https://doi.org/10.26565/2410-7360-2025-63-09
UDC 553.97(477.8):543.423.1

Received 11 October 2025
Accepted 18 November 2025

Vertical Distribution of Mobile Trace Elements in Peat Deposits of the Lviv Region and Their Relationships with Physico-Chemical Properties

Myroslava Yakovenko [1]
PhD (Geology), Senior Researcher, Senior Research Scientist,
[1] Institute of Geology and Geochemistry of Combustible Minerals of NAS of Ukraine, Lviv, Ukraine,
e-mail: myroslavakoshil@ukr.net, https://orcid.org/0000-0001-8967-0489;
Yurii Khokha [1]
DSc (Geology), Senior researcher, Leading Researcher,
e-mail: khoha_yury@ukr.net, https://orcid.org/0000-0002-8997-9766;
Myroslav Pavlyuk [1]
Academician of NASU, DSc (Geology & Mineralogy), Professor, Chief Researcher,
e-mail: pavlyuk.myroslav@gmail.com, https://orcid.org/0000-0001-8741-0624

ABSTRACT

Problem statement: Peatlands act as natural geochemical barriers that accumulate various chemical elements, including heavy metals. The qualitative characteristics of peat and its potential applications directly depend on the spectrum and concentrations of elements present in it. For the peatlands of Ukraine, no systematic studies of mobile element forms or assessments of their relationships with local geochemical and physico-chemical gradients (pH, ash content, moisture) have yet been conducted. This gap highlights the need for systematic, methodologically unified investigations with broad spatial coverage and standardized procedures for data processing.

Objective: To determine the levels, spatial (profile) distribution, and factors controlling the mobility of mobile forms of selected elements (Pb, As, Tl, Mo, Zn, Cd, Ni, Sb, Cu, Co, Mn, Cr, V) in the peats of the Lviv region; to clarify their relationships with physico-chemical properties of peat (pH, ash content, moisture content, organic matter content); and to identify depth-related trends and accumulation anomalies.

Methods: Twenty-six samples were collected from the 0–140 cm depth interval at 20 cm steps (across three profiles), supplemented with samples from upper peat layers at additional sites. Mobile element forms were extracted with 0,2 M HCl and quantified by inductively coupled plasma atomic emission spectroscopy (ICP-AES). Ash content, moisture content, and pH were determined using arbitration methods according to DSTU standards. Statistical analyses were applied to evaluate the dependence of element concentrations on depth and physico-chemical parameters, to examine relationships among trace elements and other peat characteristics, and to assess potential sources of their accumulation.

Results: Average concentrations of mobile forms of Pb, Zn, Cd, Cu, Ni, Mn, and Cr were 10,8; 15,5; 0,65; 3,86; 2,09; 16,6 and 0,96 ppm, respectively. Very high coefficients of variation (>80%) were observed for Pb, Cd, Tl, Mo, Sb, and Mn, indicating a mosaic spatial distribution. Maximum values of Pb (132,35 ppm) and Cd (8,88 ppm) occurred in the 60-80 cm horizon of the Honchary peatland, while elevated As (14,9 ppm) was found in the lower part of the Hamaliivka profile. In most samples, concentrations of mobile element forms were significantly lower than the approximate normal values for soils and the contamination thresholds established for arable soils in EU countries, indicating a generally low level of technogenic impact, despite the presence of local Pb and Cd anomalies. A positive relationship between the contents of most metals and ash content, and a negative relationship with organic matter content were identified. Significant correlations among Zn, Cu, Ni, Co, Mn, and V reflect shared sources and accumulation mechanisms. The strongest correlation (r ≈ 0,99) was observed between mobile Pb and Cd, confirming their similar geochemical behavior in peat.

Conclusions: The results expand current knowledge on the geochemistry of European peatlands and, for the first time, characterize the mobile forms of several elements in the peats of the Lviv region. The peatlands of the region act as effective geochemical barriers for potentially toxic elements, while local deep anomalies of Pb–Cd and As may reflect both geogenic influences and historical atmospheric inputs. These findings refine the understanding of the geochemistry of Ukrainian peatlands and provide a basis for future assessments of environmental risks and the suitability of peat for economic use.

Keywords*: peat, peatland, geochemistry, trace elements, mobile forms, accumulation, Ukraine, Lviv region, ICP-AES.*

In cites: Yakovenko Myroslava, Khokha Yurii, Pavlyuk Myroslav (2025). Vertical Distribution of Mobile Trace Elements in Peat Deposits of the Lviv Region and Their Re-lationships with Physico-Chemical Properties. *Visnyk of V. N. Karazin Kharkiv National University. Series Geology. Geography. Ecology*, (63), 113-127. https://doi.org/10.26565/2410-7360-2025-63-09

Introduction

Peatlands, owing to the high sorption capacity of organic matter and a unique combination of environmental conditions (waterlogging, predominantly acidic pH, and a substantial content of humic components), act as important natural geochemical barriers despite occupying only about 3% of the Earth's land surface. These geological systems accumulate various chemical elements, particularly heavy metals that are potentially toxic [1]. Potentially toxic elements (*PTE*s) include both essential (biogenic) trace elements such as Fe, Mn, Cu, Zn, Ni, and Mo, which are required for the functioning of plants and microorganisms, and strictly toxic metals and metalloids (Cd, Pb, Cr, As, Sb, Tl, V) for which no biologically beneficial roles are known [2]. Conceptually, nearly every element in the periodic table may exhibit toxicity under certain conditions, depending on concentration, biological environment, pH, and redox potential.

In peat deposits, the accumulation of *PTE*s is determined by a combination of external inputs (atmospheric deposition, inflow from surface and groundwater, local anthropogenic sources) and intrinsic properties of the peat itself (organic matter content and composition, degree of decomposition and mineralization, pH, redox conditions, and the content and proportions of oxides).

A large share of these elements in peat is incorporated into stable organo-mineral complexes with humic substances, which reduces their mobility and bioavailability. However, changes in physico-chemical conditions such as acidity, ash content, moisture level, and redox regime, can remobilize bound forms and induce their transfer into groundwater and surface waters. Therefore, assessing the mobile forms of chemical elements is of particular importance, as they determine bioavailability, ecological mobility, and potential toxicity, in contrast to total concentrations.

The qualitative characteristics of peat and its potential applications directly depend on the concentrations of elements it contains. Given the central role of fundamental geochemical research in the preliminary assessment of peat resources and their rational use, this study aims to expand possibilities for practical application and support the industrial development of peatlands in the Lviv region.

The aim of the study is to evaluate the levels, spatial (profile) distribution, and factors controlling the mobility of mobile forms of heavy metals and potentially toxic trace elements (Pb, As, Tl, Mo, Zn, Cd, Ni, Sb, Cu, Co, Mn, Cr, V) in the peats of the Lviv region; to clarify their relationships with physico-chemical properties of peat (pH, ash content, moisture content, organic matter content); and to identify depth-related trends and accumulation anomalies.

The object of the study is peat material from lowland-type deposits within the Lviv region (Bilogorshcha, Honchary, Hamaliivka, Artyshchiv, Polonychna, Sknylivka).

The subject of the study is the content of mobile forms of Pb, As, Tl, Mo, Zn, Cd, Ni, Sb, Cu, Co, Mn, Cr, and V in peat, as well as the physico-chemical characteristics of the samples (pH, ash content, moisture content, organic matter content).

A considerable body of research by authors from Northern and Eastern Europe has examined the geochemistry of heavy metals and other potentially toxic elements in peatlands and soil systems, the patterns of metal enrichment in peat bogs, mechanisms of metal fixation and mobility, and the influence of environmental changes on the migration behavior of *PTE*s. Particular attention has been devoted to peatlands in Scandinavia and the Baltic region [1, 3–8]. These studies emphasize not only total metal concentrations but also mobile fractions, which determine bioavailability and potential ecological risks [9].

In contrast to European research, Ukrainian studies devoted to the geological and geochemical characterization of peat and peatlands remain limited, despite Ukraine's considerable peat resources. Fragmentation is especially evident in studies of mobile element forms and their relationships with local geochemical and physico-chemical gradients (pH, ash content, moisture). This highlights the need for systematic, methodologically unified investigations with broader spatial coverage and standardized approaches to data comparison.

Methods

Peat samples were collected using a core sampler from depths of 0 to 140 cm in 20 cm increments; the maximum depth reached 140 cm at the Honchary and Hamaliivka sites. Samples were placed in sealed polyethylene zip-lock bags with appropriate labeling and tightly closed to minimize weathering and contamination. A total of 26 samples were obtained.

In the laboratory, the samples were air-dried at room temperature, avoiding direct sunlight, then crushed, homogenized in an agate mortar, sieved through a 2,5 mm mesh, quartered, and divided into analytical portions and duplicates.

The physico-chemical properties of the samples were analyzed in accordance with DSTU standards: moisture content [10], ash content [11], and pH [12] were determined. To ensure statistical reliability, each analytical parameter for every depth interval was measured in triplicate, with final values expressed as arithmetic means.

To determine the mobile forms of chemical elements, all samples were subjected to extraction with 0,2 M HCl following DSTU 4405:2005 [13].

The concentrations of mobile forms of Pb, As, Tl, Mo, Zn, Cd, Ni, Sb, Cu, Co, Mn, Cr, and V were measured by inductively coupled plasma atomic emission spectroscopy (ICP-AES) using a Thermo Fisher Scientific iCAP PRO Series instrument operated with Qtegra Intelligent Scientific Data Solution software. Detection limits and operational ranges complied with analytical requirements for natural soil and peat matrices. All analyses were conducted in the analytical laboratory of Alpinus Chemia Sp. z o.o., Solec Kujawski, Poland.

The concentrations of trace elements in the studied peat deposits were compared with their natural levels in the Earth's crust and soils. Concentration coefficients were calculated, and the results were evaluated in comparison with analogous studies conducted for peat deposits in Europe. Mathematical and statistical data processing included the calculation of mean, median, minimum and maximum values, variance, standard deviation, coefficient of variation, skewness, and kurtosis for the physico-chemical parameters and the mobile forms of the studied elements. Correlation analysis was applied to identify dependencies and typomorphic associations among the elements.

Results and Discussion

The investigated peatlands are located within the Lviv region and correspond to the territories of the following settlements (Fig. 1): Honchary (Pustomyty district), Hamaliivka (Zhovkva district), Artyshchiv (Horodok district), Polonychna (Radekhiv district), Bilogorshcha (Lviv district), and Sknylivok (Lviv district). The last two sites are situ-

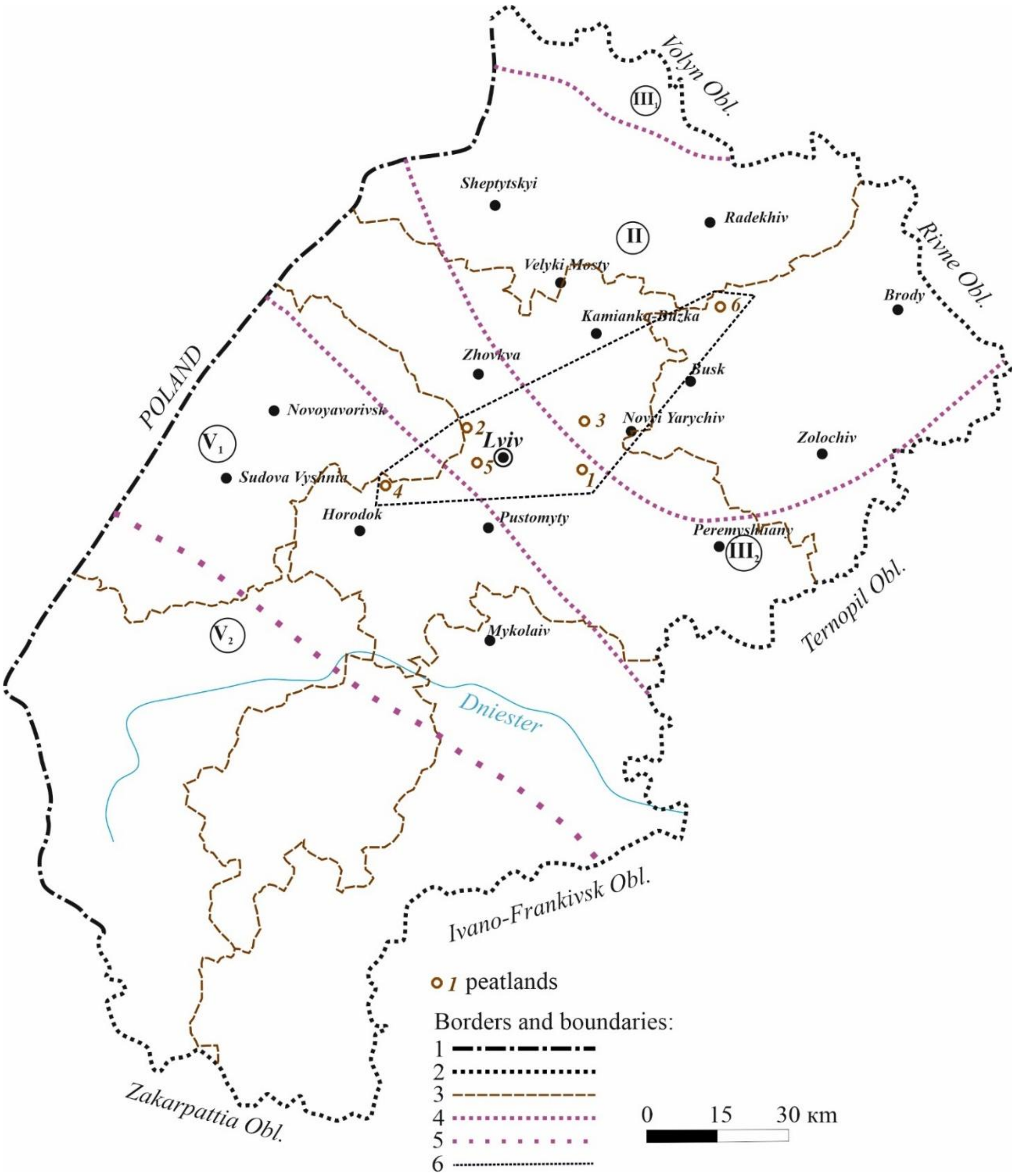


Fig. 1. Map-scheme of the location of research objects
(based on a schematic map of the zoning of the Lviv region (Scale 1:1 500 000)

Symbols for fig. 1:

Borders and boundaries: 1 – the state border of Ukraine; 2 – border of the Lviv region; 3 – districts of the Lviv region; 4 and 5 – peat regions and districts (based on materials [14]): II – Malopilska peat region. III – Forest-steppe peat region: III1 – Volyn foreststeppe region, III2 – Podilsk forest-steppe region. V – Carpathian peat region: V1 - Pre-Carpathian region, V2 – Carpathian; 6 – research area;
Peatlands: 1 – Honchary, 2 – Bilorhoshcha, 3 – Hamaliivka, 4 – Artyshchiv, 5 – Sknyilivok, 6 – Polonychna

ated directly within or adjacent to the city of Lviv.

According to the physical-geographical zoning of peat bogs in Ukraine [14], the peatlands of the study area belong to the Male Polissya peat-bog region with Roztochchya. Most sites – Bilogorshcha, Honchary, Hamaliivka, Sknylivok, and Artyshchiv – are located within the Podilskyi district of the Forest-Steppe peat region, while Polonychna belongs to the Male Polissya peat region.

The study area is situated in a temperate continental climate zone with sufficient moisture supply, which favors waterlogging in low-lying landforms. The local hydrological network consists of valleys of the tributaries of the Western Bug (including the Poltva) and the Dniester (including the Vereshchytsia).

The oldest geological units that directly influence the surface morphology, hydrogeology, and the formation of the soil profile are the Upper Cretaceous silicate-carbonate sequences of the Roztochchya area (gray sandy marls, limestones, and marly sandstones, locally fractured), as well as the underlying or adjacent Miocene (Badenian-Sarmatian) sediments of the Pre-Carpathian Foredeep. These comprise sands, sandstones, limestones, marls, and clays (locally containing gypsum or anhydrite), which form alternating permeable and impermeable layers. This alternation controls the regimes of groundwater and confined aquifers and locally promotes overmoistening, stagnation of runoff, and the development of wetlands in floodplains and depressions: conditions typical for the Male Polissya region and the foothills of Roztochchya.

Everywhere, the near-surface section is covered by Quaternary deposits: alluvial-lacustrine sands and loams dominate in valley floors and depressions, deluvial loams occur on slopes, and locally, on elevated surfaces, loess-like loams are preserved.

The studied peat deposits are of Holocene age and belong to the lowland (eutrophic, minerotrophic) type, formed under conditions of mineral-rich groundwater feeding and dominated by herbaceous vegetation, sedges, hypnum mosses, and woody remains. They overlie alluvial-lacustrine sediments, and their thickness ranges from decimeters to several meters depending on basin morphology and the degree of drainage.

Physico-chemical characteristics of peat.

The analyzed peat samples exhibit a wide range of *moisture content (W)*, varying from 14,98 to 87,41%, with a mean value of 59,06% and a median of 63.89% (Tables 1, 2). The substantial variability (coefficient of variation ≈ 36%), together with negative skewness and a moderately flattened distribution (kurtosis < 0), indicates the predominance of relatively well-moistened layers and the presence of locally desiccated horizons in the upper parts of some profiles. The highest moisture values were recorded in the Artyshchiv peatland (W ≥ 80%) and in the lower horizons of Bilogorshcha and Hamaliivka (W ≥ 76%).

The high dispersion and marked variability of moisture values with depth reflect the complex interplay of changes in mineral composition, micro- and mesopore structure, degree of peat decomposition and compaction, as well as the dynamics of the hydrological regime and groundwater level. A general increase in peat moisture with depth (Fig. 2a) is observed at all sites, primarily due to proximity to the stable groundwater table, reduced influence of evaporation, and changes in the physical properties of peat.

The ash content of peat (proportion of residue after oxidation, expressed as a percentage of dry matter) reflects the amount of inorganic and mineral components present. Ash content is one of the key characteristics of peat, since the total quantity of chemical elements, including those available to plants, depends on the share of the mineral fraction. The ash content of the studied peats from the Lviv region exhibits a relatively uniform distribution (coefficient of variation: 41,28; variance: 71,41; standard deviation: 8,45) and ranges from 9,69% to 37,08%, with an average of 20,47% (median = 16,05%). These lowland peats formed under conditions of mineral-rich groundwater inflow, which explains their relatively high ash values, genetically linked to secondary inputs of inorganic sedimentary material into the peat mass. Elevated ash content is also associated with river flooding and the wash-in of mineral particles from steep valley slopes.

High ash values are characteristic primarily of the deeper horizons of Profile 1 (Honchary, 80-140 cm) and several samples from the Artyshchiv and Polonychna peatlands (Table 1), indicating a greater proportion of mineral impurities and potentially stronger groundwater influence. A downward-to-upward decrease in ash content is observed in the Honchary profile, while an opposite trend – an increase toward the surface is found in the Bilogorshcha and Hamaliivka profiles (Fig. 2b). These patterns are likely controlled by local geological and hydrological conditions, including the presence of mineral interlayers and fluctuations in the hydrological regime during different stages of peat formation.

The acid-base properties (pH) of peat are largely determined by the type and composition of organic acids present (primarily humic and fulvic acids) and by their associated compounds. pH is one of the most influential factors controlling the mobility and chemical speciation of metals. Microcomponents dissolved in peatland waters form various organometallic complexes with organic matter, and the transition of these complexes into solution depends

Table 1

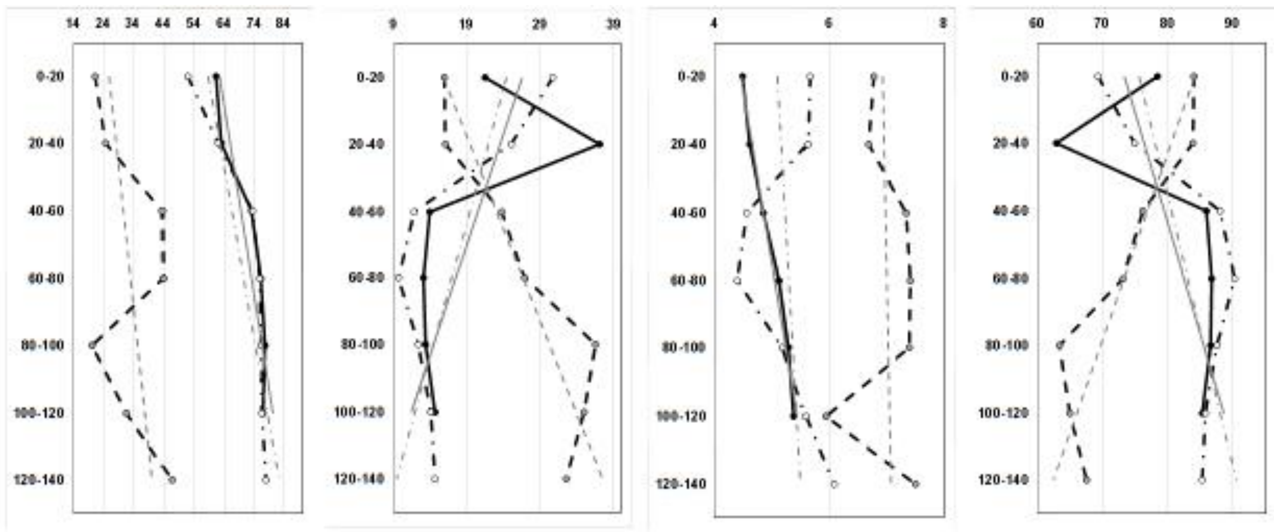
Content of mobile forms of chemical elements (ppm) and general physico-chemical characteristics of peatlands of the Lviv region

Peatland	Depth, h, cm	Trace element, ppm													Physyco-chemical parameter			
		Pb	Tl	Zn	Cd	Cu	As	Sb	Mo	Ni	Co	Mn	Cr	V	Moisture content, W, %	Ash, A, %	pH	Organic matter, %
Honchary, Profile 1																		
	0-20	7,200	0,005	26,083	0,250	4,367	2,850	0,005	0,067	2,075	0,500	7,833	0,367	0,350	21,38	15,95	6,78	84,05
	20-40	8,850	0,005	13,500	0,383	4,433	3,050	0,028	0,052	1,750	0,125	7,383	1,733	0,225	24,77	16,11	6,68	83,89
	40-60	3,025	0,005	16,267	0,200	6,567	1,900	0,005	0,052	2,475	0,125	5,167	1,050	0,250	43,48	23,81	7,34	76,19
	60-80	132,350	0,005	18,617	8,883	4,067	2,650	0,053	0,035	2,175	0,150	3,383	0,483	0,200	43,80	26,88	7,41	73,12
	80-100	2,650	0,253	12,967	0,167	2,683	3,200	0,005	1,833	1,225	0,050	8,817	0,450	0,150	20,21	36,55	7,39	63,45
	100-120	1,200	0,005	10,650	0,052	4,300	1,600	0,005	0,020	1,775	0,028	6,950	0,087	0,125	31,84	34,95	5,94	65,05
	120-140	27,725	0,028	13,900	1,767	2,883	1,500	0,005	0,050	1,225	0,050	6,783	0,600	0,175	46,66	32,51	7,50	67,49
Bilorhoshcha, Profile 2																		
	0-20	13,050	0,005	41,417	0,667	6,817	1,800	0,005	0,267	3,200	0,450	70,250	2,283	0,500	61,27	21,55	4,48	78,45
	20-40	10,350	0,005	29,900	0,867	6,750	3,050	0,005	0,567	3,400	0,425	59,183	1,400	1,275	63,03	37,08	4,61	62,92
	40-60	3,175	0,005	13,350	0,183	3,567	2,250	0,028	0,717	1,700	0,075	24,067	1,067	0,150	73,20	13,99	4,86	86,01
	60-80	6,025	0,005	16,683	0,183	2,667	2,550	0,103	0,068	2,550	0,075	13,600	1,017	0,150	76,37	13,20	5,12	86,8
	80-100	6,950	0,005	19,100	0,433	4,183	1,750	0,078	0,600	1,650	0,175	16,733	0,667	0,225	77,50	13,42	5,29	86,58
	100-120	6,350	0,028	16,433	0,350	4,000	3,250	0,005	0,433	1,575	0,075	26,617	0,733	0,175	77,10	14,75	5,39	85,25
Hamaliivka, Profile 3																		
	0-20	4,400	0,005	13,450	0,267	2,450	3,500	0,028	0,005	2,600	0,125	17,100	0,667	0,725	51,99	30,70	5,65	69,3
	20-40	3,200	0,053	9,533	0,183	2,350	3,000	0,005	0,005	2,025	0,150	16,883	1,317	0,500	61,97	25,08	5,62	74,92
	40-60	2,125	0,005	9,200	0,133	3,133	2,150	0,005	0,052	1,750	0,075	8,033	0,467	0,175	73,65	11,93	4,57	88,07
	60-80	2,925	0,005	18,283	0,150	2,417	1,850	0,005	0,037	1,775	0,028	6,850	0,317	0,125	75,80	9,69	4,40	90,31
	80-100	1,000	0,005	9,483	0,067	2,700	1,900	0,005	0,005	1,275	0,005	7,200	0,350	0,100	76,36	12,40	5,18	87,6
	100-120	1,475	0,103	7,550	0,133	2,950	1,750	0,028	0,052	1,350	0,028	10,083	0,417	0,100	76,73	14,16	5,59	85,84
	120-140	1,250	0,005	6,950	0,083	2,867	14,900	0,005	0,133	1,150	0,005	11,867	3,433	0,125	78,04	14,72	6,08	85,28
Artyshchiv																		
	0-20	16,150	0,005	20,383	0,650	7,183	2,50	0,005	1,983	2,900	0,475	20,033	1,283	0,450	80,77	27,41	5,46	72,59
	40-60	9,225	0,528	16,233	0,317	5,250	4,55	0,078	0,550	2,175	0,225	6,933	0,933	0,150	87,41	15,99	5,00	84,01
Sknyilivok																		
	0-30	2,400	0,028	9,700	0,167	3,333	2,60	0,005	0,005	3,325	0,275	10,367	0,950	0,600	69,58	14,10	4,63	85,90
Polonychna																		
	0-40	3,950	0,028	9,167	0,183	3,267	5,000	0,028	0,050	1,750	0,125	35,083	1,967	0,450	63,89	23,42	7,69	76,58
	0-40	2,400	0,005	13,217	0,167	2,633	2,850	0,103	0,052	1,925	0,075	7,300	0,650	0,625	63,88	18,60	5,62	81,40
	0-40	1,000	0,005	11,233	0,100	2,617	2,550	0,178	0,005	3,575	0,275	15,833	0,235	1,425	14,98	13,26	5,39	86,74

Table 2

Statistical parameters of the distribution of migration forms of chemical components and physico-chemical indicators in peats of Lviv region

Chemical elements and physico-chemical indicators	Mean	Median	Min	Max	Variance	Std.Dev.	Coef.Var.	Skewness	Kurtosis
W, %	59,06	63,89	14,98	87,41	462,38	21,50	36,41	-0,82	-0,59
A, %	20,47	16,05	9,69	37,08	71,41	8,45	41,28	0,75	-0,77
pH	5,76	5,53	4,40	7,69	1,08	1,04	18,04	0,63	-0,83
OP, %	79,53	83,95	62,92	90,31	71,41	8,45	10,63	-0,75	-0,77
Pb (ppm)	10,78	3,58	1,00	132,35	649,71	25,49	236,35	4,69	22,94
As	3,10	2,58	1,50	14,90	6,52	2,55	82,45	4,25	19,91
Tl	0,04	0,01	0,01	0,53	0,01	0,11	254,76	3,83	15,48
Mo	0,30	0,05	0,01	1,98	0,27	0,52	176,55	2,51	6,05
Zn	15,51	13,48	6,95	41,42	57,56	7,59	48,92	1,91	4,65
Cd	0,65	0,18	0,05	8,88	2,94	1,72	262,63	4,78	23,56
Ni	2,09	1,85	1,15	3,58	0,51	0,71	34,16	0,72	-0,45
Sb	0,03	0,01	0,01	0,18	0,00	0,04	139,99	2,06	4,36
Cu	3,86	3,30	2,35	7,18	2,24	1,50	38,71	1,14	0,18
Co	0,16	0,13	0,01	0,50	0,02	0,15	93,89	1,22	0,38
Mn	16,55	10,23	3,38	70,25	258,75	16,09	97,19	2,37	5,62
Cr	0,96	0,70	0,09	3,43	0,55	0,74	77,60	1,76	3,86
V	0,37	0,21	0,10	1,43	0,12	0,34	93,88	2,01	3,97



a) b) c) d)

Fig. 2. Changes in the values of moisture (a), ash content (b), pH (c), and organic matter (OM) content (d) of the studied peats in Lviv Region with depth for Profiles 1 (Honchary), 2 (Bilohorshcha) and 3 (Hamaliivka).

Symbols for fig. 2:

Honchary Bilorhoshcha Hamaliivka

(trend lines – grey color)

X-axis: values of moisture content, W (a); ash content, A (b); pH (c); organic matter, OM (d);

Y-axis: depth of the peat deposit profile, cm.

strongly on the pH of the environment. Thus, pH levels and their variations are crucial in regulating the geochemical migration and precipitation of chemical elements in peatlands.

Changes in pH directly influence the stability of metal-organic complexes. Their stability depends both on the intrinsic properties of the metal and on the functional groups participating in coordination. In general, transition metals form complexes with humic substances following the well-known Irving–Williams series [15, 16] for divalent ions: $Pb^{2+} > Cu^{2+} > Ni^{2+} > Co^{2+} > Zn^{2+} > Cd^{2+} > Fe^{2+} > Mn^{2+}$.

It should be noted that the Irving–Williams series formally applies to divalent metal ions in idealized aqueous systems. In peat environments iron commonly occurs as Fe^{3+} or is incorporated into Fe-oxide phases, which may modify its relative binding strength. Thus, the series is used here as a conceptual reference rather than as an exact predictor of metal–humic complex stability in natural peat matrices.

Lead and copper thus form the most stable complexes. Under different environmental conditions, these relationships may shift. For example, Van Dijk [17], in experiments on metal binding by humic acids, found that at pH 3 approximately 70% of metal ions remain uncomplexed, while at pH 5 the strength of complexation follows the order: $Zn^{2+} > Fe^{2+} > Ni^{2+} > Co^{2+} > Mn^{2+} > Mg^{2+} > Ca^{2+} > Ba^{2+}$.

This indicates that under mildly acidic conditions, zinc and ferrous iron form the strongest complexes.

As acidity increases (i.e., pH decreases), the stability of metal-organic complexes declines due to protonation of functional groups and displacement of metal ions from the complexes. Conversely, higher pH levels promote the formation of metal complexes with organic ligands: at neutral to slightly alkaline pH, most carboxyl and phenolic groups are deprotonated and actively bind metals [18].

The pH range of the studied peats (Fig. 2c) spans acidic, slightly acidic, neutral, and locally slightly alkaline conditions. pH values vary from 4,40 (acidic conditions in the 0-20 cm horizons of Bilogorshcha and Sknylivka, and in the 60-80 cm horizon of Hamaliivka) to 7,69 (slightly alkaline conditions in the 120-140 cm horizon of Honchary and in the upper layers of Polonychna). Most studied peats exhibit a slightly acidic environment, with an average pH of 5,76, which is typical for peatlands. In general, pH increases with depth. Under the prevailing slightly acidic conditions (pH 5,1-6,0) characteristic of these peatlands, metals do not remain in free ionic form but instead form stable organometallic complexes whose stability increases with depth.

Organic matter (OM) in peat comprises a wide spectrum of compounds, including humic substances (humic acids, fulvic acids, humin), lignin and cellulose residues, amino acids, and low-molecular-weight organic acids. These components play an important role in geochemical processes such as solubility, mobility, concentration, and accumulation of metals. The analyzed peat samples contain substantial amounts of organic matter: on average, OM accounts for 79,53% of the total mass, with values ranging from 62,92% (Bilogorshcha, 20-40 cm) to 90,31% (Hamaliivka, 60-80 cm). Such high OM concentrations indicate the dominance of biogenic material that has undergone varying degrees of anaerobic decomposition.

With depth, the OM content increases in the Bilogorshcha and Hamaliivka profiles (with maximum at 60-80 cm) and decreases in the Honchary profile (with a minimum at 80-100 cm). Vertical distributions of moisture, ash content, pH, and OM (Fig. 2) show pronounced differences between the sections:

Profile 1 (Honchary): Moisture content rises from 21-25% in the upper 40 cm to 43-47% between 40-80 cm, followed by contrasting fluctuations associated with the alternation of more mineralized and more organic horizons. Ash content increases with depth from 16% to 36%, accompanied by a decline in OM to ~63-67% in the lower part of the profile. pH increases from slightly acidic (~6.7) near the surface to neutral–slightly alkaline values (7,3-7,5) at 40-140 cm.

Profile 2 (Bilogorshcha): This peat is generally more humid (W 61-77%) and less ash-rich (A 13-21%), with predominantly acidic pH values (4,5-5,4). With depth, moisture increases and ash content slightly decreases, likely reflecting a diminished influence of the mineral substrate and a more stable hydrological regime.

Profile 3 (Hamaliivka): Moisture content gradually increases from 52% to 78%, while ash content decreases from 31% to 10-15% in the middle part of the profile before rising again to ~15% in the deepest horizons. pH is mostly acidic (4,4-6,1), with a trend toward slightly more neutral conditions at greater depths.

Overall, the peatlands of the Lviv region are characterized by generally high organic matter content and contrasting vertical trends in moisture and ash content, reflecting differences in hydrological conditions, groundwater feeding, and the degree of peat mineralization.

Distribution of mobile forms of trace elements. The general patterns of distribution of mobile forms of chemical elements in the studied peatlands illustrated by their statistical characteristics (mean, minimum and maximum values, median, variance, coefficient of variation, etc.) indicate substantial variability and pronounced spatial heterogeneity in their concentrations (Table 2, Fig. 3).

Lead (Pb) shows an average concentration of 10,78 ppm (range 1,0-132,35 ppm, median 3,58 ppm). The very high coefficient of variation (>230%) and strongly positive skewness and kurtosis values (4,69 and 22,94, respectively) indicate the presence of one or several sharply elevated measur-

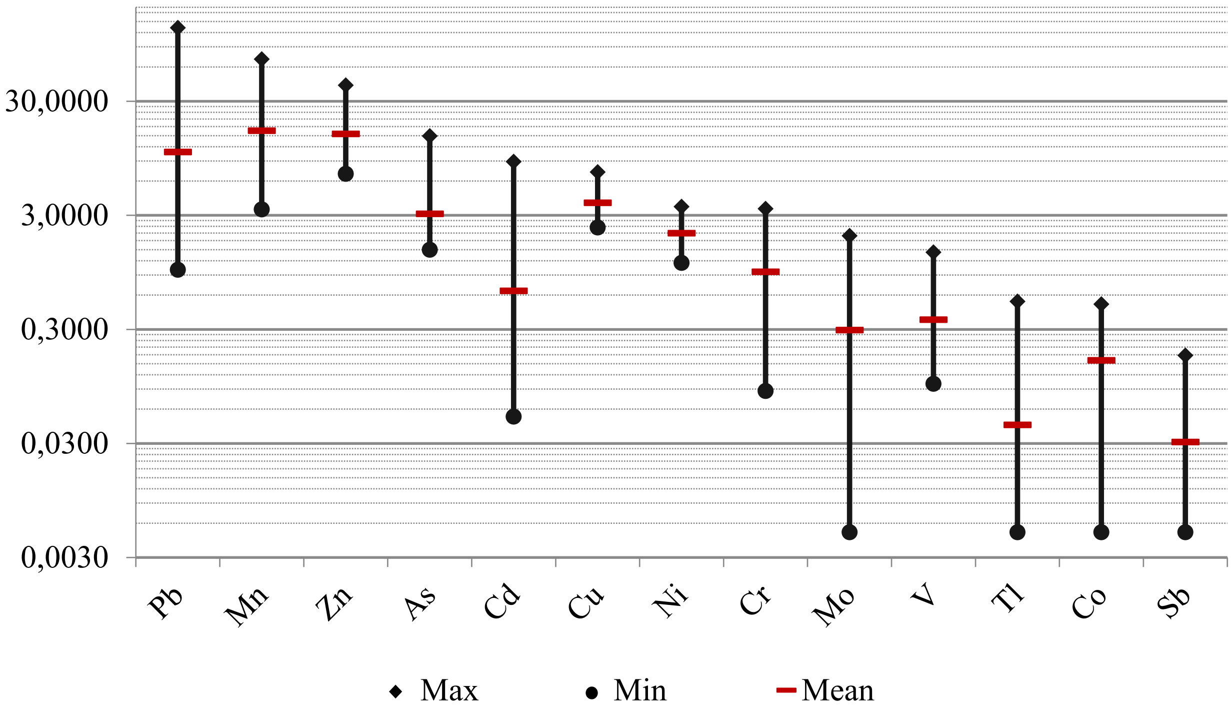


Fig. 3. Geochemical spectrum of accumulation of mobile forms (ppm) of trace elements in the studied peats of Lviv Region.

ements superimposed on a low background typical of most samples. Cadmium (Cd) exhibits similar behavior: the mean value is 0,65 ppm, with a maximum of 8,88 ppm and a coefficient of variation exceeding 260%, reflecting a highly asymmetric distribution dominated by a single anomalous sample.

Zinc (Zn) concentrations range from 6,95 to 41,42 ppm (mean 15,51 ppm, CV ≈ 49%). Copper (Cu) occurs within 2,35-7,18 ppm (mean 3.86 ppm, CV ≈ 39%), and Nickel (Ni) within 1,15-3,58 ppm (mean 2,09 ppm, CV ≈ 34%). A particularly wide concentration range (3,38-70,25 ppm) and high variability (CV ~97%) were recorded for manganese (Mn), likely reflecting heterogeneous redox conditions and the potential involvement of Mn oxides as sorbents for other *PTE*s.

Among anionic and metalloid components, arsenic (As) stands out (mean 3.10 ppm; range 1,5-14,9 ppm), characterized by high skewness (4,25) and kurtosis (19,91), which points to a pronounced deep anomaly. Other elements (Tl, Mo, Sb, Co, Cr, V) occur mainly at trace levels (tenths to hundredths of ppm), yet also display increased variability and asymmetric distributions.

Overall, most elements exhibit coefficients of variation exceeding 40%, a pattern typical for peat ecosystems where local anthropogenic inputs interact with a geogenic background. Similar variability has been reported for peatlands in Latvia, Romania, and Poland [3–8].

Assessment of distribution normality using skewness and kurtosis indicates moderate deviations from normality for Zn, Cu, Ni, Co, and Mn, whereas Pb, As, Tl, and Cd clearly follow a lognormal distribution. This reflects the presence of anomalously high values associated with local sources of input. Wide concentration ranges, high coefficients of variation, and pronounced positive skewness demonstrate that element concentrations vary significantly depending on sampling location. Such contrast and heterogeneity reflect the complex interplay of multiple factors that control the behavior of elements in peatlands, including differences in deposition and fixation conditions, migration processes, hydrological dynamics, biogeochemical transformations, and species-specific uptake patterns of peat-forming plants.

The concentration series of mobile trace elements in the studied peat samples, based on median values, is as follows: Zn > Mn > Pb > Cu > As > Ni > Cr > V > Cd > Co > Mo > (Tl, Sb).

This series highlights which elements dominate in absolute terms in the mobile phase. Biogenic and chalcophilic elements such as Zn and Mn occupy the leading positions, indicating their active participation in biochemical and geochemical processes.

The geochemical spectrum of mobile element forms, expressed through average concentration coefficients normalized to background (median) levels, is as follows (K_{cm}): Tl (8,73), Sb (6,17), Mo (5,69), Cd (3,57), Pb (3,02), V (1,72), Mn (1,62), Cr (1,37), Co (1,28), As (1,20), Cu (1,17), Zn (1,15), Ni (1,13).

This metric provides a more precise indication of anomalous enrichment. Elements with the highest concentration coefficients: Tl, Sb, Mo, Cd, and Pb, exhibit the strongest deviation from background values, reflecting their high mobility and efficient accumulation within the peat deposits.

Comparison of the concentration series of chemical elements, based on median values, in the ash of Lviv region peats [19] with the series of mobile forms obtained in this study clearly demonstrates that the geochemical behavior of elements in peat is strongly controlled by their chemical properties and forms of occurrence. In the series of mobile forms, chalcophile elements (Zn, Pb, Cu) dominate and the potentially hazardous As and Cd. Their prevalence reflects high mobility, a strong tendency to form readily soluble complexes, and consequently a high potential for migration and biological accumulation. In contrast, the concentration series based on ash content is dominated by lithophile elements (Ti, Zr, Sr, Ba) mainly associated with the mineral fraction of peat (clay minerals, quartz, feldspars), which enter peatlands from surrounding geological substrates. Thus, assessing only the total element content in peat is insufficient for a comprehensive understanding of environmental conditions: reliable evaluation of ecological risks and bioavailability requires analysis of mobile forms, which better reflect the actual environmental and biological impact.

Assessment of element accumulation or depletion relative to their Clarke values in the Earth's crust and soils revealed characteristic patterns and allowed us to infer the nature of their geochemical behavior. Based on the concentration coefficient (*CC*) relative to the continental crust values of Rudnick and Gao [20], the studied elements can be grouped as follows: *CC* > 1: Cd (7,259); *CC* < 1: As (0,645), Pb (0,634), Mo (0,269), Zn (0,231), Cu (0,138), Sb (0,077), Tl, Ni (0,044), Mn (0,021), Cr (0,01), Co (0,009), V (0,004).

The geochemical spectrum of mobile element forms, expressed as average concentration coefficients normalized to global soil values [21], is as follows (*CC*): Cd (1,866), Pb (0,899), As (0,516), Mo (0,247), Tl (0,218), Zn (0,172), Cu (0,129), Ni (0,042), Sb (0,031), Co (0,02), Mn (0,017), Cr (0,014), V (0,004).

This spectrum corresponds closely to the classical sequence described in [15] – Pb > Cu > Ni > Co > Zn > Cd > Mn, which reflects the relative affinity of metal ions to bind with common functional groups in the peat matrix. The slight displacement of Cd, Pb, and Zn within our series results from their comparatively elevated concentrations and specific interactions with the peat organic-mineral complex.

Comparison with background concentrations in European soils [22] yields the following: *CC* > 1: Cd (3,447); *CC* < 1: Mo (0,693), Pb (0,66), As (0,541), Zn (0,339), Cu (0,258), Ni (0,135), Sb (0,118), Cr (0,046), Mn (0,037), Co (0,021), V (0,014).

Relative to background values in Ukrainian soils [22], the distribution is similar: *CC* > 1: Cd (4,083); *CC* < 1: Pb (0,926), Mo (0,822), As (0,595), Zn (0,402), Cu (0,254), Sb (0,134), Tl (0,12), Ni (0,094), Cr (0,04), Mn (0,034), Co (0,018), V (0,013).

It is important to emphasize that most soil standards refer to total element concentrations, whereas this study examines the fraction extracted by weak acid – mobile forms. Therefore, actual total concentrations in peat are likely higher, particularly within anomalous horizons.

Vertical distribution of elements in peat profiles.

Profile 1 (Honchary) is the most contrasting in terms of *PTE* concentrations (Table 1). In the upper horizons (0-40 cm), mobile Pb does not exceed 8,9 ppm; Zn ranges from 13,5 to 26,1 ppm; Cd from 0,25 to 0,38 ppm; and Cu from 4,37 to 4,43 ppm. At 40-60 cm, Cu moderately increases to 6,57 ppm, accompanied by a decline in Pb, Zn, and Cd.

The most pronounced anomaly occurs at 60-80 cm: mobile Pb reaches 132,35 ppm, Cd rises to 8,88 ppm, and Zn to 18,62 ppm, while Mn decreases to 3,38 ppm and pH reaches 7,41. This horizon also displays elevated ash content (26,88%) and reduced organic matter (73,12%). Below this level (80-140 cm), Pb, Cd, and Zn concentrations drop sharply (Pb: 1,0-27,7 ppm; Cd: 0,05-1,77 ppm; Zn: 10,7-13,9 ppm), although ash content remains high (up to 36,55%) compared to the upper profile.

The position of the anomalous Pb–Cd horizon in the middle rather than the upper part of the profile suggests secondary metal migration caused by vertical redistribution/sorption/desorption on Fe/Mn oxides, transport with groundwater, or the introduction of material during land reclamation. Similar deep Pb and Cd maxima are known from other peatlands where post-depositional redistribution occurs under variable redox conditions.

Profile 2 (Bilogorshcha) contains maximum Mn (up to 70,25 ppm) and Zn (up to 41,42 ppm) values in the upper 0-20 cm, along with increased Cu (6,82 ppm) and Pb (13,05 ppm). With depth, concentrations of most metals decline, although Zn, Mn, and Ni remain relatively elevated to 40 cm, and Pb and Cu persist at moderate levels down to 120 cm.

All horizons exhibit acidic pH (4,48-5,39) and high moisture (>60%), typical for waterlogged lowland bogs. The surface maxima of Pb, Zn, Cu, and Mn correspond well with atmospheric deposition trends and local pollution inputs documented for many European peatlands.

Profile 3 (Hamaliivka) is characterized by generally lower metal contents. The upper 0-40 cm contains 3,2-4,4 ppm Pb, 9,5-13,5 ppm Zn, ~0,18-0,27 ppm Cd, and 2,35-2,45 ppm Cu. The middle part (40-80 cm) shows only minor changes, while the lower horizons (100-140 cm) feature a sharp As increase to 14,9 ppm, accompanied by low pH (5,6-6,1) and elevated ash (14-15%).

Deep As enrichment, contrasted with stable concentrations of other metals, suggests a geogenic source such as arsenic-bearing minerals in underlying sediments or inflow of mineralized groundwater. Similar patterns have been reported in peatlands influenced by metalliferous waters and historical mining zones.

The deep arsenic enrichment may reflect a geogenic source, as the Miocene and Upper Cretaceous sedimentary units underlying the peatland locally contain clay-rich horizons and dispersed sulfide minerals capable of releasing As under reducing conditions. Although no direct mineralogical data are available for the studied site, the depth-specific enrichment pattern is consistent with upward diffusion or groundwater-mediated transport from mineralized substrata.

In samples from Artyshchiv and Polonychna, relatively high concentrations of Pb (up to 16,15 ppm), Cu (up to 7,18 ppm), Zn (up to 20,4 ppm), and Mn (up to 35,1 ppm) occur, particularly in surface horizons. Sknylivok displays low to moderate metal concentrations, with high moisture and low ash content.

Overall, all sites exhibit substantial spatial heterogeneity in mobile metal concentrations – consistent with the mosaic nature of *PTE* sources such as atmospheric emissions, local human activities, microrelief variability, and hydrological differences within peatlands.

Against the broader European background, mobile *PTE* concentrations in Lviv region peats can be classified as low to moderate. Compared with industrially affected peatlands in Romania, Poland, and Ireland, where Pb may reach 50-60 ppm and Zn over 40-70 ppm [6, 23], the studied peats contain generally lower levels of Pb, Zn, Cu, and Ni. Concentrations of Mn, As, and Cr are close to or do not exceed typical values for organic soils.

Crucially, these values refer to mobile forms, which are potentially available to plant roots and soil biota. Even relatively low concentrations of such forms may be critical for sensitive species, especially under stress conditions (acid deposition, drought, fires, drainage). At the same time, the results do not indicate systematic exceedance of regulatory limits or significant human health risks during typical peat use, except for specific anomalous horizons, which require detailed assessment before possible agricultural or recreational application.

The relationship between the content of metals and physico-chemical parameters. Correlation analysis (STATISTICA, classical pairwise Pearson correlation analysis) showed several significant statistical relationships between the content of mobile forms of elements and basic physicochemical indicators of peat (Table 3).

Table 3

Correlation matrix of mobile metal forms and physico-chemical parameters in the studied peatlands of Lviv Region

	Pb	Cd	As	V	Cr	Mn	Co	Ni	Cu	Zn	Mo	Sb	Tl	pH	W	Ash	OM
Pb	1,00																
Cd	**0,99**	1,00															
As	-0,08	-0,07	1,00														
V	-0,10	-0,07	-0,06	1,00													
Cr	-0,10	-0,11	**0,73**	0,02	1,00												
Mn	-0,10	-0,10	-0,01	**0,45**	**0,46**	1,00											
Co	0,07	0,04	-0,15	**0,54**	0,15	**0,52**	1,00										
Ni	0,04	0,04	-0,22	**0,77**	0,05	**0,46**	**0,72**	1,00									
Cu	0,12	0,09	-0,14	0,15	0,27	**0,50**	**0,68**	**0,46**	1,00								
Zn	0,19	0,17	-0,25	0,24	0,15	**0,68**	**0,72**	**0,48**	**0,69**	1,00							
Mo	-0,04	-0,07	-0,02	-0,05	0,04	0,15	0,28	0,01	0,38	0,20	1,00						
Sb	0,06	0,06	-0,07	**0,40**	-0,21	-0,14	0,01	0,30	-0,23	-0,10	-0,14	1,00					
Tl	-0,06	-0,08	0,09	-0,20	-0,08	-0,16	-0,02	-0,13	0,05	-0,08	0,32	0,12	1,00				
pH	0,36	0,35	0,13	-0,21	0,03	-0,33	-0,18	-0,37	-0,06	-0,21	0,02	-0,10	0,01	1,00			
W	-0,14	-0,15	0,18	-0,28	0,25	0,16	-0,13	-0,11	0,04	-0,05	0,07	-0,12	0,13	**-0,57**	1,00		
Ash	0,23	0,24	-0,09	0,22	-0,02	0,23	0,15	0,11	0,29	0,19	0,34	-0,30	0,06	**0,44**	**-0,40**	1,00	
OM	-0,23	-0,24	0,09	-0,22	0,02	-0,23	-0,15	-0,11	-0,29	-0,19	-0,34	0,30	-0,06	**-0,44**	**0,40**	**-1,00**	1,00

Bold values indicate significant correlations at $p < 0,05$.

Ash content and organic matter. For most metals (Mo, Cu, Cd, Pb, Mn, V, Zn, Co, Ni), a positive correlation with ash content and a negative correlation with organic matter was identified. This pattern reflects the tendency of these elements to concentrate in the mineral fraction of peat and/or to accumulate in horizons with a more substantial influx of mineral material. In contrast, Sb, As, and Cr display negative correlations with ash content, indicating their relative enrichment in more organogenic, low-ash layers.

pH. pH values exhibit positive correlations with Pb and Cd, and negative correlations with Ni and Mn. This suggests reduced mobility of Ni and Mn under more neutral conditions, while Pb and Cd may form increasingly stable complexes with organic ligands as pH rises.

Relationships between metals. A remarkably strong correlation was observed between Pb and Cd ($r \approx 0{,}99$), indicating shared sources and nearly identical migration behavior. Strong positive relationships also occur among Zn, Cu, Ni, Co, Mn, and V ($r = 0{,}46$-$0{,}77$), as well as between As and Cr ($r \approx 0{,}73$). These associations align with multivariate statistical results from other European peatlands [6], where similar clusters of elements reflect either geogenic signatures or anthropogenic inputs.

The results confirm the crucial role of mineral admixture and acid–base conditions in regulating metal mobility in peat, consistent with current concepts of *PTE* chemical speciation in organic soils [9].

To further clarify geochemical associations, correlation profiles were constructed (Fig. 4), enabling a detailed examination of element relationships and their behavior during peat formation. Analysis of the ranked correlation coefficients revealed four principal paragenetic associations of mobile forms of the studied elements: (1) Zn – Ni – Cu – Co – Mn; (2) Sb – V; (3) Pb – Cd – Tl; (4) Cr – As.

These associations reflect shared sources, similar bonding mechanisms, or coordinated migration pathways within the peat deposit.

The strongly positive skewness and kurtosis values for Pb, As, Tl and Cd suggest a distribution close to log-normal; however, this conclusion is tentative, as formal normality tests (e.g., Shapiro-Wilk or Kolmogorov-Smirnov) were not performed. These deviations imply heterogeneous inputs and the presence of anomalous samples rather than a fully log-normal statistical structure.

Sources and mechanisms of PTE accumulation in the peats of the Lviv region.

The combination of statistical characteristics, vertical distribution patterns, and correlation analysis allows several inferences to be drawn regarding the sources and processes controlling *PTE* distribution in the studied peatlands.

Elevated concentrations of Pb, Zn, and Cu in the surface horizons of the Bilogorshcha peatland, as well as in composite samples from Artyshchiv and Polonychna, likely reflect the accumulation of atmospheric aerosols originating from transport emissions, fuel combustion, and local economic activities. Such profiles, with *PTE* maxima in the upper 20-30 cm, are typical of many ombrotrophic and mesotrophic peatlands across Europe [6].

Deep As enrichment in the lower part of the Hamaliivka profile, along with an increase in ash content with depth in several profiles, indicates a substantial contribution from mineral material derived from underlying rocks and groundwater. Similar peatlands have shown [8] that elements prone to binding with sulfides or Fe/Mn oxides (As, Cr, Ni, Co) may accumulate in transition zones between peat and mineral subsoil.

The pronounced mid-profile Pb–Cd anomaly in Honchary, combined with low concentrations above and below this horizon, suggests secondary migration or reworking processes – such as redistribution driven by fluctuating redox conditions, groundwater movements, or historical anthropogenic disturbances. Comparable redistributions of Pb, Zn, and Cd, driven by sulfide dissolution/precipitation and varying stability of technogenic particles, have been documented in Romanian and Polish peatlands [6, 8].

The negative correlation of most metals with organic matter and their positive correlation with ash content indicate predominant fixation to mineral phases (Fe/Mn oxides, clay minerals). High organic matter content in the upper, low-ash horizons likely promotes complexation with humic substances, forming stable organometallic compounds. These observations agree with modern concepts of competitive sorption between organic and mineral phases in peat soils [9].

Conclusions

1. Physico-chemical characteristics. Peat deposits of the Lviv region are characterized by high organic matter content (~80% on average), moderate ash content (~20%), a wide moisture range (15-87%), and pH values spanning acidic to slightly alkaline conditions (4,4-7,7). Vertical physico-chemical profiles vary markedly between peatlands, reflecting differences in hydrology and mineralization.

2. Average metal concentrations. The average concentrations of mobile Pb, Zn, Cd, Cu, Ni, Mn, and Cr are 10,8, 15,5, 0,65, 3,86, 2,09, 16,6, and 0,96 ppm, respectively. Most elements show high coefficients of variation and asymmetric distributions, indicating mosaic patterns of accumulation and the presence of local anomalies.

3. Local anomalies. The most pronounced Pb–Cd anomaly (132,35 ppm Pb and 8,88 ppm Cd) occurs at 60-80 cm in the Honchary peatland, contrast-

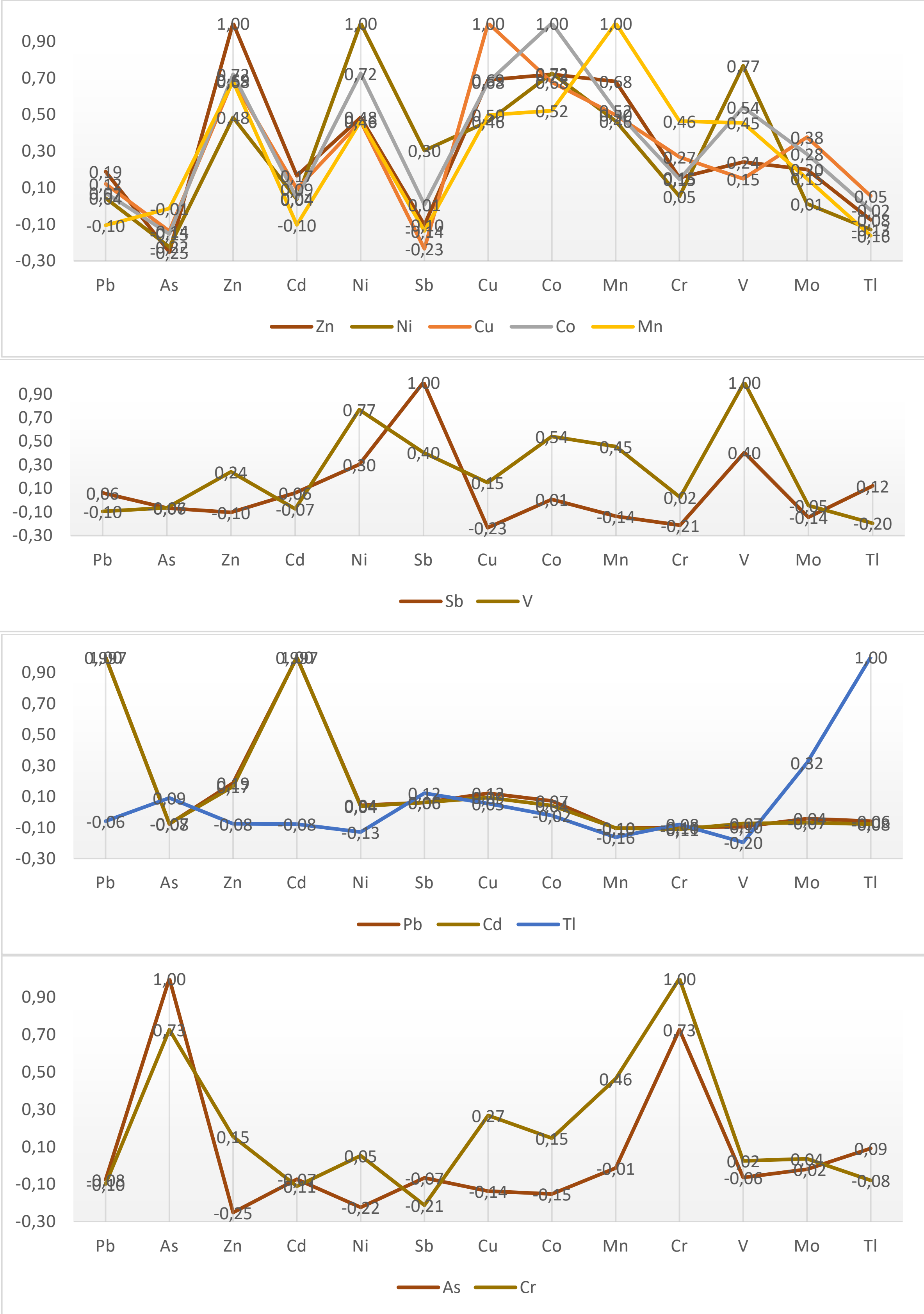


Fig. 4. Correlation profiles of the distribution of mobile metal forms in the studied peatlands of Lviv Region

ing with generally low values elsewhere. In the Hamaliivka profile, notable As enrichment (up to 14,9 ppm) occurs in deeper horizons. Most other sites show elevated Zn, Cu, Mn, and Pb in surface layers.

4. Comparison with regulatory and background values. Comparison with national and European indicative soil standards shows that the average content of mobile *PTE* in Lviv region peats does not

exceed background levels and remains significantly below pollution thresholds except for a distinct Pb–Cd anomaly in Honchary. Although the regional average concentrations of mobile *PTE* forms remain low and generally fall within background levels, the presence of sharp local anomalies, such as the Pb–Cd enrichment in the Honchary profile, indicates that the contamination pattern is spatially heterogeneous. Therefore, regional assessments should distinguish between background conditions and localized anomalies, which may reflect site-specific geochemical or anthropogenic factors rather than regional contamination.

5. Controls on metal mobility. Correlation analysis confirms the key role of ash content, organic matter, and pH in regulating metal mobility. Strong positive correlations occur between Pb and Cd, and among Zn, Cu, Ni, Co, Mn, and V, indicating shared sources and similar accumulation mechanisms.

6. Scientific and practical significance. The findings expand current knowledge on the geochemistry of European peatlands and provide the first comprehensive characterization of mobile *PTE* forms in the Lviv region. These results may inform the development of regional ecological assessment criteria, guide rational peatland use, and support further environmental monitoring. These findings also provide baseline information relevant for evaluating the suitability of peat deposits for future economic use, including agricultural substrates, land reclamation materials, or other low-impact applications.

7. Although no widespread exceedance of indicative thresholds was detected, localized anomalies, particularly the Pb–Cd horizon in the Honchary profile, may pose potential ecological risks if hydrological conditions change (e.g., drainage, drying, or enhanced groundwater flux). Under such scenarios, remobilization of metal-bearing phases could increase the availability of *PTE* to vegetation, soil biota, or adjacent water bodies. These zones therefore warrant site-specific monitoring before any agricultural or recreational use of peat from such layers.

Acknowledgements

The authors sincerely thank Alpinus Chemia Sp. z o.o. (Alpinus Chemia Ltd., Solec Kujawski, Poland) – especially Maciej Jaranowski, President of the Board, and Katarzyna Szwagrzak, Head of the Analytical Laboratory for providing access to the company's laboratory facilities, instruments, and analytical equipment.

Bibliography

1. Osborne, C., Gilbert-Parkes, S., Spiers, G., Lamit, L. J., Lilleskov, E. A., Basiliko, N., & Watmough, S. (2024). Global patterns of metal and other element enrichment in bog and fen peatlands. Archives of Environmental Contamination and Toxicology, 86(2), 125-139. https://doi.org/10.1007/s00244-024-01051-3

2. Thalassinos, G., Petropoulos, S. A., Grammenou, A., & Antoniadis, V. (2023). Potentially toxic elements: A review on their soil behavior and plant attenuation mechanisms against their toxicity. Agriculture, 13(9), 1684. https://doi.org/10.3390/agriculture13091684

3. Klavins, M., Silamikele, I., Nikodemus, O., Kalnina, L., Kuske, E., Rodinov, V., & Purmalis, O. (2009). Peat properties, major and trace element accumulation in bog peat in Latvia. Baltica, 22(1), 37–49.

4. Silamikele, I., Klavins, M., & Nikodemus, O. (2011). Major and trace element distribution in the peat from ombrotrophic bogs in Latvia. Journal of Environmental Science and Health, Part A, 46(7), 805–812. https://doi.org/10.1080/10934529.2011.572005

5. Krumins, J., Kuske, E., & Klavins, M. (2011). Major and Trace Element Accumulation in Fen Peat from Elki and Viki Mires in Western Latvia. Material Science & Applied Chemistry, (24), 71-81.

6. Adumitroaei, M. V., Iancu, G. O., Rățoi, B. G., Doru, C. S., & Sandu, C. M. (2018). Spatial distribution and geochemistry of major and trace elements from Mohoș peatland, Harghita Mountains, Romania. The Holocene, 28(12), 1936–1947. https://doi.org/10.1177/0959683618798174

7. Fiałkiewicz-Kozieł, B., Smieja-Król, B., & Palowski, B. (2011). Heavy metal accumulation in two peat bogs from southern Poland. Studia Quaternaria, 28, 17–24.

8. Smieja-Król, B., Fiałkiewicz-Kozieł, B., Sikorski, J., & Palowski, B. (2010). Heavy metal behaviour in peat – A mineralogical perspective. Science of the Total Environment, 408(23), 5924–5931. https://doi.org/10.1016/j.scitotenv.2010.08.032

9. Lu, Z., Ning, Y., Liu, C., Song, X., Pang, Y., Li, Q., ... & Zeng, L. (2025). Geochemical Regulation of Heavy Metal Speciation in Subtropical Peatlands: A Case Study in Dajiuhu Peatland. Land, 14(6), 1256. https://doi.org/10.3390/land14061256

10. Інститут ґрунтознавства та агрохімії ім. О.Н. Соколовського Української Академії аграрних наук. (2008). ДСТУ EN 13040:2005. Меліоранти ґрунту та середовища росту. Готування проб до хімічного та фізичного аналізу, визначення вмісту сухої речовини, вмісту вологи та лабораторно ущільненої насипної щільності, 14.

11. Технічний комітет стандартизації «Ґрунтознавство» (ТК 142) та Національний науковий центр «Інститут ґрунтознавства та агрохімії ім. О. Н. Соколовського» (2015). ДСТУ 7942:2015 Якість ґрунту. Визначення зольності торфу і торфового ґрунту, 9.

12. Інститут сільськогосподарської мікробіології та агропромислового виробництва НААН (2016). ДСТУ 7882:2015 Торф і продукти його перероблення для сільського господарства. Методи визначення обмінної й активної кислотності, 6.

13. *Інститут ґрунтознавства та агрохімії імені О. Н. Соколовського Української академії аграрних наук. (2006). ДСТУ 4405:2005. Якість ґрунту. Визначення рухомих сполук фосфору і калію за методом Кірсанова в модифікації ННЦ ІГА. Київ: Держспоживстандарт України, 2006. 17.*
14. *Брадіс, Є. М., Кузьмичов, А. І., Андрієнко, Т. Л., & Батячов, Є. Б. (1973). Торфово-болотний фонд УРСР, його районування та використання. К.: Наук. думка, 263.*
15. *Irving, H. M. N. H., & Williams, R. J. P. (1948). Order of stability of metal complexes. Nature, 162(4123), 746-747.*
16. *Schnitzer, M., & Khan, S. U. (1972). Humic substance in the environment. Mareel Dekker. Inc. N YP, 363, 29-54.*
17. *Van Dijk, H. (1971). Cation binding of humic acids. Geoderma, 5(1), 53-67.*
18. *Boguta, P., & Sokołowska, Z. (2013). Interactions of humic acids with metal ions. Acta Agrophysica, 2(AAM004-), 113.*
19. *Яковенко, М., Хоха, Ю., & Любчак, О. (2022). Геохімічні особливості накопичення і міграції важких металів у торфах Львівської області. Вісник Харківського національного університету імені В. Н. Каразіна, серія «Геологія. Географія. Екологія», (56), 105-121. https://doi.org/10.26565/2410-7360-2022-56-07*
20. *Rudnick, R. L., & Gao, S. Composition of the continental crust. Treatise Geochem. 2003; 3: 1–64. DOI: 10.1016/B0-08-043751-6/03016-4*
21. *Bowen, H. J. M. (1979). Environment Chemistry of the Elements. London; New-York; Toronto; Sydney; San Francisco: Academic Press, 333.*
22. *Клос, В. Р., Бірке, М., Жовинський, Е. Я., Акінфієв, Г. О., Амашукелі, Ю. А., & Кламенс, Р. (2012). Регіональні геохімічні дослідження ґрунтів України в рамках міжнародного проекту з геохімічного картування сільськогосподарських та пасовищних земель Європи (GEMAS). Пошукова та екологічна геохімія, 1(12), 51–66.*
23. *Glina, B., Kowalska, J. B., Łuczak, K., Mazurek, R., Spychalski, W., & Mendyk, Ł. (2021). Potentially toxic elements in fen peatland soils located near lignite-fired power plants in Central Poland. Geoderma Regional, 25, e00370. https://doi.org/10.1016/j.geodrs.2021.e00370 .*

Authors Contribution: All authors have contributed equally to this work
Conflict of Interest: The authors declare no conflict of interest

References

1. *Osborne, C., Gilbert-Parkes, S., Spiers, G., Lamit, L. J., Lilleskov, E. A., Basiliko, N., & Watmough, S. (2024). Global patterns of metal and other element enrichment in bog and fen peatlands. Archives of Environmental Contamination and Toxicology, 86(2), 125–139. https://doi.org/10.1007/s00244-024-01051-3*
2. *Thalassinos, G., Petropoulos, S. A., Grammenou, A., & Antoniadis, V. (2023). Potentially toxic elements: A review on their soil behavior and plant attenuation mechanisms. Agriculture, 13(9), 1684. https://doi.org/10.3390/agriculture13091684*
3. *Klavins, M., Silamikele, I., Nikodemus, O., Kalnina, L., Kuske, E., Rodinov, V., & Purmalis, O. (2009). Peat properties and trace element accumulation in bog peat in Latvia. Baltica, 22(1), 37–49.*
4. *Silamikele, I., Klavins, M., & Nikodemus, O. (2011). Major and trace element distribution in the peat from ombrotrophic bogs in Latvia. Journal of Environmental Science and Health, Part A, 46(7), 805–812. https://doi.org/10.1080/10934529.2011.572005*
5. *Krumins, J., Kuske, E., & Klavins, M. (2011). Major and trace element accumulation in fen peat from Elki and Viki Mires in Western Latvia. Material Science & Applied Chemistry, 24, 71–81.*
6. *Adumitroaei, M. V., Iancu, G. O., Rățoi, B. G., Doru, C. S., & Sandu, C. M. (2018). Spatial distribution and geochemistry of major and trace elements from Mohoş peatland. The Holocene, 28, 1936–1947. 2 https://doi.org/10.1177/0959683618798174*
7. *Fiałkiewicz-Kozieł, B., Smieja-Król, B., & Palowski, B. (2011). Heavy metal accumulation in peat bogs from southern Poland. Studia Quaternaria, 28, 17–24.*
8. *Smieja-Król, B., Fiałkiewicz-Kozieł, B., Sikorski, J., & Palowski, B. (2010). Heavy metal behaviour in peat: A mineralogical perspective. Science of the Total Environment, 408, 5924–5931. https://doi.org/10.1016/j.scitotenv.2010.08.032*
9. *Lu, Z., Ning, Y., Liu, C., Song, X., Pang, Y., Li, Q., … Zeng, L. (2025). Geochemical regulation of heavy metal speciation in subtropical peatlands. Land, 14(6), 1256. https://doi.org/10.3390/land14061256*
10. *Instytut gruntoznavstva ta agrohimii im. O. N. Sokolovskoho. (2008). DSTU EN 13040:2005. Soil improvers and growth media. Sample preparation. Kyiv. [in Ukrainian]*
11. *Tekhnichnyi komitet «Hruntoznavstvo»; NNTs IHA im. O. Sokolovskoho. (2015). DSTU 7942:2015 Soil quality. Determination of peat ash content. Kyiv. [in Ukrainian]*
12. *Instytut silskohospodarskoi mikrobiolohii NAAN. (2016). DSTU 7882:2015. Peat and peat products. Determination of acidity. Kyiv. [in Ukrainian]*
13. *Instytut gruntoznavstva ta agrohimii im. O. N. Sokolovskoho. (2006). DSTU 4405:2005. Soil quality. Determination of mobile P and K. Kyiv. [in Ukrainian]*
14. *Bradis, Ye. M., Kuzmychov, A. I., Andriienko, T. L., & Batiachov, Ye. B. (1973). Peat-bog resources of the Ukrainian SSR. Kyiv: Naukova dumka. [in Ukrainian]*

15. *Irving, H. M. N. H., & Williams, R. J. P. (1948). Order of stability of metal complexes. Nature, 162, 746–747. https://doi.org/10.1038/162746a0*
16. *Schnitzer, M., & Khan, S. U. (1972). Humic substances in the environment. Marcel Dekker.*
17. *Van Dijk, H. (1971). Cation binding of humic acids. Geoderma, 5(1), 53–67. https://doi.org/10.1016/0016-7061(71)90024-3*
18. *Boguta, P., & Sokołowska, Z. (2013). Interactions of humic acids with metal ions. Acta Agrophysica, 2, 113.*
19. *Yakovenko, M., Khokha, Yu., & Liubchak, O. (2022). Geochemical features of heavy metal accumulation and migration in peats of the Lviv region. Visnyk of Kharkiv National University. Geology. Geography. Ecology, 56, 105–121. https://doi.org/10.26565/2410-7360-2022-56-07*
20. *Rudnick, R. L., & Gao, S. (2003). Composition of the continental crust. Treatise on Geochemistry, 3, 1–64. https://doi.org/10.1016/B0-08-043751-6/03016-4*
21. *Bowen, H. J. M. (1979). Environmental Chemistry of the Elements. Academic Press.*
22. *Klos, V. R., Birke, M., Zhovynskyi, E. Ya., Akinfiiev, H. O., Amashukeli, Yu. A., & Klamens, R. (2012). Regional geochemical study of soils of Ukraine. Poshukova ta ekolohichna heokhimiia, 1(12), 51–66. [in Ukrainian]*
23. *Glina, B., Kowalska, J. B., Łuczak, K., Mazurek, R., Spychalski, W., & Mendyk, Ł. (2021). Potentially toxic elements in fen peatland soils located near lignite-fired power plants. Geoderma Regional, 25, e00370. https://doi.org/10.1016/j.geodrs.2021.e00370*

Рухомі форми мікроелементів у торфових відкладах Львівської області: вертикальний розподіл та зв’язок із фізико-хімічними властивостями

Мирослава Яковенко [1]
к. геол. н., ст. досл., ст. наук. співробітник,
[1] Інститут геології і геохімії горючих копалин НАН України, Львів, Україна;
Юрій Хоха [1]
д. геол. н., ст. дослідник, пров. наук. співробітник;
Мирослав Павлюк [1]
академік НАН України, д. геол.-мін. н, професор, радник при дирекції

У роботі досліджено вертикальний розподіл рухомих форм важких елементів (Pb, Tl, Zn, Cd, Cu, As, Sb, Mo, Ni, Co, Mn, Cr, V) у торфових відкладах Львівської області та встановлено їх зв’язок із базовими фізико-хімічними параметрами (вологість, зольність, pH, вміст органічної речовини). Відібрано 26 зразків з глибинного інтервалу 0–140 см з кроком 20 см (для трьох розрізів) та з верхніх шарів інших торфовищ; рухомі форми елементів екстрагували 0,2 М HCl і визначали методом атомно-емісійної спектроскопії з індуктивно-зв’язаною плазмою (ICP-AES). Проведено дослідження залежності концентрацій хімічних елементів від глибини та фізико-хімічних властивостей торф’яного шару, взаємозв’язків і взаємодії між вмістом мікроелементів та іншими характеристиками торфу й оцінки можливих джерел їх накопичення за допомогою статистичного аналізу. Встановлено, що середній вміст рухомих форм Pb, Zn, Cd, Cu, Ni, Mn та Cr становив відповідно 10,8; 15,5; 0,65; 3,86; 2,09; 16,6 та 0,96 мг/кг (ppm), при дуже високих коефіцієнтах варіації для Pb, Cd, Tl, Mo, Sb, Mn (більше 80 %), що вказує на мозаїчну просторову структуру розповсюдження елементів. Максимальні значення Pb (132,35 мг/кг) та Cd (8,88 мг/кг) зафіксовані у горизонті 60–80 см торфовища Гончари, а підвищений вміст As (14,9 мг/кг) – у нижній частині профілю Гамаліївка. У більшості зразків концентрації рухомих форм елементів є значно нижчими за орієнтовні нормальні значення для ґрунтів та порогові рівні забруднення, встановлені для орних ґрунтів у країнах ЄС, що свідчить про загалом низький рівень техногенного навантаження за наявності локальних аномалій вмісту свинцю та кадмію. Вологість торфу в середньому становила 59 % (15–87 %), зольність – 20 %, вміст органічної речовини – близько 80 %, pH варіював від кислого до слабколужного (4,4–7,7). Для профілів Білогорща та Гамаліївка характерне зростання вологості з глибиною, тоді як у Гончарах спостерігається чергування більш зволожених і відносно підсушених горизонтів. Встановлено позитивний зв’язок вмісту більшості металів із зольністю та негативний – з вмістом органічної речовини, а також істотну кореляцію між Zn, Cu, Ni, Co, Mn та V, що відображає спільність джерел та механізмів акумуляції; найвищу кореляцію ($r \approx 0,99$) виявлено між рухомими формами Pb і Cd, що підтверджує їх спільну геохімічну поведінку в торфі. Результати свідчать, що торфовища Львівщини є ефективним геохімічним бар’єром для акумуляції потенційно токсичних елементів, водночас локальні глибинні аномалії Pb–Cd та As можуть бути пов’язані як із геогенною складовою, так і з історичними епізодами атмосферного надходження. Отримані дані уточнюють уявлення про геохімію українських торфовищ та формують основу для подальшої оцінки екологічних ризиків і придатності торфу до господарського використання.

***Ключові слова**: торф, торфовище, геохімія, мікроелементи, рухомі форми, накопичення, Україна, Львівський регіон, ICP-AES.*

Внесок авторів: всі автори зробили рівний внесок у цю роботу
Конфлікт інтересів: автори повідомляють про відсутність конфлікту інтересів

Надійшла 11 жовтня 2025 р.
Прийнята 18 листопада 2025 р.