, while chromium (Cr) is toxic in both its trivalent and hexavalent forms. However, some metals, such as iron (Fe), copper (Cu), zinc (Zn), manganese (Mn) and molybdenum (Mo), are essential for the life and functioning of ecosystems [2]. Beyond toxic impacts on human health, heavy metals have negative effects on terrestrial and aquatic ecosystems, causing a decline in plant and animal populations, as well as disrupting the functioning and dynamics of the food chains [2, 10]. These impacts, which often act in combination and accumulate over time, show the importance of reliable and continuous environmental monitoring. However, due to the interaction and simultaneous presence of different pollutants, assessing the impacts of pollution on living organisms presents considerable difficulties. Although field measurements and distribution models can provide information on pollution sources, these approaches have limitations in assessing the biological effects of pollutants on ecosystems and are usually only applicable to limited geographical areas [11, 12].

To address these challenges bioindicators are used [2, 6, 13, 14]. The term “bioindicators” is used to describe organisms that indicate the presence of pollutants in the environment through specific symptoms, morphological changes, their visibility, or changes in distribution and disappearance within the ecosystem [2]. Among those organisms, mosses and lichens have been successfully used over the years as a good biomonitors and indicators of metal pollution as reported by many researchers [15-20]. Numerous studies used different pollution indices as a tool to analyse the risk posed by potentially toxic metals in different environments such as soil, sediments, and plants [21-23]. Therefore, mosses and lichens were used in our study as the main bioindicators to investigate the accumulation and distribution of heavy metals across Kosovo, providing a clear assessment of environmental contamination and potential ecological risks.

The aim of this study was to investigate the atmospheric deposition of heavy metals in the Prishtina region (Republic of Kosovo) using mosses and lichens as bioindicators, and to evaluate spatial variations related to urbanisation, transport, and nearby industrial activities. In particular, the study focused on three main objectives:

- i. to determine the concentrations and spatial distribution of selected heavy metals (Cu, Mn, Ni, Pb, Zn, and Cr) in moss and lichen samples collected across the Prishtina region;

- ii. to assess the degree of environmental contamination and ecological risk using several pollution assessment metrics, including the Contamination Factor (*CF*), Pollution Load Index (*PLI*), Ecological Risk Index (*Eri*), and the Potential Ecological Risk Index (*PERI*); and
- iii. to identify possible relationships and sources of the studied metals. To address these objectives, spatial distribution patterns were analysed using the Inverse Distance Weighting (*IDW*) interpolation method, while Pearson correlation and principal component analysis (*PCA*) were applied to evaluate relationships among metals and potential common sources.

The study was guided by the following research questions: whether mosses and lichens differ in their capacity to accumulate heavy metals in the study area; whether higher metal concentrations are associated with locations influenced by industrial activities and transport; and which elements contribute most to the ecological risk in the Prishtina region. By combining biomonitoring with statistical analysis, pollution indices, and spatial mapping, the study aims to identify areas most affected by anthropogenic and geogenic sources of pollution.

Materials and methods

Study area

The Prishtina region is one of the seven administrative regions of the Republic of Kosovo and consists of seven municipalities: Prishtine, Podujeva, Drenas, Lipjan, Fushe Kosove, Kastriot, and Graçanice. It covers an area of 2,081 km², representing approximately 19 % of the country's total surface area. Located in the central and northeastern parts of Kosovo, the region is characterised by complex geological settings, diverse landforms, a continental climate, an extensive network of rivers and streams, and varied vegetation types. The geological framework of the Prishtina administrative region is highly complex and includes diverse lithological units associated with the Vardar Geological Zone and the Drenica Unit. Magmatic and metamorphic rocks predominantly occur in hilly and mountainous areas, while unconsolidated sediments are mainly distributed in the lowlands, including the Kosovo, Llapi, and Drenica plains [24]. The regional relief is marked by an alternation of plains and hilly-mountainous landscapes, with extensive tectonically formed flat plains. The region experiences a continental climate, with mean annual precipitation ranging from 600 mm to 1,000 mm and average annual temperatures between 6 °C and 11 °C. Hydrologically, most of the territory belongs to the Sitnica River basin, with surface waters draining toward the Black Sea. The prevailing wind direction is from the north, and during the sampling period, wind speeds ranged between 11 km/h and 24 km/h. Vegetation is predominantly continental, while alpine vegetation occurs at higher elevations [25]. Over the past two decades, numerous studies have documented significant land-use and land-cover changes, particularly the conversion of agricultural land into artificial surfaces. These changes are most pronounced in the Llapi Plain and the Kosovo Plain [26, 27], where the capital city of Prishtina is located and where major industrial zones, including power-plant complexes, are concentrated. According to the most recent population census, the region is home to approximately 506,000 inhabitants distributed across 270 settlements, with an average population density of 243 inhabitants per km². The area surrounding Prishtina exhibits the highest residential density in the country, intensifying pressure on agricultural land and groundwater resources [28].

Sample collection and preparation

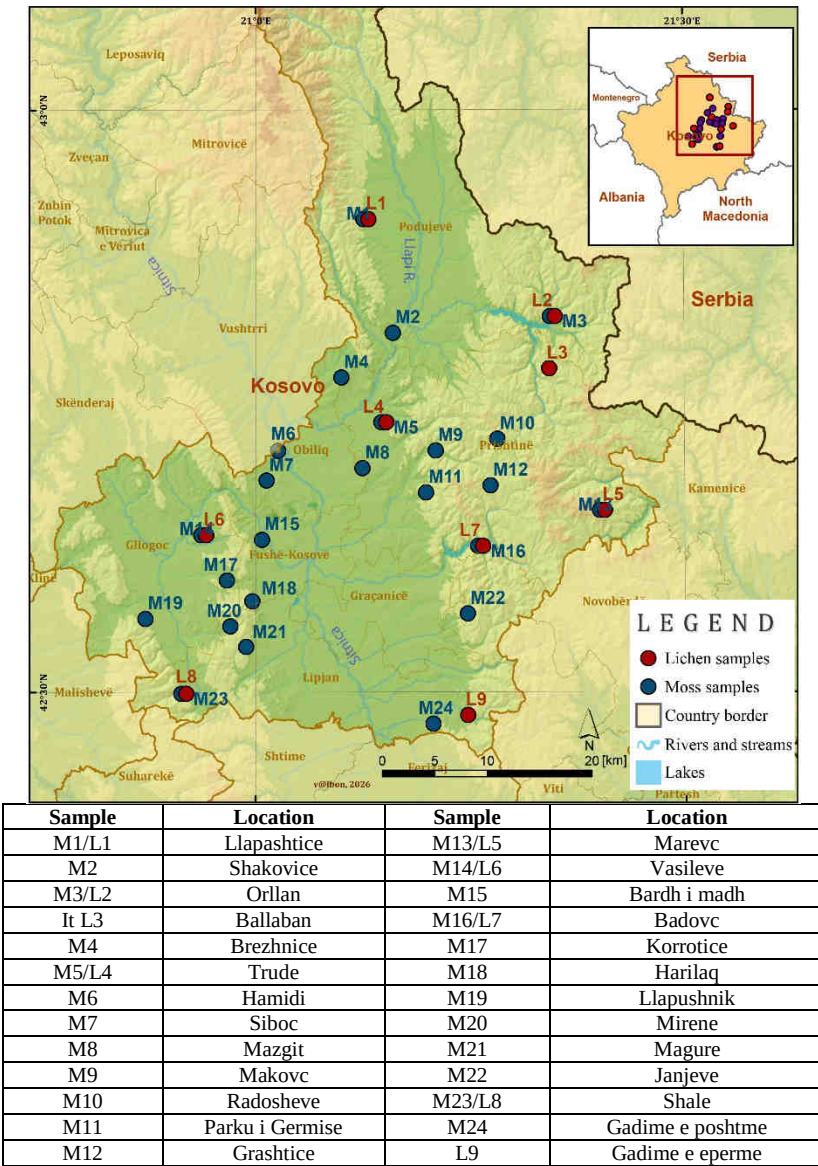


Fig. 1. Sampling locations of moss (*Hypnum cupressiforme*) and lichen (*Cladonia portentosa*) in the Prishtina region

Moss and lichen samples were collected following the moss sampling protocol (Manual of ICP Vegetation, 2020) between June and August 2025. In total, 24 moss samples (*Hypnum cupressiforme*) and 9 lichen samples (*Cladonia portentosa*) were

collected from the Prishtina region (Fig. 1). The number of lichen samples was smaller than that of moss samples because they could not be found at all locations. At each site, 5-10 subsamples were collected, placed in paper bags, and stored in a dry location until further analysis. In the laboratory, samples were carefully cleaned of extraneous plant material, leaves, and debris, and then manually ground using clean equipment while wearing gloves to avoid contamination. Approximately 0.5 g of each sample was digested in aqua regia (HCl : HNO₃, 3 : 1) following standard procedures. Digested samples were diluted to a fixed volume 25 cm³ with deionised water and analysed for Cu, Mn, Ni, Pb, Zn, and Cr using inductively coupled plasma-atomic emission spectrometry (ICP-AES). The lower detection limits for ICP-AES were 1 mg/kg for Cu, Ni, and Cr; 2 mg/kg for Pb and Zn; and 5 mg/kg for Mn.

Quality control was ensured through the inclusion of procedural blanks, duplicate samples, and the moss material M3 as the certified reference materials (CRMs). Recovery rates of metals in the reference materials ranged from 92 % to 105 %, and replicate measurements showed relative standard deviations below 5 %, confirming the reliability and reproducibility of the analytical procedure.

Pollution indices

Based on the concentrations of chemical elements measured in moss and lichen samples, four different contamination indices were calculated. The contamination factor (*CF*) is used to estimate the level of hazardous metals in the environment, according to the method proposed by Fernández and Carballeira [29]. Its mathematical formula is:

$$CF = \frac{C_{metal}^i}{C_{reference}^i} \quad (1)$$

where: C_{metal}^i - indicates the amount of metal present at the studied site, and $C_{reference}^i$ - background indicates the metal concentration in a clean or uncontaminated area. In this study, as a reference we took samples of mosses and lichens collected at the same location (M16 and L7) which is located in the mountains, away from industrial areas and we expected to be less affected by anthropogenic pollution.

According to Fernández and Carballeira [29], the following intervals are used to classify the contamination level: $CF < 1$ indicates no contamination; $1 \leq CF \leq 2$ indicates; $2 \leq CF \leq 3.5$ indicates slight contamination; $3.5 \leq CF \leq 8$ indicates moderate contamination; $8 \leq CF \leq 27$ indicates severe contamination; and $CF > 27$ represents extreme contamination.

The pollution load index (*PLI*) is calculated as the *n*th root of the product of the contamination factors (*CF*) for *n* metals calculated by Tomlinson et al. [30], and Kowalska et al. [31], and expressed by the following formula:

$$PLI_{site} = \sqrt[n]{CF_1 \cdot CF_2 \cdots CF_n} \quad (2)$$

In this study, the *PLI* for the entire area. Specifically, the area of Prishtina region, is calculated using the following formula:

$$PLI_{zone} = \sqrt[m]{PLI_1 \cdot PLI_2 \cdots PLI_m} \quad (3)$$

In this formula, *m* represents the number of sampling locations. According to Zhang et al. [32], pollution levels are classified as follows: a *PLI* of 0 corresponds to background concentration; values of $PLI \leq 1$ indicate unpolluted conditions; *PLI* between 1 and 2

corresponds to unpolluted to moderately polluted; $2 < PLI \leq 3$ indicates moderate pollution; $3 < PLI \leq 4$ corresponds to moderate to high pollution; $4 < PLI \leq 5$ indicates high pollution; and $PLI > 5$ represents very high pollution.

The Potential Ecological Risk Index (*PERI*) can be used to assess the ecological risks of chemical elements [33, 34] in moss and lichen samples and is expressed using the following formulas:

$$PERI = \sum Eri \quad (4)$$

$$Eri = Tr \cdot CF \quad (5)$$

where *PERI* is determined as the summation of all risk values of all heavy metals in moss and lichen samples, while *Eri* is considered as “the monomial ecological risk value”, *CF* is taken as the contamination factor, while *Tr* is termed as the toxic response value or factor. The toxic-response factors for Cu, Mn, Ni, Pb, Zn, and Cr are 5, 1, 6, 5, 1, and 2, respectively [34]. The ecological risk is classified into five categories based on the ecological risk index [33-35] as follows: *Eri* < 40 - low ecological risk; $40 \leq Eri < 80$ - moderate ecological risk; $80 \leq Eri < 160$ - considerable ecological risk; $160 \leq Eri < 320$ - high ecological risk; *Eri* ≥ 320 - very serious ecological risk. Also, *PERI* was classified: *PERI* < 95 - low ecological risk; $95 < PERI < 190$ - moderate ecological risk; $190 < PERI < 380$ - considerable ecological risk, and *PERI* > 380 - very high ecological risk.

Statistical analysis

Statistical analyses were performed using PAST 4.11 software. These analyses included the calculation of basic statistics, such as minimum, maximum, mean, median, standard deviation, skewness, kurtosis, and coefficient of variation. The Box-Cox transformation (optimal power parameter determined by software) was used to achieve a normal distribution of the data, which allows the calculation of Pearson correlation and principal component analysis (PCA).

Inverse Distance Weighting (IDW) interpolation is a deterministic spatial interpolation method used to estimate values at unsampled locations based on nearby measured points. The method assumes that points closer to the prediction location have a greater influence on the estimated value than those farther away.

The predicted value at an unknown location is calculated as a weighted average of the surrounding sampled points:

$$Z(x_0) = \frac{\sum_{i=1}^t w_i Z(x_i)}{\sum_{i=1}^t w_i} \quad (6)$$

where: $Z(x_0)$ - predicted value at location x_0 , $Z(x_i)$ - observed value at known point i , w_i - weight assigned to point i , t - number of neighboring points used in the estimation.

Based on the sampling sites, the points with their spatial coordinates were introduced into ArcMap 10.8, where Inverse Distance Weighting (IDW) interpolation was applied. Using the default settings, an individual raster surface was generated for each analysed chemical element, with an output cell size of 250 m. Thematic maps were created for each analysed chemical element, with colour gradients classified according to standard deviation to illustrate spatial variability and distribution patterns.

Results

Heavy metals Cu, Mn, Ni, Zn, and Cr were determined in 24 moss samples and 9 lichen samples (Table 1). Lead was detected in only 18 moss samples, as concentrations in 6 moss samples and all lichen samples were below the limit of detection (< 2 mg/kg). The mean concentration of metals in moss and lichen samples decreased in the order $Mn > Zn > Ni > Cu > Cr$. The mean values of all analysed metals in mosses were higher compared to lichens. Copper and zinc show a relatively uniform distribution across the study area, as indicated by the small differences between their minimum and maximum concentrations and by low values of skewness, kurtosis, and coefficient of variation ($CV < 30\%$). In contrast, nickel, lead, and manganese display high skewness, kurtosis, and coefficient of variation values ($CV > 165\%$).

Table 1
Basic statistics of chemical elements in moss and lichen samples

Metal	Moss						Lichen				
	Cu	Mn	Ni	Pb	Zn	Cr	Cu	Mn	Ni	Zn	Cr
Number of samples	24	24	24	18	24	24	9	9	9	9	9
Min	3.0	41	2	2.0	14.0	2.0	2.00	19	1.0	12.0	1.0
Max	10.0	407	112	32.0	31.0	11.0	3.00	121	7.0	25.0	6.0
Mean	5.7	96	13	4.2	20.2	5.4	2.33	51	2.3	15.2	2.0
Stand. dev	1.6	73	22	7.0	4.5	2.4	0.50	32	1.8	4.1	1.6
Median	5.0	75	6.0	2.0	19.5	5.0	2.00	50	2.0	14.0	2.0
25 prcntil	4.2	62	4.0	2.0	16.0	3.2	2.00	24	1.5	12.5	1.0
75 prcntil	7.0	108	12	3.2	23.7	6.7	3.00	64	2.0	16.5	2.0
Skewness	0.79	3.70	4.06	4.16	0.61	0.72	0.86	1.44	2.65	2.06	2.44
Kurtosis	0.66	15.81	18	17.48	-0.27	0.07	1.71	2.40	7.62	4.51	6.57
CV [%]	28.8	75.96	167	165	22.35	44.8	21.4	62.9	77.3	26.8	79.1

To calculate the pollution factors, the Badovc location was used as the background site, as it is situated in the mountains far from industrial activities, and both mosses (M16) and lichens (L7) were found at the same place.

Table 2 presents the distribution of elements across contamination factor (CF) categories. In moss samples, nickel was categorised as follows: 3 locations in C2, 8 in C3, 7 in C4, 4 in C5, and 1 location showed extreme contamination. In lichens, nickel was classified as 1 location in C2, 6 in C3, and 1 location as moderate contamination. Chromium was classified as C2 at 5 moss locations and 3 lichen locations. Category C3 included 12 moss locations and 4 lichen locations, while 6 moss locations and 1 lichen location were classified as moderate contamination. Lead showed severe contamination at 1 moss location, 6 locations were in C2, and 16 locations fell into C1 (no contamination). Copper in moss samples was classified as C2 in 12 locations and C3 at 11 locations, whereas in lichens it was found as C1 at 6 locations and C2 at 2 locations. For the other metals (Mn and Zn), most locations fell into C2 (suspected contamination) or C1 (no contamination).

PLI values for the Prishtina region in moss samples ranged from 1.16 (M4) to 2.51 (M17), while in lichen samples they ranged from 0.88 (L6) to 1.80 (L8). The site-specific PLI classifications are presented in Table 3.

Table 2

Contamination factor of heavy metals in moss and lichen samples

Categori-sation	Class	Moss						Lichen				
		Cu	Mn	Ni	Pb	Zn	Cr	Cu	Mn	Ni	Zn	Cr
$CF < 1$	C1	-	6	-	16	8	-	6	4	-	6	-
$CF = 1-2$	C2	12	13	3	6	15	5	2	3	1	2	3
$CF = 2-3.5$	C3	11	3	8	-	-	12	-	1	6	-	4
$CF = 3.5-8$	C4	-	1	7	-	-	6	-	-	1	-	1
$CF = 8-27$	C5	-	-	4	1	-	-	-	-	-	-	-
$CF > 27$	C6	-	-	1	-	-	-	-	-	-	-	-
CF mean		1.93	1.54	6.93	1.43	1.13	1.82	0.75	1.01	2.5	1.02	2.13

"-": no location

Among the lichens, 3 samples (37.5 %) were classified as unpolluted ($PLI < 1$), and 5 samples (62.5 %) as unpolluted to moderately polluted ($1 < PLI \leq 2$). In moss samples, 14 locations (60.9 %) were categorised as unpolluted to moderately polluted, while 9 samples (39.1 %) were moderately polluted ($2 < PLI \leq 3$).

The overall PLI for the study area was 1.77 for mosses and 1.18 for lichens.

Table 3

Pollution load index of heavy metals in moss and lichen samples

PLI site	Class	Moss	Lichen
$PLI < 1$	Unpolluted	-	3
$1 < PLI \leq 2$	Unpolluted to moderately polluted	14	5
$2 < PLI \leq 3$	Moderately polluted	9	-
PLI zone		1.77	1.18

"-": no location

The potential ecological risk index ($PERI$) for heavy metals in moss and lichen samples from the Prishtina region is presented in Table 4. The ecological risk factor (Eri) for nickel showed high values, ranging from 6.00 to 336 in mosses and from 6.00 to 42.00 in lichens. Lead showed Eri values ranging from 3.33 to 53.33 in mosses, while concentrations in lichens were below the detection limit. Copper had Eri values ranging from 6.67 to 16.67 in mosses and from 3.33 to 5 in lichens. Manganese showed values ranging from 0.65 to 6.46 in mosses and from 0.38 to 2.42 in lichens. Chromium and zinc showed similar Eri values in both plants: in mosses, 2.00-11.00 (Cr) and 0.78-1.72 (Zn), and in lichens, 2.00-12.00 (Cr) and 0.78-1.67 (Zn).

To better understand the origin of the investigated metals, maps of the spatial distribution of elements by location were prepared (Fig. 4). These maps show that, in both plant types, Cu and Zn exhibit a relatively homogeneous distribution, whereas the other metals display a more heterogeneous distribution, reflecting pollution sources at specific locations.

Table 4

Potential ecological risk index of heavy metals in moss and lichen samples

<i>Eri</i>	Cu	Mn	Ni	Pb	Zn	Cr	PERI
M1	6.67	6.46	75.00	3.33	0.83	7.00	99.29
L1	3.33	1.00	12.00	-	0.87	4.00	21.20
M2	6.67	2.05	12.00	-	0.89	3.00	24.60
M3	8.33	1.73	6.00	-	1.06	2.00	19.12
L2	5.00	2.42	12.00	-	0.80	2.00	22.22
L3	5.00	1.50	12.00	-	1.67	4.00	24.17
M4	10.00	0.83	9.00	3.33	1.00	3.00	27.16
M5	11.67	1.37	15.00	5.00	1.39	4.00	38.42
L4	3.33	0.38	12.00	-	0.93	4.00	20.65
M6	8.33	0.75	15.00	3.33	1.17	5.00	33.58
M7	10.00	0.65	15.00	3.33	0.78	5.00	34.76
M8	8.33	1.08	21.00	-	1.11	7.00	38.52
M9	11.67	1.03	15.00	-	1.44	6.00	35.14
M10	11.67	1.19	27.00	3.33	1.72	10.00	54.91
M11	8.33	2.10	24.00	-	0.83	6.00	41.26
M12	10.00	2.46	24.00	6.67	1.39	6.00	50.52
M13	13.33	1.68	36.00	3.33	1.22	9.00	64.57
L5	3.33	1.08	6.00	-	0.80	2.00	13.21
M14	6.67	0.98	15.00	5.00	0.89	4.00	32.54
L6	3.33	0.42	12.00	-	0.93	2.00	18.69
M15	6.67	1.32	18.00	-	0.89	6.00	32.87
M17	8.33	1.10	21.00	53.33	1.22	6.00	90.98
M18	10.00	1.68	60.00	6.67	0.83	5.00	84.18
M19	6.67	1.19	69.00	6.67	1.11	8.00	92.63
M20	13.33	1.19	33.00	5.00	1.50	4.00	58.02
M21	16.67	0.84	336.00	3.33	1.06	3.00	360.9
M22	11.67	1.75	12.00	3.33	1.33	3.00	33.08
M23	8.33	0.83	90.00	3.33	1.28	11.00	114.77
L8	3.33	0.56	42.00	-	1.20	12.00	59.09
M24	8.33	1.16	9.00	3.33	0.94	4.00	26.77
L9	3.33	0.74	12.00	-	0.93	4.00	21.01

"- " - below detection limit

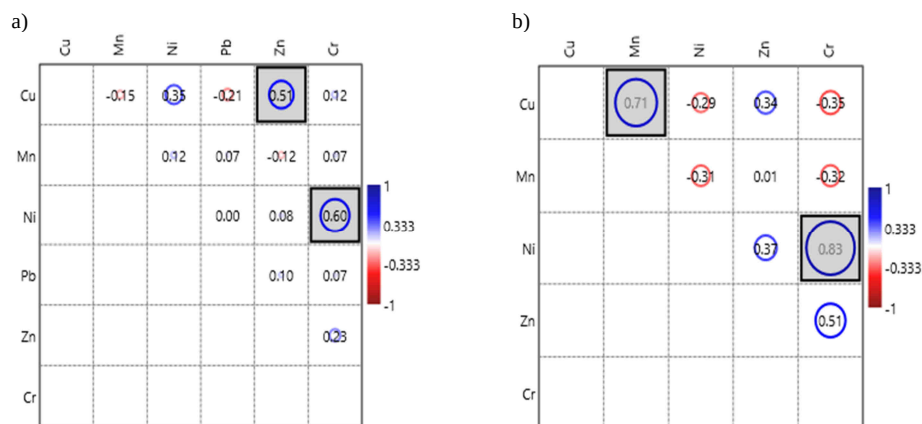


Fig. 2. Pearson correlation of heavy metals after Box Cox transformation: a) moss and b) lichen samples; numbers in box ($p < 0.05$); blue = positive correlation, red = negative correlation

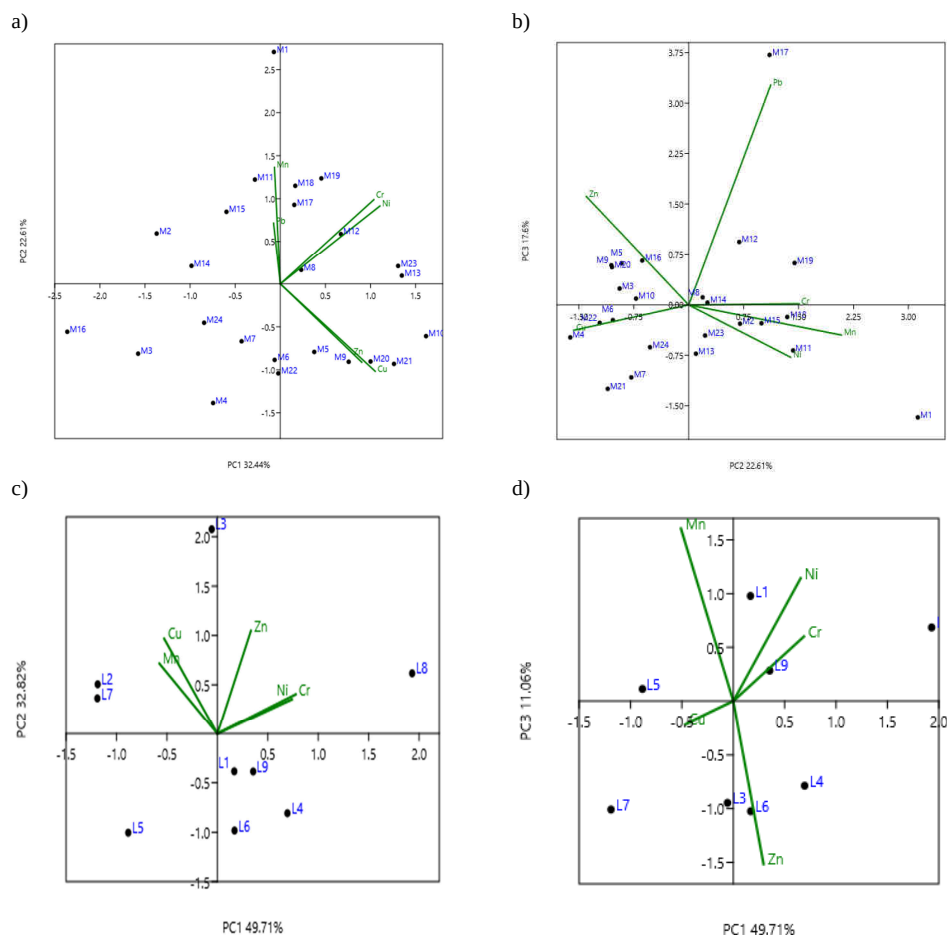


Fig. 3. Principal component analysis (PCA) of heavy metal, based on correlations of locations and chemical elements: a) and b) in moss and c) and d) in lichen samples

The Pearson correlation coefficients (r) for the analysed heavy metals are presented in Figure 2. In moss samples, good positive correlations were observed between Ni and Cr (0.60) and Cu and Zn (0.51). In lichen samples, strong positive correlations were observed between Ni and Cr (0.83) and Cu and Mn (0.71). Other element pairs exhibited weak positive or negative correlations. Associations with $r > 0.5$ and a significance level of $p < 0.05$ were considered strong and statistically significant, serving as indicators of potential common sources or similar geochemical behaviour. Absolute r values between 0.70 and 1.00 indicate a strong correlation, while values between 0.50 and 0.70 indicate a good correlation [36].

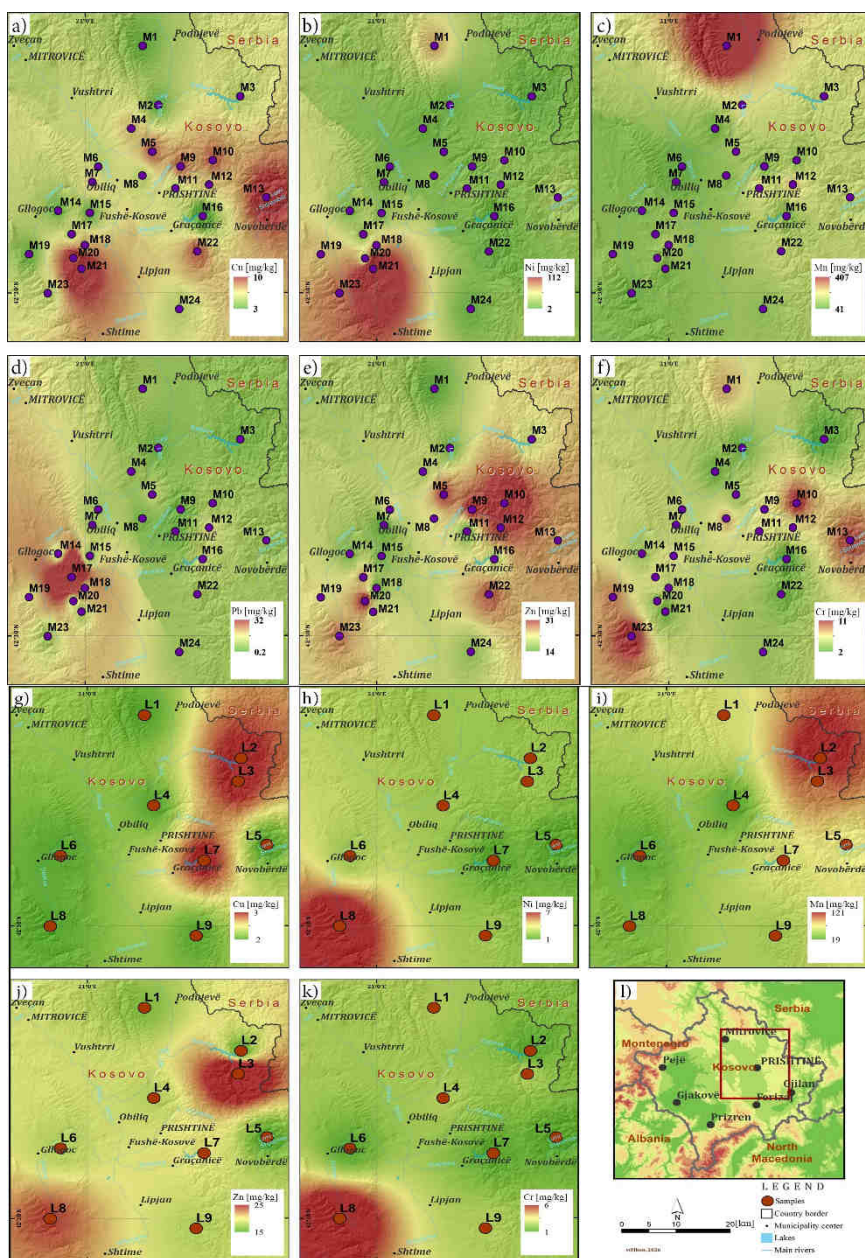


Fig. 4. Map distribution of heavy metals: a) to f) in moss samples; g) to k) in lichen samples, and l) map of the research area

To identify the spatial distribution of heavy metals in moss and lichen samples and to assess potential sources of contamination, principal component analysis (PCA) was performed. In Figure 3, the three principal components (PC1, PC2, and PC3) are presented,

based on correlations between locations and chemical elements that contributed most to the total variance - 72.65 % in moss and 93.59 % in lichen samples. In the PCA results for mosses (Fig. 3a), it is evident that Ni and Cr contribute strongly to PC1 and PC2, and the small angle between their vectors indicates a common origin. Cu and Zn also contribute significantly to PC1 and PC2, but their vector orientations are opposite to those of Ni and Cr, reflecting a strong influence from industrial activity in the studied area. Manganese is strongly influenced by location M1 and primarily affects PC2, reflecting its geological origin. Lead contributes mainly to PC3 and is most affected by vehicle traffic. Similar patterns were observed in lichens (Fig. 3b), where Ni and Cr contribute most to PC1, Cu and Zn to PC2, and manganese strongly influences PC3.

Discussion

Heavy metals in the environment serve as critical markers of both natural processes and human impact due to their persistence and potential toxicity. When comparing our results presented in Table 1 with those of research conducted in Kosovo and the surrounding region, we observe that the mean values of Cu (5.67 mg/kg), Ni (13.38 mg/kg), and Cr (5.38 mg/kg) are higher than those reported in the 2020 Kosovo moss survey [37], but lower than values reported for mosses from Golesh [14] and the industrial zone of Obiliq [18]. In contrast, the mean concentrations of Mn (95.54 mg/kg), Zn (20.17 mg/kg), and Pb (4.22 mg/kg) are lower than those reported in previous moss studies conducted in Kosovo [14, 18, 37]. The mean concentrations of all heavy metals in lichens were lower than those in mosses, ranging from 1.3 times lower for Zn to 5.7 times lower for Ni. Similar findings were reported in North Macedonia by Balabanova et al. [38]. Based on the values of skewness, kurtosis, and the coefficient of variation, Cu and Zn show a more homogeneous distribution, likely due to the geological background and widespread industrial influence in the study area. In contrast, Cr, Ni, Mn, and Pb exhibit a more heterogeneous distribution, reflecting localised anthropogenic impacts [35, 36].

The highest contamination factor (*CF*) values were observed for nickel in areas surrounding the ferronickel mines in Golesh, with moss samples showing *CF*s of 56 (M21), 15 (M23), 11.5 (M19), and 10 (M18), and lichens showing *CF* = 6 (L8). Lead also showed elevated levels at location M17, influenced by heavy traffic, with *CF* = 10.7. Chromium contributed significantly to pollution, with six moss sites and one lichen site classified as C4, including *CF* = 5.5 (M23) and 6.0 (L8). The mean contamination factor for nickel across the study area was 6.93 in mosses and 2.5 in lichens, while for chromium it was 1.82 in mosses and 2.13 in lichens. Mean *CF* values for zinc were 1.13 in mosses and 1.02 in lichens. Comparable results have been reported for mosses in New Zealand [39]. *PLI* values effectively reflect the dominant industrial activities in a region, with the highest values associated with mining and heavy industry, intermediate values linked to transportation and urbanisation, and the lowest values observed in protected or non-industrialised areas [39, 40]. The overall *PERI* values ranged from 19.12 in Orllan (M3) to 360.9 in Magure (M21) in mosses, and from 13.21 in Marevc (L5) to 59.09 in Shale (L8) in lichens. The most polluted sites were located around the Golesh massif, where elevated nickel and chromium levels reflect the influence of the ferronickel open-pit mines in Golesh and the smelter in Drenas [18, 38].

Based on Figures 3 and 4, copper and zinc exhibit a wide distribution across the study area, indicating a strong influence of anthropogenic sources related to industrial activities

and transportation [39]. This pattern aligns with the presence of open coal mines and the lignite-fired power plant in Obiliq, as well as the tailings landfills in Kishnica and Novoberda (Artana), which are known contributors to atmospheric Cu and Zn pollution in the region [36, 41]. Elevated concentrations of nickel and chromium were observed in moss and lichen samples collected around the Golesh massif (M21, M23, and L8), reflecting both geogenic and anthropogenic influences associated with the ferronickel mines and smelter in Drenas [18, 37, 38]. Manganese concentrations were higher in the northeastern part of the region (M1, L2, and L3), near the border with Serbia, suggesting a predominantly geogenic origin, as these sites are distant from major industrial sources. Lead concentrations in moss samples were higher at sites near the Prishtina-Peja highway (M17, M18, and M19) and the nearby industrial zone in Korrotice [18, 37]. This pattern is consistent with observations from other countries, where elevated lead levels in soils and plants were reported near busy roads and industrial areas [42-46]. In addition, the results also indicate that some metals, such as nickel and chromium, can travel farther from their sources and accumulate in higher amounts, while others, like zinc and manganese, remain at lower levels. This difference may be related to the environmental behaviour of each metal, as well as factors such as wind, rainfall, and soil characteristics. Overall, these findings confirm that mosses and lichens are effective bioindicators for monitoring pollution and can help identify areas that require attention to reduce environmental risks. The cleanest sites were Orllani (M3) and Marevci (L5), both mountainous locations situated far from industrial activities. These results highlight the impact of human activity on environmental pollution, indicating that areas away from industry and heavy traffic generally present much lower ecological risks [47-50].

Conclusion

In this study, we investigated the atmospheric deposition of heavy metals (Cu, Mn, Ni, Pb, Zn, and Cr) in the Prishtina region using mosses and lichens as bioindicators. Our results indicate that the area is most contaminated with nickel and chromium, primarily due to transport of these metals by wind from industrial activities at the open-pit ferronickel mines in Golesh and the ferronickel smelter in Drenas. Vehicles and heavy traffic were identified as the main sources of lead pollution in locations near the Prishtina-Peja highway. Copper showed a relatively homogeneous distribution across the study area, reflecting the influence of open coal mines and the Kosovo A and Kosovo B lignite power plants. Zinc also exhibited a fairly uniform distribution, likely due to the geological composition of the region, which forms a belt between the lead-zinc mines of Trepca and Artana (Novoberda). Elevated manganese concentrations were observed in the northeastern part of the study area, near the border with Serbia, resulting from geogenic factors, as these locations are distant from industrial activity.

Pollution indices (*CF*, *PLI*, *Eri*, and *PERI*) indicated that heavy metal concentrations in mosses were 2-7 times higher than in lichens at the same locations. In moss samples, 39.1 % of sites were classified as moderately polluted and 60.9 % as unpolluted to moderately polluted, while in lichens 37.5 % of sites were unpolluted and 62.5 % were unpolluted to moderately polluted. The most polluted locations were those near industrial zones and highways, reflecting the impact of human activities, whereas the cleanest sites were found in mountainous areas far from industrial influences.

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